

PROCEEDINGS

UNIVERSITY OF NIŠ | **FACULTY OF CIVIL ENGINEERING AND ARCHITECTURE**

INTERNATIONAL SCIENTIFIC CONFERENCE | **NIŠ, SERBIA**

GREEN BUILDING | 2026

INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

15-16 OCTOBER 2026

UNIVERSITY OF NIŠ
FACULTY OF CIVIL ENGINEERING
AND ARCHITECTURE

Republic of Serbia
MINISTRY OF SCIENCE,
TECHNOLOGICAL DEVELOPMENT AND INNOVATION



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PREFACE

Following the successful first edition held in 2024, the Green Building 2026 Conference returns as an **International Scientific Conference**, supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, continuing its mission of bringing together contemporary scientific research and practical knowledge in architecture, urban planning and design, civil and hydraulic engineering. The second edition of the Conference is dedicated to advancing sustainability and climate resilience of the built environment and to fostering the exchange of innovative approaches, technologies, methodologies, and professional experience in response to the complex challenges facing cities and communities today.

The Conference addresses a broad range of interconnected topics, including sustainable urban planning and architecture, green buildings and energy efficiency, sustainable structures and circular engineering, adaptive reuse and built heritage, water, environment and blue-green infrastructure, smart and climate-adapted cities, and digital technologies and data-driven approaches. This interdisciplinary scope reflects the need to move beyond sectoral solutions and develop integrated approaches capable of addressing the environmental, technical, social, and economic dimensions of sustainable development.

The response of the scientific and professional community to the 2026 Conference has been highly encouraging. This year's program features three invited keynote papers, alongside 73 contributions accepted for publication in these Conference Proceedings. The papers bring together 151 authors and co-authors, including 40 affiliated with institutions outside the host country. A total of 17 international papers enrich the scientific program, while 12 contributions are presented within the dedicated PhD Student Session. This special session was established to support doctoral researchers by providing a forum for presenting ongoing work, receiving constructive feedback, and building academic connections.

The scientific quality of the submissions was ensured through an extensive peer-review process involving 71 reviewers. Each paper underwent evaluation by two reviewers, with 22 reviewers contributing to the assessment of three or more papers. The international character of the Conference is further reflected in the participation of authors, co-authors, Scientific Committee members, and reviewers representing institutions from 22 countries.

We sincerely thank all authors, reviewers, members of the Scientific Committee, and participants for their valuable contributions and engagement. We hope that these Proceedings will serve as a useful source of knowledge, stimulate research and collaboration, and contribute to the application of sustainable and climate-resilient solutions in the built environment.

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INVITED PAPERS

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

RESILIENT WATERSHEDS FOR SUSTAINABLE SOCIETIES

Jasna Plavšić[1]

Abstract

Climate change, land-use change, environmental degradation and increasing competition for water are placing growing pressure on river basins and the communities that depend on them. Addressing these pressures requires moving beyond isolated measures towards an integrated watershed perspective that recognizes the interactions between hydrological processes, ecosystems, land use, infrastructure and governance. This paper discusses a conceptual pathway to resilience linking watershed resilience with spatial planning, green infrastructure (GI) and nature-based solutions (NBS). Watersheds are considered as social-ecological-technological systems in which natural storage, connectivity and water regulation provide the physical basis for resilience. GI and NBS can strengthen these functions across forests, agricultural areas, wetlands, floodplains, rivers and urban areas, while providing multiple hydrological, ecological and socio-economic benefits. However, their wider implementation is constrained by institutional, regulatory, political, financial and knowledge-related barriers. These barriers interact and may reinforce each other, requiring interventions that address the most influential constraints within a particular governance context. The paper therefore emphasizes the integration of NBS and GI into watershed-scale spatial planning and infrastructure development, supported by coordinated governance, technical capacity and long-term institutional commitment. Such an approach can strengthen both rural and urban resilience as it provides a link between climate adaptation, water security and sustainable development.

Key words: *watershed resilience; nature-based solutions; green infrastructure; integrated governance; spatial planning*

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1. INTRODUCTION

River watersheds are among the most important natural systems. They provide water, food, energy, biodiversity, and livelihoods to people globally. However, growing climatic, environmental, and socio-economic pressures increasingly threaten their ability to deliver these essential services. Climate change, interacting with other challenges such as land degradation, biodiversity loss, pollution, river fragmentation, and growing competition for water resources create complex and interconnected risks across entire river basins.

Climate warming is altering the hydrological cycle and increasing the intensity and frequency of extreme events, including heavy rainfall, floods, droughts, or heatwaves [1]. Warmer air can hold more moisture, leading to more intense precipitation events and greater flood risk in many watersheds. At the same time, rising temperatures increase evaporation from soils, rivers, lakes, and reservoirs, contributing to more frequent and severe droughts. Both flood and drought risks are projected to increase under all scenarios of global warming [2]. Heat also places additional stress on river ecosystems by raising water temperatures, reducing dissolved oxygen levels, and increasing water demand from cities and agriculture.

Land-use change and land degradation considerably affect the hydrological cycle and amplify hydrological extremes. Urbanization, deforestation, and intensifying agricultural practices reduce the landscape's ability to absorb and store water. As a result, rainfall is converted into surface runoff more rapidly, increasing flood peaks and erosion. At the same time, degraded soils are less able to retain moisture and recharge groundwater, making watersheds more vulnerable during dry periods. The Food and Agriculture Organization [3] identifies land degradation, water scarcity, and climate change as closely linked challenges that threaten the sustainability of land and water resources.

Another major concern is the rapid loss of freshwater biodiversity, which is declining rapidly because of multiple human pressures accumulated across entire watershed systems [4]. Rivers, wetlands, floodplains, and riparian forests provide critical ecosystem services, including flood regulation, water purification, groundwater recharge, and habitat for countless species. Yet freshwater ecosystems are among the most threatened ones due to pollution, water abstraction, dam construction, and climate change. With degrading ecosystems, watersheds lose part of their natural capacity to buffer floods, sustain water quality, and remain resilient during droughts.

Increasing competition for water resources adds further pressure. Agriculture, which accounts for more than 70% of global freshwater withdrawals [3], competes with growing municipal, industrial, energy, and environmental water needs. During drought periods, these competing demands become particularly acute, often leading to difficult trade-offs between economic development and ecosystem protection. Water scarcity limits water supply, reduces agricultural productivity, threatens energy generation, damages ecosystems, and increases the potential for social and political tensions, especially in transboundary river basins shared by several countries.

The greatest challenge for watersheds is therefore the interaction of multiple pressures rather than any single issue taken alone. Addressing these interconnected

challenges requires integrated river basin management that simultaneously considers water, land, ecosystems, climate adaptation, and governance across the whole catchment. Despite this, many current responses remain fragmented and sectoral in nature. Water resource management, flood and drought risk management, urban development, agricultural policy, and biodiversity conservation are often addressed through separate institutional and planning processes, limiting their ability to deliver integrated outcomes.

Water security and hence the community resilience in urban and rural areas is therefore closely linked to the health of upstream watersheds or the watershed from which they are supplied with water. Disturbed hydrological and ecological processes in a watershed directly influence the quantity, quality, and timing of water reaching downstream areas. With growing pressures on both land and water resources and the intensification of hydrological extremes due to climate change, there is a need to strengthen watersheds' health by moving beyond separated interventions towards a more integrated systems perspective. Such an approach must recognize watersheds as complex systems shaped by interdependencies among biophysical processes, human settlements, infrastructure, ecosystems, and governance arrangements across multiple spatial and temporal scales.

In response to this need and building on a synthesis of current research and the most recent European policies [5], this paper discusses a conceptual pathway to resilience that integrates watershed processes, ecosystem services, green infrastructure, spatial planning, and governance. The aim is to demonstrate how decision- making that is both integrated and synergistic can enhance the capacity of watersheds and communities to adapt to and manage increasingly complex environmental and societal risks.

2. WATERSHEDS AS SOCIAL-ECOLOGICAL SYSTEMS

Watersheds are not merely hydrological units but complex social-ecological-technological systems in which the water cycle is tightly interconnected with ecological processes and human socio-economic activities [5][7]. Resilience of the communities is closely linked to the health of upstream watersheds because the ecological and hydrological processes occurring across a watershed directly influence the quantity, quality, and timing of water reaching downstream areas (see Figure 1).

Healthy watersheds are characterized by natural land cover, functioning headwater streams, riparian corridors, connected floodplains, wetlands, and intact hydrological and geomorphological processes that operate within their natural range of variation [8]. These elements function as natural infrastructure [9], regulating the movement and storage of water across the landscape. They intercept, store and gradually release water, facilitate infiltration and groundwater recharge, regulate sediment transport, filter pollutants, and sustain water quality and ecological integrity. For example, groundwater storage maintains streamflow during drought, while large soil storage reduces rapid runoff generation and floodplain storage attenuates flood peaks. Natural ecosystems like forests and wetlands purify water, regulate flow regimes, and sustain

biodiversity, which directly underpins public water supplies, agriculture, and power generation [5][10].

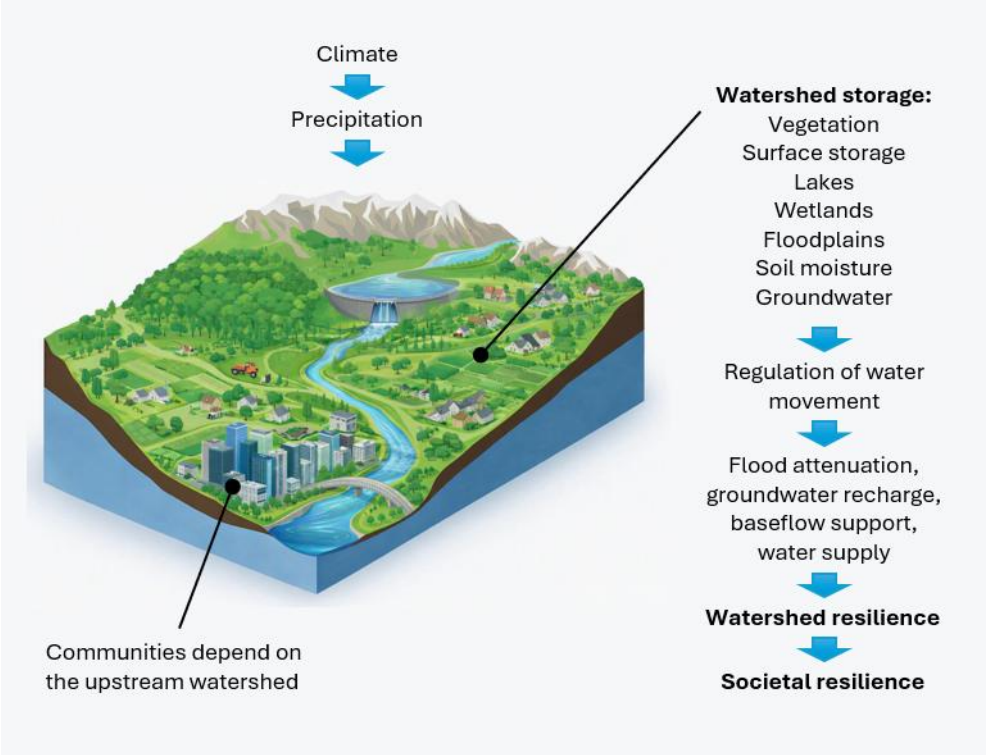


Figure 1. Watershed as an interconnected social-ecological system.

Human systems are embedded within and dependent on these biophysical processes. Anthropogenic interventions, such as intensive water abstraction and environmental degradation disrupt water cycle by deteriorating both water quality and water quantity, also intensifying risks like droughts and floods, which all threaten socio-economic stability [5][11]. Land-use conversion, deforestation, and intensive irrigation and artificial drainage accelerate runoff, increase sediment and pollution loads, reduce groundwater recharge, and diminish the natural capacity of landscapes to buffer climatic extremes, thereby amplifying downstream flood, drought, and water-quality risks. Cumulative degradation can push a watershed past critical ecological thresholds, triggering a regime shift into a permanently degraded, alternative state (such as persistent lake eutrophication or land subsidence) that is difficult or impossible to reverse [5].

Therefore, sustainable human societies, public health, water and food security, and economic development depend fundamentally on healthy, resilient watersheds [5] [12]. Building watershed resilience requires integrated, multi-benefit actions across scales and sectors [5] [13]. These actions should be grounded in integrated water resources management, spatial planning that safeguards landscape functions and reconnects storage elements, and measures that preserve natural water retention and recharge, such as nature-based solutions or managed aquifer recharge [11]. Agricultural and

forest practices that enhance infiltration and reduce erosion are equally vital. Combining green and grey infrastructure also creates a diversified and redundant portfolio that buffers communities against climate variability, protects aquatic biodiversity, and secures a resilient water future.

3. GREEN INFRASTRUCTURE AS THE BACKBONE OF WATERSHED RESILIENCE

Green infrastructure (GI) and nature-based solutions (NBS) are fundamentally landscape-scale approaches [14], although they are often perceived primarily as urban tools. While much research focuses on their role in addressing urban flooding, heat and pollution [15] [16], their application extends throughout entire river catchments across forests, agricultural landscapes, wetlands, rivers and floodplains. By using and restoring natural processes, NBS and GI can regulate water, reduce hazards, improve water quality and support biodiversity, creating a connected network of natural and semi natural areas from headwaters to the sea [5][14]. To be effective, these measures must be planned and managed with a broad landscape perspective that recognizes the interlinked dynamics of whole watersheds.

The appropriate measures depend on the biophysical characteristics and land uses within each part of the watershed. Forests in headwater areas can increase interception and soil storage, slow runoff, reduce erosion and sediment transport, and regulate water availability. Sustainable forest management, afforestation, forest preservation and continuous-cover forestry can therefore contribute to both flood and drought resilience [14]. Floodplain restoration and reconnection, including levee setbacks and removal of obsolete embankments, restore lateral river-floodplain connectivity and provide space for temporary flood storage, reducing downstream flood levels. Wetland restoration and rewetting, including peatlands, can increase landscape water storage, regulate runoff and improve water quality [5] [16]. River restoration, through re-meandering, natural bank stabilization, removal of barriers and the use of woody structures or permeable barriers, can restore channel complexity, slow flow and improve longitudinal and ecological connectivity weirs [16].

In agricultural landscapes, conservation tillage, cover crops, contour farming, agroforestry, vegetated buffer strips and farm ponds can increase soil water retention, reduce erosion and intercept nutrients and sediments. These measures can simultaneously reduce rapid runoff during wet periods and retain water for use during dry periods. In cities, where soil sealing has disrupted natural water pathways, GI and sustainable urban drainage systems translate these principles into space-efficient interventions such as green roofs, permeable surfaces, swales and rain gardens. By retaining and infiltrating rainfall close to where it falls, they reduce pressure on drainage systems while providing additional environmental and social benefits.

The importance of NBS and GI lies in their multifunctionality. By restoring the storage and regulatory capacity of landscapes, they can attenuate flood peaks, retain water during wet periods, support groundwater recharge and sustain baseflows during droughts. At the same time, they create and reconnect habitats, improve water quality, support carbon storage and enhance ecological connectivity [18]. These ecological

functions generate socio-economic benefits, including more reliable water supplies, protection of agricultural productivity and infrastructure, reduced exposure to hazards, recreational opportunities and improved human wellbeing.

Thus, NBS and GI should not be considered alternatives to conventional infrastructure in a simple "green versus grey" distinction. Rather, they form a complementary layer of natural and semi-natural infrastructure that works across spatial and temporal scales. At watershed scale, their combined effect is to strengthen the capacity of landscapes to store, regulate, filter and redistribute water while maintaining ecological functions. This makes NBS and GI a central means of translating the concept of watershed resilience into practical spatial planning and climate adaptation.

4. GOVERNANCE: FROM FRAGMENTATION TO RESILIENCE

The effectiveness of watershed-scale GI and NBS depends not only on their technical performance, but also on the conditions under which they are planned, implemented and maintained. Watersheds cross administrative boundaries, while the responsibilities for water management, spatial planning, forestry, environmental protection, agriculture, infrastructure and economic development are distributed among different authorities. Decisions are therefore frequently made according to different objectives and regulatory frameworks, so the measures are planned for individual sectors or locations rather than as parts of an integrated watershed management.

Although there is increasing support to GI and NBS in strategic policies, their implementation and mainstreaming into governance remain fragmented and context-specific [19]. This "implementation gap" (as coined by [19]) is driven by a combination of institutional, legal, technical, financial, and knowledge-related barriers, including unclear responsibilities, fragmented regulations, insufficient funding, limited technical expertise and evidence of NBS performance, difficulties in assessing their multiple benefits, and stakeholder conflicts. Additionally, conventional grey infrastructure is often favoured because its design standards, costs, and performance are more familiar to decision-makers.

However, the barriers to NBS implementation are not independent problems; they are interconnected through feedback mechanisms among knowledge and awareness, political will and financial resources, institutional fragmentation, and implementation challenges [20]. These interactions can create self-reinforcing cycles in which one barrier strengthens other ones. Conversely, actions directed at overcoming strategically important barriers (i.e., those strongly affecting the emergence of other barriers) can produce positive spillover effects beyond overcoming the individual problem being addressed. Evidence from two Serbian pilot cases [20] illustrates these interactions: although funding was identified as a major barrier, its availability alone would have limited effect without adequate regulation, spatial planning, implementation procedures and qualified personnel. The analysis therefore points to education and raising awareness, stronger regulatory and planning frameworks, political commitment,

and better evidence on the costs and wider ecological and societal benefits of NBS as potentially more transformative intervention points.

Based on these findings, the first step in improving the GI/NBS uptake and watershed resilience should be to identify the dominant constraints and their interactions within a particular watershed. For example, floodplain or wetland restoration may conflict with economic development objectives, creating pressure on spatial plans to allocate land for housing, infrastructure, agriculture, or industry rather than retain it for flood storage and ecological functions. Loss of these natural functions can subsequently increase flood risk and the need for costly engineered protection, creating feedback in which short-term development benefits contribute to higher long-term risk.

The second requirement is to move from individual projects towards their systematic integration into watershed-scale spatial planning and infrastructure development. Spatial planning, river basin management, climate adaptation, flood-risk management, biodiversity conservation and rural development should not be treated as separate activities when they affect the same watershed processes. Planning at the watershed scale can identify where natural storage, infiltration, flood conveyance and ecological connectivity should be protected or restored, and where NBS can complement conventional infrastructure. Landscape architecture is also an important component of NBS design, closely linked to spatial planning in translating ecological and hydrological objectives into spatial interventions [21].

For watershed resilience, governance should consequently provide three basic functions: coordination, capacity and continuity. Coordination is needed to align decisions across sectors, administrative levels and upstream-downstream interests. Capacity includes technical knowledge, reliable evidence on NBS performance, appropriate design and maintenance practices, and methods for assessing multiple benefits. Continuity requires stable regulations, financing and institutional responsibilities that extend beyond individual projects and political cycles. Many of these factors (dedicated funding, polycentric governance, cross-sector coordination and alignment among governance levels, evidence, expertise, and stakeholder engagement) are identified in [22] and [19] as important enablers of NBS implementation.

Effective governance should therefore be seen as a part of the infrastructure required for watershed-scale resilience. Its role is to create conditions for individual GI/NBS measures to function as a connected system: integrated through spatial planning, supported by appropriate institutions and financing, monitored for performance, and adapted as knowledge and climate conditions evolve. In this way, governance is the mechanism through which watershed resilience can lead to long-term societal resilience.

5. AN INTEGRATED PATHWAY TO SOCIETAL RESILIENCE

The preceding sections show that watershed resilience cannot be achieved through separate interventions or within administrative boundaries. It requires an integrated approach in which: (i) the watershed is considered as a connected social-ecological-

technological system, (ii) spatial planning determines how land, water and people interact, and (iii) GI/NBS measures strengthen the natural processes that regulate water and support ecosystems. In this way, resilience should not be a single function of flood protection or water supply, but an outcome of interactions among hydrological, ecological and socio-economic functions.

A watershed resilience pathway can therefore be understood through four interconnected elements (Figure 2). First, watershed processes provide the physical foundation of resilience. The capacity of forests, soil, groundwater, rivers, wetlands, and floodplains to store, regulate, redistribute and purify water determines how the watershed responds to climatic extremes. Maintaining connectivity among these components, while restoring it where it has been lost, is essential for reducing both flood and drought risks.

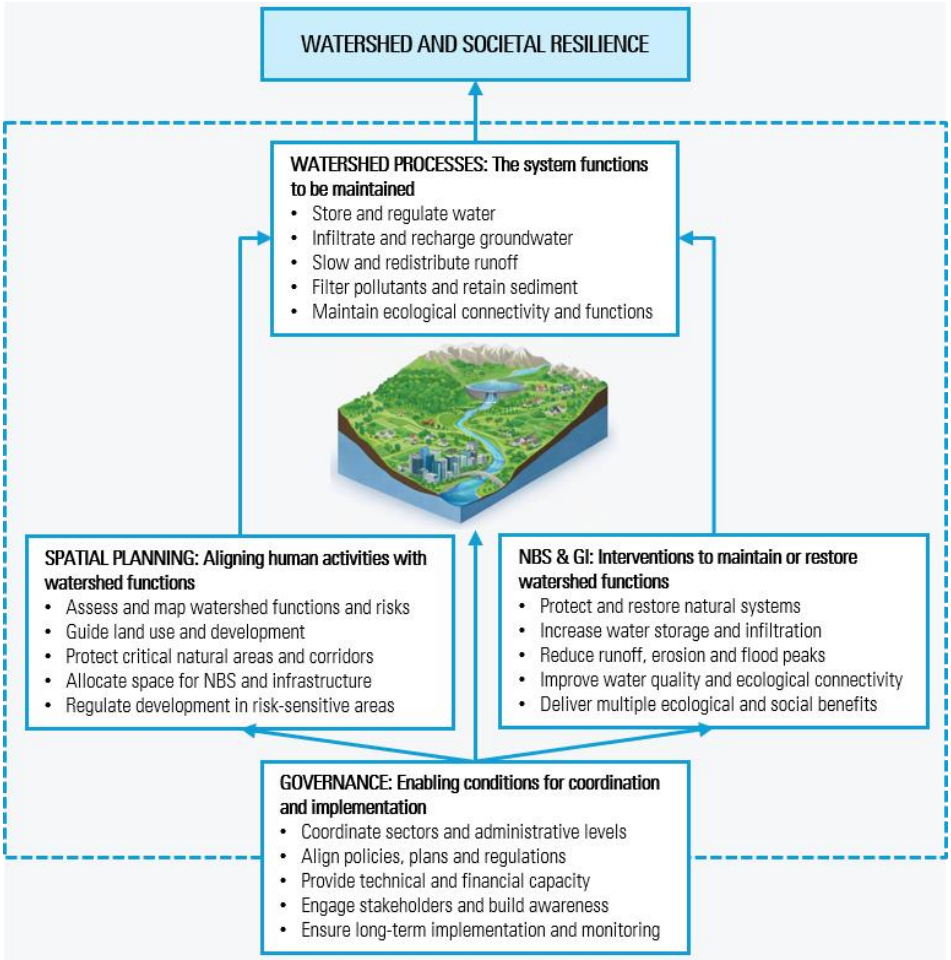


Figure 2. Integrated pathway towards watershed resilience.

Second, spatial planning provides the means to protect and enhance these functions. Decisions on land use, urban development, agriculture, forestry and infrastructure directly influence runoff, infiltration, storage and water quality. Planning should therefore recognize the watershed as a functional unit and identify where natural

processes should be protected, restored or complemented by engineered infrastructure. This includes identifying areas where interventions such as headwater forest protection, floodplain restoration or urban green infrastructure can provide significant risk reduction benefits, as well as strategically locating appropriate measures that reduce downstream risks using knowledge of hydrological and hydrogeological pathways. Spatial planning can incorporate connected networks of strategically located landscape elements, including ecological and freshwater corridors, into territorial plans. Spatially distributed but coordinated interventions can provide multiple simultaneous benefits (including flood attenuation, groundwater recharge, water-quality improvement, heat mitigation, carbon storage and recreational opportunities) and can further increase the robustness of the overall system by avoiding excessive dependence on individual locations or interventions. This also implies moving beyond the conventional separation between urban and rural planning and considering upstream-downstream relationships explicitly.

Third, GI and NBS provide practical measures for translating these principles into action. Their value lies not only in reducing individual hazards but also in generating multiple ecological, social and economic benefits from the same intervention. For example, restoring a floodplain can reduce flood risk while improving biodiversity, water quality, habitat connectivity and recreational opportunities; improving agricultural soil management can reduce runoff and erosion while increasing soil moisture, productivity and soil health; and protecting headwater forests can support water regulation, water quality, biodiversity and carbon storage. Across the watershed, connected GI/NBS can contribute to groundwater recharge, ecosystem functioning, climate regulation, landscape quality and human wellbeing, while also reducing damage to settlements, infrastructure and productive activities. Such multifunctionality can increase the overall efficiency and societal value of resilience investments. However, the evidence that these benefits are achieved simultaneously or without adverse effects is still limited, and therefore potential disbenefits, conflicts and trade-offs should be identified and assessed during the planning stage.

Fourth, governance determines whether these opportunities can be realized at the required scale. Effective watershed resilience requires coordination across administrative levels, sectors and stakeholder groups, supported by coherent policies, appropriate financial mechanisms and long-term institutional commitment. Financial mechanisms may include public investment programmes, dedicated climate-adaptation funds, green bonds, payments for ecosystem services, and emerging instruments such as flood credits that can reward or finance measures providing verified flood-risk reduction. Governance should also enable learning and adaptation, since the performance of NBS and GI depends on local conditions and may change under future climatic and socio-economic conditions. This requires systematic monitoring of hydrological, ecological and socio-economic performance, regular assessment of whether measures deliver their intended benefits, and mechanisms for adjusting their design, operation, maintenance or spatial distribution as conditions and knowledge evolve.

These elements form a reinforcing system rather than a linear sequence. Healthy landscapes improve hydrological regulation and generate visible environmental and socio-economic benefits; these benefits can strengthen public support and political commitment for further investment and protection. Conversely, fragmented planning, weak institutions or inappropriate land-use decisions can undermine natural regulation and increase risks, creating further pressure on infrastructure and public resources.

The ultimate objective is therefore not simply watershed resilience, but the capacity of society to remain secure and functional under changing environmental conditions. A resilient watershed supports reliable water resources, reduces exposure to floods and droughts, sustains ecosystems and livelihoods, and provides healthier and more liveable settlements. In this sense, watershed resilience provides a bridge between climate adaptation and sustainable development: protecting and restoring the functions of the watershed becomes an investment in the resilience and sustainability of society as a whole.

6. CONCLUSIONS

Climate change and increasing pressures on land and water resources require a shift from fragmented responses towards a watershed-scale approach to resilience. This paper has argued that the watershed provides an appropriate framework for connecting hydrological processes, ecosystems, human settlements and infrastructure. Its capacity to store, regulate, filter and redistribute water is a fundamental component of resilience to both floods and droughts.

Green infrastructure and nature-based solutions can strengthen these natural functions across the watershed, from headwater forests and agricultural landscapes to wetlands, floodplains, rivers and urban areas. Their main advantage is their multifunctionality: the same measures can reduce hydrological risks while improving water quality, biodiversity, ecosystem services and human wellbeing. Their value is therefore greater when they are considered as a connected network rather than as individual projects.

However, achieving watershed-scale resilience is not only a technical challenge. Spatial planning and infrastructure decisions determine whether natural storage and connectivity are protected or lost, while governance determines whether individual measures can be coordinated, implemented and maintained at the required scale. Institutional fragmentation, lack of political will, competing land-use objectives, limited capacity, inadequate evidence and financing can reinforce each other and constrain implementation. Identifying these interactions and addressing strategically important constraints is therefore essential.

The proposed pathway links watershed processes, spatial planning, GI/NBS and governance within a common resilience perspective. Its central message is that resilient societies depend on resilient watersheds. Protecting and restoring watershed functions should therefore be considered not only as an environmental objective, but as a long-term investment in water security, climate adaptation, economic stability and societal sustainability.

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Research paper

WHO HAS ACCESS TO GREEN RELIEF? A COST-DISTANCE EQUITY INDEX FOR GREEN INFRASTRUCTURE PLANNING IN NIŠ

Petar Vranić[1]

Abstract

The ecosystem services of Urban green infrastructure (UGS) are well-documented, however conventional accessibility measures like Euclidean buffers and arbitrarily weighted composite indices poorly capture real pedestrian access or defensible priority-setting. This study develops a network-based cost-distance equity index for green infrastructure in the urban core of Niš, Serbia, using a 100 m analysis grid. Walking-time costs to local, district, and city parks were derived via GRASS r.cost, transformed through negative exponential decay functions calibrated wiht planning standars, and combined into a non-compensatory composite deficit score. Bivariate Local Indicators of Spatial Association (LISA), tested across three spatial weight specifications, identified statistically robust priority clusters overlapping deficit with four age-vulnerable population subgroups. In total, 6,134 grid cells are examined. Of these, 917 cells, or 15.0%, fall into robust Tier 1 priority zones. These zones hold about 57 to 59% of the vulnerable population for each subgroup. That is a large share, even though the zones cover only 15% of the study area. The resulting three-tier classification, together with descriptive attributes for each cluster, gives a ranked set of planning outputs that can be used for decission making procecss. This approach avoids arbitrary weights at each step, and keeps the same logic from the decay calibration, through the deficit index build, cluster robustness test. Thus it offers a transparent, reproducible framwork that other mid-sized cities with comparable open data availability could adapt to their own green infrastructure planning processes.

Key words: *Green infrastructure accessibility, Cost-distance analysis, Spatial equity, Bivariate LISA, Decision making, Urban planning*

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1. INTRODUCTION

UGS are essential to Urban Green Infrastructure (UGI), facilitating the creation of a network of linked green and semi-green habitats that enhance urban ecosystem services [1]. With the rapid pace of global urbanization, it is essential to implement strategic planning and prioritize investments in urban green spaces, especially parks, to optimize environmental and social advantages amid constrained municipal resources [2]. Emphasizing UGS necessitates a harmonious integration of environmental sustainability, social equality, economic efficiency, and ecological connectedness [3,4]. Certain types of UGS offer more advantages than their counterparts. Expansive and intricate green areas, particularly parks, offer vital ecological benefits and community roles [5].

Parks are the most efficient and versatile urban green spaces, providing vast, uninterrupted areas for a variety of ecological functions and human endeavors. Multifunctional parks represent a more sustainable alternative to traditional gray infrastructure, since green infrastructure offers enhanced management flexibility and long-term adaptation [1].

Many studies, also confirms a significant effect on park proximity to our health. The effects seem to shift based on how big the green spaces are, how well they are kept, and whether people can access them fairly. A study of [6,7] found that people near larger and better equipped parks have more physical activity, and better mental well-being. Similar study in Brazil [8] reported that green space nearness and how suitable the spaces are can lower psychological distress. Liu et al. in Guangzhou in 2025 described two linked pathways. Visits to green space help explain how high city density harms mental health. At the same time, how much green space is available changes the strength of that harm, which means it can lessen the impact [9]. Overall, parks appear to support both physical and mental well-being only when they come with enough size, good quality, and fair access for residents.

Serbian legislation and policy frameworks emphasize the advancement of parks and urban green spaces, as well as sustainable urban development. The 2019 Serbian Sustainable Urban Development Strategy, together with the 2021 Action Plan, aims to create resilient and sustainable urban environments. Insufficient human, organizational, and financial resources, together with inadequate training for urban planning stakeholders, persist as institutional constraints. National strategic objectives and local development agendas frequently diverge due to reliance on experiential knowledge and ad hoc criteria, rather than systematic assessment of urban green spaces, encompassing parks and ecosystem services [10].

These problems are likewise evident in the urban environment of Niš, the third-largest city in Serbia. Research indicates that hardly 30% of the residents in Niš have access to parks over 1.5 hectares within an 800-meter proximity [11]. A simiilar study found that 36.7% of urban areas are within a 15-minute walk to parks, with 62.6% in any park, rising to 62.6% for larger district and city parks [12]. Reduced distance criteria (e.g., 400 meters) reveal considerable underserved regions, necessitating tailored planning. These results indicate that intentional park planning and spatial allocation enhance ecological standards and equity.

Building on previous findings this study deepen the accessibility analysis focusing on vulnerable groups that can be more at risk: those under 5, those under 15, those 65 and older, and those 70 and older. These groups tend to get more health value from nearby green areas. At the same time, they move around on their own less often. Because of that, they react more to the walking time cutoffs that are studied here than the overall public does. For this reason, it makes more sense to use a risk measure that fits each subgroup. A single combined vulnerability value would be less useful for planning. The study is organized around a single overarching research question:

Which zones of the Niš urban core exhibit statistically significant spatial overlap between high cost-distance deficit in access to hierarchically distributed parks and high concentrations of age-vulnerable population? Correspondingly, the specific objectives were to: (1) quantify green-space accessibility by park type (city, district, and local) using a cost-distance approach; (2) derive a single per-cell accessibility deficit measure from park-type-specific planning standards; (3) identify statistically significant spatial clusters of overlapping accessibility deficit and vulnerable-population concentration.

2. MATERIALS AND METHODS

The analysis was conducted for the urban core of Niš, using a regular 100 m grid as the unit of analysis, covering 6,134 cells within the defined urban boundary. All spatial layers were processed in EPSG:32634 (UTM zone 34N), a projected, metric coordinate reference system, ensuring that grid cell dimensions and network distances were measured accurately in metres.

2.1. Park inventory and type definitions

The anlysis focuses Niš urban core and cnsiders local, district, and city parks (Figrue 1), as defined by UN Habitat [13]. Regional and peri-urban parks were eliminated. In practice, these parks sit in catchments that are wider and less walk-oriented. Comparing walking time, most homes in the area would reach a regional park on walking cost beyond threshold for the city park. That limit is 12.0 minutes. It is set as the upper bound for the biggest park group kept in the study. On the other extreme pocket parks are also excluded. The reason is definitional. Many items labeled as “pocket parks” in Niš cadastral data and in OpenStreetMap are actually paved squares or plazas. They usually bring only a small set of ecosystem services. Keeping the pocket parks would mix real green infrastructure with places that do not give walkable “green relief.” That is what this index is meant to measure. It would weaken the deficit logic used in the composite score.

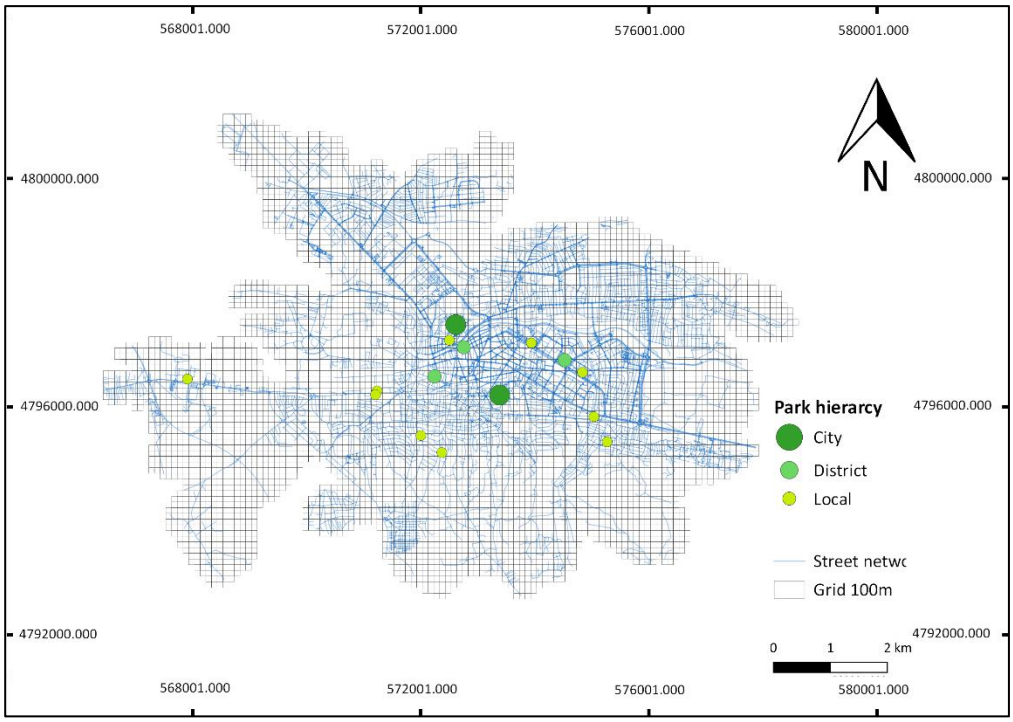


Figure 1. Study area

2.2. Population data, street network and data coverage

Population data are derived form WorldPop (2026) [14] for four age-vulnerable subgroups: 1) children under 5, children under 15, residents 65 and older, and residents 70 and older. Each subgroup raster was aggregated to the 100 m analysis grid by zonal summation, giving four population fields per cell.

The pedestrian street network was derived from OpenStreetMap data for the study's urban extent. Data set is filtered by the highway attribute to retain only segments relevant to pedestrian movement. The network was subsequently prepared for topological consistency in QGIS through a standardised sequence of operations: geometry validation, conversion of multi-part to single-part features, node snapping within a 1 m tolerance, and explicit line-splitting at every intersection. Thus, the full network connectivity is ensured to enable correct functioning of network-analysis algorithms. Grid cells that lack buildings or buildings with a valid cost-distance value to one or more park types, were excluded from the deficit calculation rather than assigned an imputed value. This approach was preferred over imputation because it avoids introducing artificial accessibility values into locations where no residential exposure exists.

2.3. Access thresholds and distance decay

Access thresholds for each park type were derived from UN Habitat [13] service-radius planning recomendation: local parks (300–400 m), district parks (400–600 m), and city parks (800–1,000 m). They are converted to walking-time equivalents using the

midpoint of each radius range and an assumed walking speed of 4.5 km/h. This resulted in thresholds of 4.67, 6.67, and 12.0 minutes for local, neighbourhood, and city-wide parks, respectively.

Raw walking time was turned into an accessibility score from 0 to 1. The rule used a negative exponential decay function (1) that was calibrated for each park type. The score equal 0.5 exactly at the relevant trashold (2). The score of 1 relate to minimal walking cost, while the score approaching 0 indicate progressively poorer accesibility with increased walking time.

$$score = e^{-\lambda \cdot \mathrm{gcost}} \tag{1}$$

$$\lambda = \frac{\ln(2)}{threshold} \tag{2}$$

2.4. Composite accessibility deficit

The three specific accessibility scores were combined into a single composite accessibility deficit per cell using the geometric mean:

$$deficit = 1 - \sqrt[3]{score_{local} \cdot score_{district} \cdot score_{city}} \tag{3}$$

The geometric mean penalizes cells scoring poorly on any single tier more than a simple average, following standard composite-index construction practices, such as the post-2010 revision of the Human Development Index [15,16]. Data-sparse cells without a valid score for any of the three park categories were assigned a missing composite deficit value instead of an imputed score to prevent overstating accessibility or deficit.

2.5. Bivariate spatial cluster analysis (LISA) and priority tier classification

Local Moran's I statistic, were computed using GeoDa [17,18]. Rook contiguity, queen contiguity, and k-nearest-neighbor weights (k = 8) were used to test cluster classification sensitivity to neighborhood definition. Using 999 conditional permutations and a significance criterion of $p < 0.05$, Bivariate Local Moran's I was calculated for each of the four population subgroups against the composite deficit under three weight specifications. Twelve cluster classifications per cell were classified using the standard LISA typology. The main outcome was high-high clusters, cells with high accessibility deficit surrounded by high vulnerable-population concentration.

A robust High-High cluster was only identified for each population subgroup if it was significant under all three weight requirements at once. Cells that were significant under at least one weight specification but not all were labeled as partially robust. The number of population subgroups for which each cell had a resilient High-High cluster was used to construct a priority count (0–4). Tier 1 (priority count ≥ 1: robust High-High cluster for vulnerable subgroup), Tier 2 (priority count = 0 but partially robust for subgroup under weight specification: flagged for field verification), or Tier 3 (no significant High-High classification for any subgroup) were assigned to cells.

2. RESULTS

The study used 6,134 grid cells. For 3,114 of them, 50.8%, the buildings in that cell did not have a valid cost-distance value that covered all three park types. Because of that, these cells were left out of the deficit composite. That left 3,020 cells for the main analysis. The coverage was rather binary, not a gradual split. Out of 3,021 cells that had at least one building with a valid cost value for at least one park type, 3,020 had valid values for all three park types at the same time. Only one cell had a valid value for exactly one park type. Overall, this suggests that the key factor is whether a cell has any building that connects to the street network at all. It is less about having different levels of connection for each park type. The missing data is not spattialy random. Cells with no buildings mostly cover parks, water, and undeveloped land. The high exclusion rate fits the mixed land use in Niš. The final set of 3,020 cells covers most of the city's built residential area. Figure 2 shows the continuous composite deficit surface genrated before cluster classification.

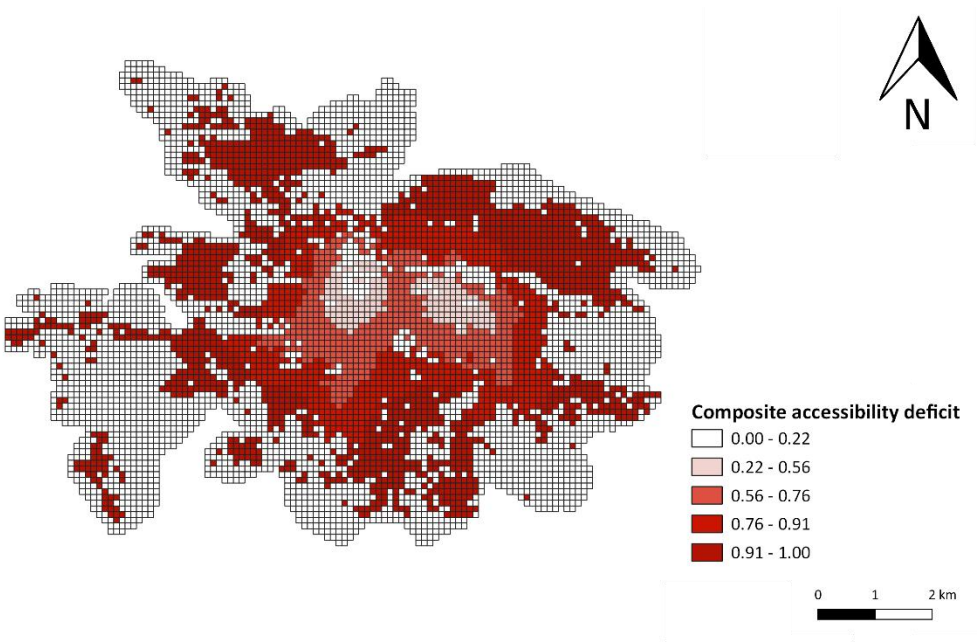


Figure 2. Composite accessibility deficit across the 100 m analysis grid

Out of 6,134 grid cells, 917 of them (15.0%), were classified as Tier 1. These cells showed a strong High-High bivariate LISA relationship between the composite accessibility deficit and at least one vulnerable group. This result held up under all three spatial weight choices. Next, 212 cells (3.5%) fell into Tier 2. They had a significant High-High relationship under at least one weight choice. These are marked for extra field checks. They are not meant for immediate investment priority. The last group, Tier 3, was 5,005 cells (81.6%). Tire 3 shuld not be treated as „well served." Tier 3 includes cells with low deficit. It also includes cells left out of the LISA test because building level accessibility data was missing. Rsults of the Indivudal LISA test is shown in Figure 3.

Distribution of how many people under each vulnerable group falls under each tire is shows in Table 2. Despite comprising only 15.0% of grid cells, Tier 1 clusters are home to 57–59% of the city's population in every vulnerable subgroup (57.4% of children under 5; 57.2% of children under 15; 58.5% of residents 65+; 59.1% of residents 70+). Looking at Tier 1 and Tier 2 together, about 18.4% of grid cells cover most of the vulnerable population. This uneven concentration bolsters the equity justification for tiered prioritization: the accessibility shortfall in Niš is not uniformly spread throughout the vulnerable demographic but is significantly concentrated within a limited, geographically defined segment of the urban center. Total population reported in Table 2 are the sum of WorldPop-modelled subgroup estimates across the 6,134-cell analysis grid (and should not be compared directly to official census or municipal registry population figures for the full administrative territory of Niš, which extends considerably beyond the study area.

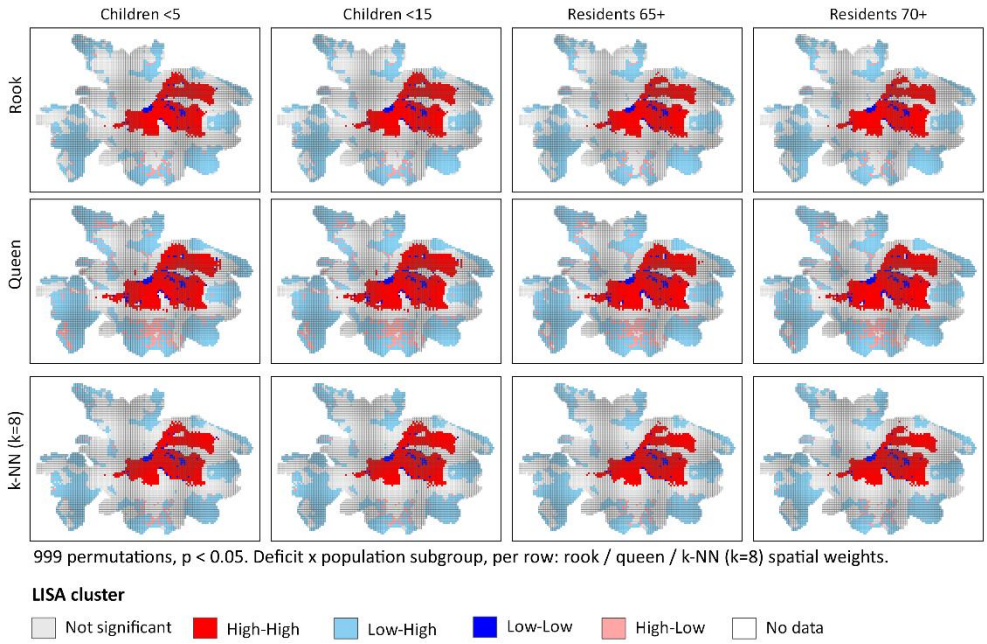


Figure 3. Bivariate LISA cluster maps: composite deficit × vulnerable population subgroups

Table 1. Distribution of grid cells by priority tier

Tier	Definition	n	% of total
Tier 1	Robust High-High for ≥1 subgroup (all 3 weight matrices)	917	15.0%
Tier 2	Partially robust High-High (1–2 of 3 weight matrices)	212	3.5%
Tier 3	No significant High-High clustering	5,005	81.6%

Table 2. Vulnerable-population totals by priority tier and demographic subgroup

Tier	n cells	Under 5 (%)	Under 15 (%)	65+ (%)	70+ (%)
Tier 1	917	6,104 (57.4%)	19,087 (57.2%)	27,294 (58.5%)	19,250 (59.1%)
Tier 2	212	737 (6.9%)	2,320 (7.0%)	3,188 (6.8%)	2,204 (6.8%)
Tier 3	5,005	3,793 (35.7%)	11,956 (35.8%)	16,191 (34.7%)	11,136 (34.2%)

In order to illustrate results following text describes typical cells from each tire (Figure 4). Cell 5259 illustrates a typical Tier 1 case. A composite accessibility deficit of 0.98 (near the upper value of the index) coincides with a substantial resident population across all four vulnerable subgroups (4.4 children under 5, 14.1 children under 15, 17.3 residents aged 65 and over, and 12.0 residents aged 70 and over) and was classified High-High for every subgroup under all three weight specifications (priority count = 4). Such cells constitute the strongest candidates for new green infrastructure investment.

Cell 2259 illustrates the Tier 2 category and the practical value of the weight-matrix sensitivity check: with a deficit of 0.73 and a comparable resident population (4.7 children under 5, 14.7 children under 15, 21.1 residents 65+), the cell was classified High-High for the under-5 and under-15 subgroups under rook and queen contiguity, but not under k-nearest-neighbour weights. This divergence illustrates why such cells are treated as candidates for field verification rather than automatically included in, or excluded from, the priority list.

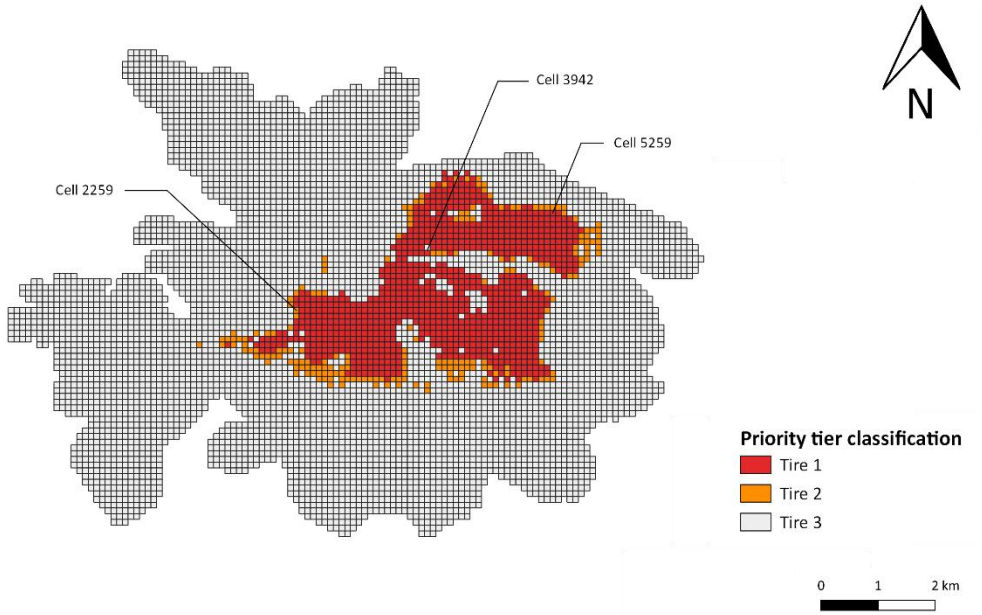


Figure 4. Final priority tier classification for green infrastructure investment in the Niš urban core

Cell 3942 illustrates a typical Tier 3 case: despite a substantial resident population (10.1 children under 5, 32.0 children under 15, 39.5 residents 65+), the cell recorded a composite deficit of 0.00 — indicating that all three park types were within their respective planning-standard walking-time thresholds — and consequently showed no significant High-High clustering for any subgroup. This example demonstrates that Tier 3 is not synonymous with "high vulnerable population", but rather reflects adequate measured accessibility regardless of population size.

4. CONCLUDING REMARKS

The results from the composite deficit work and the bivariate LISA show clear priority areas. In these spots, weak access to parks lines up with higher numbers of residents who are more at risk by age. The findings are strong enough to treat as reliable, and the locations match across the analysis.

To turn the results as an decision making imput for planning, the study uses a three level map. Tier 1 is the highest priority. Tier 2 is only partly robust. Tier 3 is not a priority. This setup gives a simple order for action. It avoids the need for planners to read a smooth deficit surface that is harder to explain.

The population results in Table 2 support the equity argument. Tier 1 covers just 15.0% of the grid. Even so, it holds about 57 to 59% of the city's vulnerable residents in every demographic group tested. When Tier 2 is added, the coverage rises to 18.4% of the city. At the same time, it brings in about 64 to 66% of vulnerable people. However, Tier 2 cells are a bit different. They were not labeled as strong priorities. Still, they should be checked with more field work before they are fully ruled out. The reason is that the result can shift when the spatial weights change.

This pattern is not small or random. It shows that in Niš, the access gap in the main urban area falls hardest on the residents who have the least ability to cope with it using their own mobility. So the case points to targeting resources in specific places, not spreading them evenly across the whole city.This section should be read with the note from Section 2.2 about data coverage. In short, about half of the grid was left out of the deficit numbers. The reason was that there were no buildings with usable network links there. This gap shows up mainly in non-residential land uses, like parks, water areas, and institutional sites. It is not just a random data issue. So the population concentration that study report is best seen as a low estimate of how much unfair exposure may exist. It should not be treated as a full city-wide measure.

Study also built a repeatable accessibility index for green infrastructure in the Niš city core. The index uses a network perspective on accessibility. It combines cost-distance modelling, decay cutoffs taken from planning standards, and a deficit method that does not allow trade offs. Then it utilize bivariate spatial cluster tests, checking the results with extra robustness using three different spatial weight setups. The output is a three-level priority map.

For planners, this gives a spatially precise starting point: 1) a ranked set of priority clusters, where each cluster comes with a reported deficit size, a count of vulnerable people, and a note on how solid the result is, and 2) an equity reason to focus limited funds on these spots in the next budget round. The same logic can guide the next update to the city’s plan for green infrastructure planning processes.

ACKNOWLEDGMENT

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Review paper

A BACKCASTING APPROACH TO BUILDING RENOVATION OBLIGATIONS IN SLOVENIA AND SERBIA

Domen Zupančič[1]

Abstract

On 15 July 2026 the European Commission opened infringement procedures against all twenty-seven Member States for incomplete transposition of the recast Energy Performance of Buildings Directive, whose transposition deadline had passed on 29 May 2026. This paper takes that general failure of implementation as its origin and asks a question that is institutional rather than technical: for a binding obligation with a fixed date, what has to be true for a state to deliver it, and is it true? A reproducible capability-gap protocol is set out. Binding obligations are enumerated with their dates from primary legal sources; for each, the delivery preconditions are identified; each precondition is tested against measured national indicators; and every gap is classified as a measurement, legal or capacity gap. The protocol requires only public data and is replicable for any Member State. Applied to Slovenia, it finds a country reporting a renovation rate but not the stock of which it is a rate, nor the primary energy metric in which the Article 9(2) obligation is expressed. Of the fifteen draft renovation plans assessed by the Joint Research Centre in July 2026, Slovenia is the only one omitting both the residential renovation trajectory and the non-residential performance thresholds. The co-owner consent threshold governing deep renovation is unchanged and is named as a barrier in the state's own renovation strategy. Close to half the construction workforce hold foreign nationality. A comparison with Serbia shows the carbon border adjustment mechanism substituting for the acquis as the operative decarbonisation pressure in a candidate country. The paper finds the binding constraint to be institutional rather than technological. In architecture and construction only legislation, and the standards it makes binding, are obligations; everything else is read by practice as a wish list.

Key words: *building renovation, Energy Performance of Buildings Directive, capability gap, condominium ownership, carbon border adjustment mechanism*

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1. INTRODUCTION

On 15 July 2026 the European Commission sent letters of formal notice to all 27 Member States for failing to transpose fully the recast Energy Performance of Buildings Directive (EPBD) [1] into national law [2]. The transposition deadline had expired on 29 May 2026. No Member State met it. At the same date only sixteen of twenty-seven had filed even a draft national building renovation plan, and the Joint Research Centre (JRC), assessing the first tranche of those plans, found projected primary energy reductions to 2050 ranging from 24 % to 73 % [3].

A universal failure is analytically more interesting than a national one. If every Member State missed the same deadline, the explanation is unlikely to lie in the will or diligence of any administration; it is more plausibly structural. This paper asks what was missing.

The question posed is institutional rather than technical: for a binding obligation with a fixed date of application, what has to be true for a Member State to be capable of delivering it, and is it true? **This paper makes no forecast; it is an ordered reading of what has already been reported.** Its inputs are obligations that already exist in law and carry a date; its output is a statement about whether the preconditions for meeting them are in place. This distinguishes it from the scenario-based foresight that dominates the literature on building-stock decarbonisation, which asks what a state may face rather than what it has already undertaken.

Four contributions are claimed: a capability-gap protocol replicable for any Member State from public, dated sources; the finding that Slovenia reports an annual renovation rate but not the stock of which it is a rate, nor the primary energy metric in which the Article 9(2) obligation is expressed, while the one obligation that is unambiguously measured has been met in a single year out of eleven; the finding that the co-owner consent threshold governing deep renovation remains unchanged although the state's own renovation strategy identifies it as a barrier; and the comparative observation that for a candidate country the carbon border adjustment mechanism substitutes for the acquis as the non-deferrable pressure on material decarbonisation.

2. THE BINDING CALENDAR

Obligations bearing on the European building stock are frequently reported in a form that conflates three kinds of instrument: **level 1** binds and applies now; **level 2** binds but applies at a future date; and **level 3** is programmatic, reserves the substantive decision to the Member State, or remains in draft. Table 1 sets out the three levels and their contents. The separation is not presentational.

At least five widely repeated claims concern level 3. The most persistent, and the one most often put to designers by clients, is that fossil-fuel boilers will be prohibited by 2040. There is no such prohibition: Article 13 of and Annex II to the EPBD impose a duty to set out policies with a view to a phase-out, and the only binding provision is the prohibition on financial incentives for stand-alone boilers, applicable since 1 January 2025. Each such claim arises from reading a level 3 instrument as though it were level 1.

Digital product passports are not mandatory: the Construction Products Regulation [4] establishes the legal architecture and the registry of unique identifiers opened on 19 July 2026, but no construction product carries an obligation until the corresponding delegated act, expected for cement, building limes and hydraulic binders around the fourth quarter of 2027 [8]. Limit values on life-cycle global warming potential are not set at Union level: Delegated Regulation (EU) 2026/52 [5] harmonises the calculation, while the values remain national competence, roadmapped by 1 January 2027 and applying from 2030. The class-based minimum standards for individual dwellings that appeared in the 2021 proposal were removed from the adopted text: Article 9(2) sets a stock average and Article 9(1) a threshold calibrated to each Member State's own 2020 non-residential stock by floor area, neither being a requirement for any individual building.

Table 1. Obligations bearing on the building stock, classified by legal force. Dates are dates of application, not of adoption.

Instrument	Obligation	Applies from	Note
Level 1 — binding and already applying			
EPBD, Art. 17(15)	No public incentives for stand-alone fossil-fuel boilers	1 Jan 2025	In force
EPBD	Transposition into national law	29 May 2026	Missed by all 27
Del. Reg. (EU) 2026/52	Union framework for calculating life-cycle GWP	24 May 2026	EN 15978; Level(s) 1.2
Reg. (EU) 2023/956 (CBAM)	Definitive regime; 2.5 % factor on embedded emissions	1 Jan 2026	Cement, steel, aluminium
Reg. (EU) 2021/1119, as amended	−90 % net GHG emissions by 2040 against 1990	Adopted 5 Mar 2026	≥ 85 pp domestic
Level 2 — binding, applying at a future date			
EPBD, Annex III	National roadmap for GWP limit values	1 Jan 2027	Roadmap, not values
EPBD, Art. 7	New buildings owned by public bodies zero-emission	1 Jan 2028	Ownership, not use
EPBD, Annex III	Life-cycle GWP disclosed on the EPC above 1 000 m²	1 Jan 2028	Disclosure, no cap
EPBD, Art. 7	All new buildings zero-emission; GWP disclosure extended	1 Jan 2030	NZEB applies until then
EPBD, Art. 9(1)	Worst-performing 16 % of non-residential floor area above a national threshold; 26 % by 2033	2030 / 2033	A threshold, not a mandate
EPBD, Art. 9(2)	Residential stock average primary energy −16 %, then −20 to −22 % against 2020	2030 / 2035	≥ 55 % from the worst 43 %
Dir. 2003/87/EC, Art. 10a(1a)	CBAM factor to 48.5 %, then 100 %	2030 / 2034	Inflection 2029→2030

Level 3 — programmatic, national competence, or in draft; frequently misreported as binding			
EPBD, Art. 13, Annex II	Phase-out of fossil-fuel boilers by 2040	—	A planning duty, not a ban
EPBD, Annex III	Limit values on life-cycle GWP	from 2030	National competence
ZURE-1 (Slovenia)	Transposition of the EED and the recast EPBD	—	Unadopted at Sep 2026

Sources for Table 1. Level 1 and level 2 entries are taken from the Official Journal of the European Union: the recast EPBD [1]; Delegated Regulation (EU) 2026/52 [5]; the Construction Products Regulation [4] and its working plan [8]; the carbon border adjustment mechanism and the emissions trading directive [6]; and the amended European Climate Law [7]. The transposition status is from the Commission's infringement package of 15 July 2026 [2]. The 3 % public-sector renovation duty referred to elsewhere in the paper is set by the Energy Efficiency Directive [10]. The level 3 entry for ZURE-1 refers to the draft Slovenian act in public consultation since October 2024.

3. METHOD

We used regulatory backcasting approach combined with an institutional capability assessment. Its inputs are obligations that already exist in law and carry a date of application; its output is a statement about whether the preconditions for meeting them are in place. General steps visioning, baseline, capability assessment and pathways as final possible outcome were tailored for specific theme of the paper. The protocol has given four steps.

Step 1 — Enumeration. Every obligation bearing on the building stock is extracted from primary legal sources with its date of application. Two inclusion criteria apply: the obligation must be legally binding with defined date. Programmatic provisions, those reserving the substantive decision to the Member State, and those still in draft are excluded and listed separately in level 3 of Table 1 — several are reported as binding in the professional literature, and treating them as such would misstate both obligation and gap.

Step 2 — Delivery preconditions. Four recur: transposition into an instrument binding on the permitting authority and therefore on the designer; an observation system capable of producing the indicator in which the obligation is expressed; a decision-making mechanism able to authorise works at the level of the individual building; and implementation capacity — labour, skills, finance, administrative process. A precondition is admitted only where the obligation cannot be met without it.

Step 3 — Testing. Each precondition is confronted with measured national data from official sources. Where the required indicator cannot be computed from any published national source, is recorded as a result of the assessment rather than a limitation of it: an obligation expressed as a proportional change in an unobserved quantity is not merely hard to meet but hard to demonstrate having met.

Step 4 — Classification. A **measurement gap** exists where the indicator in which the obligation is expressed cannot be computed; a **legal gap** where a statutory provision or consent threshold conditions the works irrespective of technical and financial feasibility;

a **capacity gap** where the obligation is measurable and lawful but exceeds available labour, skills, finance or administrative throughput. The categories are ordered by remedy rather than severity — they identify who would have to act — and are not mutually exclusive.

Every input is public and dated and the classification criteria are stated, so the assessment is reproducible for any Member State. That transferability, rather than the Slovenian result itself, is the methodological contribution claimed here.

Limitations. Taken example of two countries (Slovenia and Serbia) are not a sample; the findings are generalised analytically, through the mechanism identified. The Slovenian and Serbian demographic series derive from methodologically distinct projection exercises — Serbia lies outside EUROPOP [18] — and establish direction and order of magnitude only. The classification in step 4 involves **a judgement**, which is why the criteria are stated explicitly: a reader may reclassify a gap, and the reasoning remains inspectable. Serbia is treated as a structural comparison rather than a parallel case study, no measured national renovation rate being published for it.

4. SLOVENIA: DELIVERY CAPACITY

Slovenia is an informative case: a small Member State with an otherwise largely transposed acquis; an overwhelmingly owner-occupied residential stock, which sharpens the ownership question; and a draft renovation plan independently assessed, which makes the measurement question answerable from public documents rather than by inference.

4.1. The measurement gap

Article 9(2) of the recast EPBD requires each Member State to reduce the average primary energy use of its residential stock by at least 16 % by 2030 and 20–22 % by 2035 against 2020, achieving at least 55 % of the 2030 reduction through renovation of the worst-performing 43 % [1]. The obligation is expressed in three quantities: a primary energy baseline, a trajectory from it, and an identification of the worst-performing tail. Slovenia submitted its draft renovation plan on 8 January 2026; the Joint Research Centre assessed it with fourteen others in July 2026 and classified it as partially complete [3].

All three are absent. The plan reports no primary energy consumption for the residential stock, the non-residential stock or the total, for 2020 or any subsequent year, and sets no primary energy target for 2030, 2040 or 2050; the indicator checklist marks primary energy use and targets ‘No’, noting that the figures are expected later, once the primary energy factors have been updated, and the factors themselves are recorded as not available. The Article 9(2) trajectory is likewise not provided and is described as still under development. The worst-performing buildings have not been defined: thresholds are to be set per building type, which requires a shift from the existing heat-demand classification to one based on total primary energy. As an interim indication, Slovenia estimates that 15–20 % of buildings exceed 300 kWh/(m²·y) [3].

What the plan does report is a renovation rate. Slovenia states annual rates of approximately 2 % at stock level across 2020–2050 — rising in the non-residential

sector from 2.1 % to 2.9 % and falling in the residential sector from 2.2 % to 1.5 % — against a baseline floor area of 66.5 million m² residential and 23.8 million m² non-residential, and a cumulative renovated area of 66.5 million m² over the period. The renovation-rate indicator is marked 'Yes'. The difficulty is that it is not a rate of anything the plan establishes. The stock overview omits the number of buildings entirely, marked 'No' with the explanation that a detailed structure will be developed later, and the assessment finds the reported floor-area values inconsistent with the stock baseline, concluding that it is not clear whether the targeted renovation will contribute to the plan's own energy and emission targets. Its judgement on calibration is explicit: because neither the residential trajectory nor the non-residential thresholds were provided, it is not possible to assess whether the annual renovation targets are calibrated to them [3].

This is the measurement gap in its precise form, and it is sharper than the familiar observation that renovation activity is poorly monitored across Europe [9]. **Slovenia reports a rate; it does not report the stock of which it is a rate, nor the metric in which the obligation is expressed.** A percentage has been supplied where a quantity was required.

The condition is long-standing. Recorded renovation of roofs, façades and windows in the Slovenian real-estate register falls from 2.4–5.6 % in 2000 to approximately zero by 2014, a collapse attributed to the cessation of owner self-reporting after the 2007 property census rather than to any change in physical activity [13]. The register was never an observation system; it was a self-declaration system that stopped receiving declarations.

Two qualifications are owed. First, Slovenia is not alone, and the argument does not depend on its being exceptional: of the fifteen draft plans in the first tranche, six — Bulgaria, France, Cyprus, Austria, Slovenia and Sweden — lack the Article 9(2) residential trajectory, and three — Germany, the Netherlands and Slovenia — lack the Article 9(1) non-residential thresholds. Slovenia is, however, the only one recording both as not available, and the only one for which the primary energy factors are recorded the same way. Second, these are draft plans; the final plans were due on 31 December 2026, and the missing elements may by then have been supplied. The finding concerns readiness four years before the obligations apply, not a prediction that they will not be met.

The contrast with the one obligation in the Slovenian building sector that is unambiguously measured completes the point. Under the Energy Efficiency Directive [10] the narrow public sector must renovate 3 % of its floor area annually. Here the state is owner, client and regulator at once, the stock is enumerated, and performance is reported by the government's own monitoring programme. Over 2014–2024 the target was met in a single year, 2018; cumulative delivery stands at 91 146 m², or 31 % of the cumulative target; in 2024, 16 709 m² were renovated against a requirement of 28 254 m² [12]. **The absence of measurement elsewhere cannot therefore be read as concealing better performance: where the quantity is observed, the obligation is not met.**

Table 2. Capability gaps for Slovenia, classified by step 4 of the protocol.

Obligation	Delivery precondition	Status in Slovenia	Gap
EPBD Art. 7 — ZEB from 2028 / 2030	Transposition into an instrument binding on the permitting authority	ZURE-1 in draft since October 2024, unadopted; infringement opened 15 July 2026	Legal
EPBD Art. 9(2) — residential −16 % by 2030	Primary energy baseline and targets for the stock	Not provided for any year; checklist marks primary energy use and targets 'No'; to be calculated later	Measurement
EPBD Art. 9(2)	Trajectory for progressive renovation	Not provided; recorded as still under development	Measurement
EPBD Art. 9(2) — 55 % from the worst 43 %	Definition of worst-performing buildings	Partial. Thresholds to be set per building type; requires a shift from heat demand to total primary energy	Measurement
EPBD Art. 9(1) — non-residential	National maximum energy performance thresholds	Not provided; recorded as not yet determined	Measurement
EPBD Annex II — stock overview	Enumeration of the building stock	Number of buildings marked 'No'; floor-area values inconsistent with the stock baseline	Measurement
EPBD Art. 9(2) applied to multi-apartment buildings	A consent mechanism able to authorise works at building level	SZ-1 Art. 29: above 75 % of ownership shares; unanimity where works alter common parts, change use, or are financed against the reserve fund	Legal
EED — 3 % annual public-sector renovation	Administrative and financial throughput	Met in one year of eleven; 91 146 m² delivered, 31 % of the cumulative 2014–2024 target	Capacity
Plan target of ≈2 % annual stock renovation	Labour and skills	37 805 of 76 957 construction workers are foreign nationals; skilled-labour shortage named the largest constraint by close to half of firms	Capacity
Investment need of €4.1 bn to 2030	Identified financing	€3.2 bn identified; no sources identified for the €11.5 bn to 2040 or €19.4 bn to 2050	Capacity

4.2. The legal gap

Where the measurement gap concerns whether compliance can be demonstrated, the legal gap concerns whether the works can be authorised at all. In Slovenia the relevant provision is not in building or energy legislation but in housing and property law.

The Housing Act [14] establishes a three-step ladder of co-owner consent for multi-apartment buildings. Ordinary management — operation and maintenance — requires more than one half of the ownership shares. Acts exceeding ordinary management, expressly including construction works requiring a building permit, require more than three quarters. Unanimity is required where the works alter the ratio between common and individual parts, restrict or change use, or are financed by borrowing against the reserve fund. These provisions displace the general rule of the Property Code [15], under which such acts would require the consent of all co-owners in any event.

The significant point is not that the threshold exists but that the state has identified it and not moved it. Slovenia's own long-term renovation strategy names fragmented ownership as a barrier and states explicitly that where energy renovation forms part of a wider renovation, a unanimous decision is required [11]. The 2025 amendment to the Housing Act nevertheless left Articles 25 and 29 untouched; the draft ZURE-1 does not address consent thresholds; and no bill amending them was pending as at September 2026.

Two European precedents exist and neither has been evaluated. Lithuania lowered the threshold for homeowner associations to a simple majority; France, under its 2015 energy transition legislation, permits decisions on energy-efficiency measures by a majority of those present at the general assembly rather than an absolute majority of shares [16]. Whether either produced a measurable change in renovation activity appears untested. Given that roughly 48 % of EU residents live in apartments, this is a conspicuous evidential gap.

The threshold bites harder in Slovenia than the European average would suggest, because the tenure structure concentrates decision rights in owners rather than landlords: 74.8 % of the Slovenian population lived in owner-occupied dwellings in 2024, against an EU-27 average of 68.4 % [18]. Roughly 15 000 multi-apartment buildings are subject to mandatory professional management. Each is a separate decision-making body whose consent is required before deep renovation can proceed, and the Article 9(2) obligation is weighted precisely towards the part of the stock where those bodies are most numerous and least well resourced.

4.3. The capacity gap

The third precondition is the ability to carry out the work. Slovenia's draft plan targets an annual renovation rate of approximately 2 % of the stock, against a European average estimated at roughly 1 %, of which deep renovation accounts for 0.2 % [9]. Meeting it would require close to a doubling of activity sustained for a quarter of a century.

The workforce available to do so is already constrained. In 2025 an average of 76 957 persons were work-active in Slovenian construction, a decline of 1.4 % on the previous year, of whom 37 805 — close to 49 % — were foreign nationals. Shortage of qualified workers was the single most frequently cited constraint, named on average by nearly half of firms, with the skills gaps identified as project management, building information modelling, digital technologies, sustainable construction and energy efficiency [17].

Demography compounds rather than causes this, though not in the way usually asserted. The projections do not show a collapsing pipeline of young entrants: Slovenia's 19–24 cohort contracts by only some 3 % to 2046, because the current student cohort was already born in the fertility trough of the early 2000s. What changes is the ratio between those able to build and the stock requiring renovation and maintenance — the old-age dependency ratio rises from 35.9 in 2026 to 50.9 in 2046, crossing fifty in 2045, against an EU-27 figure of 48.8 [18].

Financing shows the same shape, and is taken up in Section 4.4.

4.4. Financing after the Recovery and Resilience Facility

The capacity constraint is sharpest in the instrument that has carried most Slovenian building renovation over the past five years, and which closed while this paper was being written. The Recovery and Resilience Facility required all milestones and targets to be completed by 31 August 2026, final payment requests to reach the Commission by 30 September 2026, and all payments to be executed by 31 December 2026; amounts not paid by that date are decommitted rather than reprogrammed [19]. Slovenia devoted one component of its national plan, C1.K2 Sustainable renovation of buildings, to the subject, with a final allocation of €86.65 million — €64.15 million in grants and €22.50 million in loans [20].

Two observations follow, and neither is a finding of failure. Slovenia met the targets. The four physical targets under the component — 59 574 m² and 21 398 m² of deep renovation, 29 392 m² and 8 965 m² of technical building system upgrades — were recorded as fulfilled in the July 2026 implementation report, and the technical-system strand overshot, delivering roughly 55 000 m² against a target of 38 357 m² [20].

The observations concern scale and scope. Scale: the 80 972 m² of deep renovation is 0.09 % of the 90.3 million m² stock reported in the draft renovation plan, and €86.65 million is about 2 % of the €4.1 billion that the same plan identifies as needed by 2030 [3]. Scope: the component was confined to publicly owned buildings. The single strand addressed to multi-apartment residential buildings was worth €5 million, at a co-financing rate of €250 per square metre, restricted to publicly owned buildings with four or more dwellings and conditional on a 30 % reduction in primary energy use.

The most telling evidence is what became of money that could not be spent on construction. **In the sixth and final amendment to the plan, agreed on 10 July 2026, seven weeks before the deadline, twelve investments were reduced and the savings directed to a contribution to a European joint undertaking for artificial-intelligence computing, worth €71.65 million [20].** An instrument that absorbs funds by transfer can clear a deadline; renovation, which requires procurement, site works and

commissioning, cannot be compressed into seven weeks. Building renovation was not cut. It could not be scaled up either — which is the capacity gap in its most concrete form.

What follows the Facility is smaller. The draft Social Climate Plan for 2026–2032 proposes €475.9 million in total, of which €239.5 million is allocated to buildings and directed at energy-poor and low-income households [21]. That is roughly 2.8 times the Facility's renovation envelope spread over more than twice the period, against an investment need of €4.1 billion by 2030 and €19.4 billion by 2050, for which the draft plan identifies €3.2 billion to 2030 and nothing thereafter [3].

The second amendment to the plan makes the mechanism explicit. Grants for C1.K2 were cut from €66.05 million to €63.55 million, and the official summary gives the reason without circumlocution: because of a lack of interest from potential applicants, the milestone "Completed energy and sustainable renovation of residential buildings in public ownership" was removed and the €2.5 million earmarked for it redirected to a district-heating measure, itself restructured after receiving far fewer applications than expected [20]. The sum is small against the plan as a whole; what was removed is not. It was the only milestone in the component addressed to residential buildings, and it was withdrawn for want of applicants rather than for want of money. This is a demand-side failure, and it is the clearest available evidence that the binding constraint on renovation in Slovenia is not the availability of funds.

5. SERBIA: THE CANDIDATE-COUNTRY POSITION

Serbia is treated as a structural comparison rather than a parallel case study, for the reason given in Section 3: no measured national renovation rate is published. What can be compared is the mechanism by which decarbonisation pressure reaches the building sector.

Serbia opened Cluster 4, covering energy and environment, in December 2021; neither Chapter 15 nor Chapter 27 has been provisionally closed, and the 2025 enlargement assessment finds the country moderately prepared on energy and recommends that it finalise the implementing legislation on the energy performance of buildings [22]. Its integrated national energy and climate plan sets renovation rates of approximately 1 % annually for residential buildings, 3 % for public buildings and 2.3 % for other non-residential buildings [23]. These are targets; achieved rates are not published.

The decisive difference lies elsewhere. **For a Member State, decarbonisation pressure arrives through transposition, and transposition can be deferred — as all twenty-seven have demonstrated. For a candidate country outside the emissions trading system but exporting into the single market, it arrives through a price at the border, which cannot be deferred by any domestic decision.** The carbon border adjustment mechanism entered its definitive regime on 1 January 2026 [6]. Its immediate effect is slight: the factor applied to embedded emissions is 2.5 % in 2026. The inflection falls between 2029 and 2030, when the factor rises from 22.5 % to

48.5 % as free allocation under the emissions trading system is withdrawn, reaching 100 % in 2034. Cement, iron and steel, and aluminium are covered.

This is the one genuinely non-deferrable instrument examined here. Every other obligation depends for its effect on an act of national implementation that may be late, partial or absent. The border price does not.

The order of magnitude can be indicated, with the caution that the available figures are estimates rather than official statistics. Published analysis of the Smederevo steelworks puts its emissions intensity at approximately 2.3 tCO_2 per tonne of hot-rolled coil, some 68 % above the CBAM benchmark, with around 55 % of output directed to EU markets. These are single-author estimates published outside the peer-reviewed literature and are reported here as such.

6. THE HORIZON MISMATCH: REGULATION AND CLIMATE PROJECTION

The obligations in Table 1 are dated between 2025 and 2040 and are expressed in two quantities: primary energy and greenhouse gas emissions. The climate they are meant to address is projected on a different timetable and in different quantities. Table 3 sets the two national projections side by side.

Table 3. National climate projections for the end of the twenty-first century. Slovenian values are changes against 1981–2010 from a multi-model regional ensemble at 12 km resolution [24]; Serbian values are changes against 1986–2005 from a nine-member EURO-CORDEX ensemble [25], [26].

Indicator	Slovenia	Serbia
Mean annual temperature, RCP4.5	+2.0 °C	+1.9 °C
Mean annual temperature, RCP8.5	+4.1 °C (range 3.0–5.1)	+4.4 °C
Summer temperature, RCP8.5	above the annual mean	+4.5 °C
Hot days above 30 °C, RCP8.5	up to +60 in the lowlands	not reported
Days above 35 °C, RCP8.5	not reported	+30 to +50
Tropical nights, RCP8.5	up to +60 in some regions	not reported
Summer precipitation, RCP8.5	winter increase; summer signal weaker	−40 % in southern Serbia
Heatwaves	longer and more frequent under every indicator	duration rising sharply
National assessment issued by	Environment Agency (ARSO)	none; university ensemble, published via UNDP

Two features matter more than the individual figures. The indices governing building design move further than the mean: Slovenian hot days rise by 5 to 10 in the lowlands as early as 2011–2040 [24]. And the spatial signal matters for a conference held in Niš: warming is more pronounced and water availability more reduced in central

and southern Serbia than in the north [26]. Niš recorded 49 tropical days a year and an absolute maximum of 44.2 °C in the 1981–2010 normal [28].

Three mismatches follow, and each is a design problem before it is a policy one.

The first is a mismatch of horizon. The regulatory calendar ends at 2040; the projections are indexed to 2041–2070 and 2071–2100. A building completed to the zero-emission standard in 2030, with a service life of fifty to a hundred years, will spend almost all of it inside the periods the projections describe, and not one of the obligations in Table 1 is expressed for those periods.

The second is a mismatch of quantity. The obligations measure primary energy and global warming potential. Neither measures whether a building remains habitable in a heatwave, and a building can satisfy both while overheating. The one Serbian study to quantify this found that under 3.8 °C of warming, heating degree days fall by 35.7 % while cooling degree days rise from 113 to 566, close to a fivefold increase in primary cooling energy [29]. A framework that rewards reductions in annual demand can therefore be satisfied by a building whose summer performance is deteriorating, because for most of the projection period the heating saving is the larger number.

The third is a mismatch of assessment capacity, and it belongs with the gaps in Table 2. Slovenian designers can consult a state-issued, index-level projection; Serbian designers have a journal article, a UNDP report and a web atlas, and a Third National Communication that reproduces headline figures without index-level detail [27]. The two countries share a projection domain, so this is not a difference in climate but in the institutional infrastructure for turning projection into design practice. It is a measurement gap in the sense of Section 3, one step earlier in the chain.

The consequence for design is concrete. The loads that will decide whether a building performs in 2060 are not the loads it is sized for in 2026. Shading, thermal mass, night ventilation and orientation answer projected summer conditions, and they are not what the instruments in Table 1 credit; those credit installed efficiency and disclosed carbon. Where the two coincide, regulation carries the design. Where they diverge, the designer is on their own.

7. DISCUSSION

The three gap types are not of equal standing in the case examined. **The binding constraint on delivery is institutional, not technological or financial.** No finding in Section 4 turns on the unavailability of a construction technique, a material, or a demonstrated retrofit solution. The measurement gap is a question of statistical infrastructure; the legal gap is a question of a consent threshold in housing law; the capacity gap is a question of who is trained and employed. Each has a known remedy, and none of the remedies belongs to the disciplines represented at a building conference.

That observation cuts two ways, and the second is the more important. A profession that treats measurement, property law and workforce as somebody else's brief will find that they are nobody's. The designer occupies the only position at which all three

constraints meet a specific building on a specific plot with a specific set of owners — the point at which a renovation either is or is not authorised, financed and built.

As analysis show *six of the fifteen assessed plans omit the Article 9(2) trajectory, so this is a European rather than a Slovenian condition. It is also worth considering that the disclosure obligations, and in particular the life-cycle global warming potential carried on the energy performance certificate from 2028, may prove more consequential in practice than the performance obligations, because a figure printed on a certificate is enforced by the property market rather than by an inspector. The mission being green and simultaneously following complete legal framework in architecture and constructing is a steep way. Nevertheless, construction is in the field of natural sciences architecture is in-between human science and natural science. Our daily basis at the building site is to shape a common decision among available resources (material, financial and human), cognitive capabilities of involved people and reasoning genius loci. Including those inputs in the matrix of directives and binding regulations follow toward almost to common direction involved team. This direction is not granted to be parallel with goals given from in direction from top to bottom.*

8. CONCLUSIONS

This paper set out a capability-gap protocol for assessing whether a Member State is positioned to deliver obligations that already exist in law and carry a date. The protocol requires only public, dated sources, states its classification criteria explicitly, and is replicable for any Member State.

Applied to Slovenia, it finds a country reporting an annual renovation rate but not the stock of which it is a rate, nor the primary energy metric in which the Article 9(2) obligation is expressed; the only one of fifteen assessed draft plans omitting both the residential trajectory and the non-residential thresholds; an unambiguously measured obligation met in a single year out of eleven, at 31 % of cumulative target; a consent threshold left unchanged although the state's own strategy names it as a barrier; and close to half the construction workforce holding foreign nationality. The comparison with Serbia identifies the carbon border adjustment mechanism as the single instrument examined here whose effect cannot be deferred by a national act.

Two recommendations follow directly. First, reporting obligations on renovation should be attached to a document with established compliance — the energy performance certificate, the building permit, or the subsidy procedure — rather than to voluntary declaration in a property register, which has already been shown not to work. Second, the Lithuanian and French reforms of co-owner consent thresholds should be evaluated before further jurisdictions decide whether to follow them.

The Slovenia–Serbia comparison is not a benchmark test; the intention was to separate the wheat from the chaff. Regulatory backcasting is not the only possible pathway, but the results it yields open a constructive discussion and invite researchers to actively contribute and reshape possible outcomes of this conference.

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Table of abbreviations

Abbr.	Meaning	Abbr.	Meaning
CBAM	Carbon border adjustment mechanism	NBRP	National building renovation plan
CDD	Cooling degree days	NOO	Načrt za okrevanje in odpornost — Slovenia's recovery and resilience plan
C1.K2	Trajnostna prenova stavb — building renovation component of Slovenia's NOO	NZEB	Nearly zero-energy building
EED	Energy Efficiency Directive	OPS21	Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja
EPBD	Energy Performance of Buildings Directive	RCP	Representative concentration pathway
EPC	Energy performance certificate	RRF	Recovery and Resilience Facility
ETS	Emissions Trading System	SPZ	Stvarnopravni zakonik — Property Code, Slovenia
EURO-CORDEX	European branch of the Coordinated Regional Climate Downscaling Experiment	SZ-1	Stanovanjski zakon — Housing Act, Slovenia
EUROPOP	Eurostat population projections	TNC	Third National Communication to the UNFCCC
GHG	Greenhouse gas	UNDP	United Nations Development Programme
GWP	Global warming potential	UNFCCC	United Nations Framework Convention on Climate Change
HDD	Heating degree days	URSOO	Urad RS za okrevanje in odpornost — Office for Recovery and Resilience
INECP	Integrated National Energy and Climate Plan (Serbia)	ZEB	Zero-emission building
JRC	Joint Research Centre of the European Commission	ZURE-1	Zakon o učinkoviti rabi energije — draft Energy Efficiency Act, Slovenia
MEPS	Minimum energy performance standards		

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TOPIC 01

SUSTAINABLE URBAN PLANNING, URBAN DESIGN & ARCHITECTURE

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Research paper

USER-DRIVEN URBAN GREENERY: INTEGRATED FAÇADE PLANTERS AS A BOTTOM-UP NATURE-BASED SOLUTION, PERSPECTIVE OF NIŠ

Nataša Petković[1], Vladana Petrović[2], Hristina Krstić[3]

Abstract

The paper examines the potential balconies, terraces and window planters, as carriers of decentralized urban greenery within the specific context of Niš, Serbia. In contrast to large-scale green infrastructure, which is often limited by planning constraints and investment capacity in post-socialist urban environments, the study investigates user-driven, small-scale interventions as a feasible and scalable alternative.

The research combines a comparative analysis of selected international case studies with an assessment of local housing typologies characteristic of Niš, particularly multi-family residential buildings with underutilized balcony spaces. The study identifies key parameters influencing the performance of planter-integrated systems, including technical complexity, vegetation strategy, and the degree of user involvement. Special attention is given to the relationship between system simplicity and long-term resilience in conditions where maintenance is largely dependent on residents, rather than institutional support.

In the climatic and urban context of Niš, characterized by hot summers, increasing heat stress, and a deficit of accessible green areas, the introduction of façade planter-integrated greenery is evaluated as a microclimatic and socio-ecological strategy. The findings indicate that adaptable, low-tech planting systems can contribute to façade shading, reduction of heat gain, and improved air quality, while simultaneously fostering user engagement and environmental awareness.

The paper positions the integration of vegetation in a form of façade planter into residential spaces, as a context-responsive strategy, and emphases its relevance in environments with limited institutional capacity. In the case of Niš, such an approach reveals how small-scale, user-driven interventions can collectively contribute to the broader urban resilience. Rather than relying on large infrastructural transformations, the findings suggest that the incremental activation of existing architectural elements can play a meaningful role in shaping sustainable housing environments.

Key words: *Balconies, Façade openings, Planters, Terraces, Vertical greenery*

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1. INTRODUCTION

Green urban spaces contribute significantly to the provision of ecosystem services in cities. They help filter air, reduce pollution, lower temperatures, and mitigate noise. [1] Unfortunately, in many urban environments, the availability of green spaces is highly inadequate. Traditional forms of greenery, such as parks, street trees and various types of public and communal open spaces are no longer sufficient to meet the growing demand for green areas in cities. Dense urban environments often contain more vertical surface area than ground-level space. Therefore, there is greater biological potential for vertical greening compared to horizontal, ground-based green space development. [2, 3]

From a residential perspective, research indicates that nearly 90% of city dwellers live in buildings, while only a small proportion reside in individual houses [3]. This highlights the increasing importance of integrating greenery into vertical building elements, such as terraces, balconies, roofs and building façades. This alternative forms of urban greening also provide significant benefits [2-5]. Façade greenery have notable cooling effects during summer and can act as insulation layers, helping to retain heat during winter [3, 4]. Additionally, façades covered with vegetation are less exposed to direct solar radiation, while plant leaves contribute to cooling through evapotranspiration [3,4].

Moreover, greenery enhances the aesthetic value of buildings and residential environments, thereby significantly increasing their overall value [2, 5].

1.1. Green urban spaces in the local context

Within the post-socialist model of urban development in Serbia, the planning and design of urban green spaces have been systematically marginalized. Available data indicate that the proportion of green areas in Niš is below 10% of the total urban territory, which is significantly lower than the World Health Organization recommendations of 20–25%. This deficit is closely linked to urban planning regulations that have historically underestimated the importance of green open spaces, particularly at the level of individual residential plots. The earlier version of the General Regulation Plan (GRP) required that a minimum of 10% of plot areas be allocated to greenery; however, it failed to define the qualitative parameters and typologies of vegetation. Such an approach proved particularly inadequate in the context of multi-family housing, where green spaces were often reduced to residual or purely formal elements.

Amendments to the Plan adopted at the end of 2021 introduced more stringent requirements, increasing the minimum share of green areas to 25%, with at least 10% required to be in direct contact with the ground. In addition, the revised framework differentiates between categories of greenery, such as: trees, green roofs, green façades and greenery above underground structures, assigning them different coefficients in the calculation of total green area. For example, a single tree is equated to 5m² of greenery, while green roofs, façades and greenery above underground levels are counted as 50% of their surface area, in contrast to ground-level greenery, which is valued at 100%. Despite these regulatory improvements, their practical

implementation remains limited. The prevailing model of investor-driven urban development effectively transfers responsibility for the provision of green spaces to private developers, often without adequate control mechanisms.

Empirical evidence suggests a discrepancy between planning documentation and onsite conditions. Green areas are frequently represented in project designs to fulfill formal requirements for building permits, yet are omitted or significantly reduced during construction [6]. Moreover, the issue of maintenance presents an additional challenge. Although some examples of implemented green roofs exist, insufficient planning (particularly regarding irrigation systems and plant selection) often leads to their functional degradation over time, thereby undermining their intended environmental and spatial benefits.

3. IMPLEMENTATION OF FAÇADE PLANTER-INTEGRATED GREENERY

The application of green walls is aassociated with several practical limitations that may hinder their wider implementation [7]. Their successful integration depends not only on their design, but also on long-term management and technical reliability. In this context, the integration of vertical greenery through façade planters on windows, balconies and terraces, emerges as a particularly appropriate and feasible approach. Unlike technologically complex green walls, this model relies on simple, low-tech solutions that are easily accessible to users and do not require significant structural modifications to the building envelope. Planters can be installed, replaced and maintained directly by residents, ensuring a higher level of control and long-term sustainability. Moreover, such systems are largely independent of the building's structural framework, which makes them adaptable to both new constructions and existing residential buildings. Their accessibility enables regular maintenance activities such as watering, pruning and plant replacement, thereby reducing the risk of system failure commonly associated with less accessible green infrastructure. This makes it particularly suitable for contexts characterized by limited institutional control or investor-driven development. As a result, planter-integrated greenery represents a resilient and scalable strategy for enhancing urban environmental quality, while actively engaging residents in the co-creation of greener living environments.

3.1. Ecosystem benefits

Private open areas represent an underutilized yet highly effective spatial resource for enhancing environmental performance in dense urban environments. Within contemporary sustainable architecture discourse, these elements are increasingly recognized as microclimatic interfaces that mediate between indoor and outdoor conditions, contributing to both energy efficiency and user comfort. Their environmental contribution can be understood through several interrelated functions.

First, in microclimatic terms, vegetated private open areas act as passive shading devices, reduce solar heat gain and contribute to cooling through evapotranspiration. They also function as buffer zones that support natural ventilation and mitigate temperature fluctuations [1].

Second, from an ecological perspective, vegetation on windows, balconies and terraces contributes to air purification, noise attenuation and the capture of airborne particulates. Through photosynthesis and evapotranspiration, plants actively participate in urban ecological cycles, improving air quality and contributing to atmospheric moisture regulation [3]. In addition, such spaces can serve as microhabitats, supporting urban biodiversity at the building scale.

Third, at the urban scale, the cumulative effect of distributed greenery across private open spaces can contribute to mitigating the urban heat island effect. Empirical studies demonstrate that even partial implementation can yield measurable benefits. For example, a ten-story residential building with densely vegetated balconies has been shown to provide environmental benefits equivalent to approximately 8.8 small urban trees [8, 9]. More broadly, urban vegetation plays a key role in climate regulation by reducing CO_2 concentrations and mitigating heat accumulation in densely built environments

3.2. Residential benefits

In addition to their environmental role, vegetated balconies, terraces and window planters have a significant impact on residents' psychological well-being and everyday spatial experience [1, 3, 9].

From a perceptual standpoint, the presence of greenery has a well-documented positive effect on human well-being. Green, in particular, is associated with relaxation and visual comfort [3, 9]. Studies have shown that even indirect exposure to greenery, such as views from windows toward plants or trees, can reduce stress levels and improve overall mental health. Vegetation contribute to sensory richness and aesthetic diversity, thus transforms otherwise monotonous architectural surfaces, such as bare façades, walls or railings, into more pleasant and engaging environments.

Direct access to vegetated private open spaces further amplifies these benefits. These spaces provide opportunities for small-scale, routine gardening activities such as watering, pruning and plant care, which engage multiple senses and contribute to stress reduction [3]. The act of interacting with plants through touch, smell and visual observation introduces a calming, restorative dimension into daily life [3]. Research indicates that balconies and terraces actively used and maintained by residents provide higher levels of satisfaction, support emotional restoration and contribute to a sense of personal control and attachment to the living environment [1, 10]. Beyond individual effects, greenery integrated into everyday residential spaces also has a behavioral dimension. It encourages more frequent use of outdoor areas, fosters routine interaction with the environment and supports healthier lifestyle patterns.

4. MODELS OF FAÇADE PLANTER-INTEGRATED GREENERY – CASE STUDY

The case studies were selected based on the following criteria: (1) integration of vegetation through façade planters rather than complex green wall systems; (2) applicability to residential buildings; (3) medium to low level of technical complexity;

and (4) potential transferability to the local context of Niš, considering economic and maintenance constraints.

The comparative analysis is based on four key parameters: system type, vegetation strategy, technical complexity, and level of user involvement. These parameters were derived from a review of relevant literature and refined through the analysis of selected case studies. Technical complexity was assessed qualitatively (low, medium, high) based on structural integration, irrigation requirements, and maintenance demands. User involvement was evaluated based on the degree to which residents participate in planting, maintenance and system adaptability.

4.1. Individual planters with climbing support

On parisian multifamily apartment building *EdisonLite* (Figure 1) 290 large planters punctuate the windows of the façade, with an average of 14 planters per unit [11]. The façade planters are designed as lightweight, prefabricated aluminum elements that are structurally integrated into the façade system. Each planter is supported by a secondary steel substructure. The aluminum casing ensures durability and reduced weight, while the interior accommodates a planting substrate with integrated drainage. Positioned slightly away from the insulated façade layer, the planters allow for ventilation and prevent moisture-related damage, forming an efficient and rational system for integrating greenery into the architectural envelope. More than 6,000 plants were planted before the residents' arrival, ensuring the established planted landscape. Each planter has two large *Passiflora caerulea,* which were planted before the residents moved in. Other plants have also been established in each planter, a sort of gardening starter kit for residents with different bulbs and rushes (*Luzula*). Each family has the responsibility of looking after it, ensuring that it flourishes and spreads across the façade.

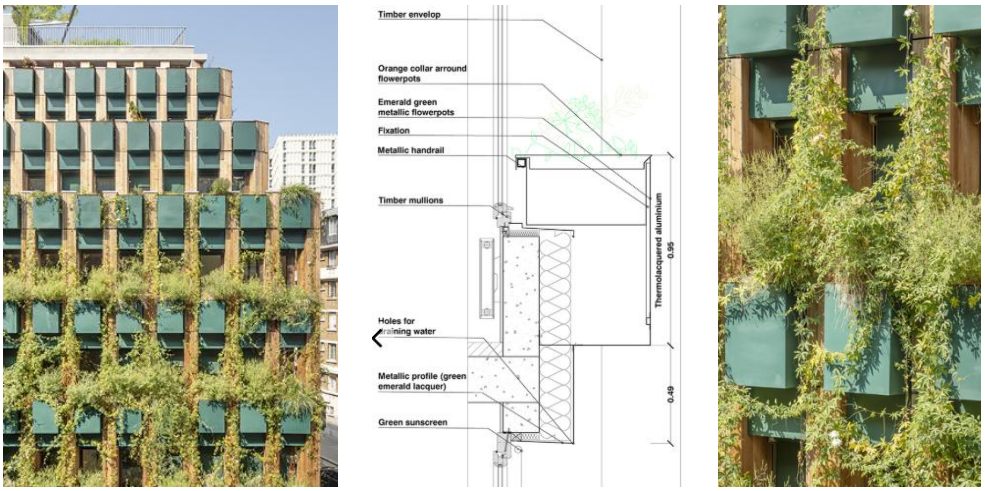


Figure 1. Edison Lite Apartment Building / Manuelle Gautrand Architecture

The greening system implemented on the *Villa M* (Figure 2) in Paris represents a contemporary hybrid approach to the development of green façades [12]. The total vegetated surface area amounts to approximately 140 m². The system is based on a

secondary steel exoskeleton structure positioned in front of the building's thermal envelope, which supports modularly organized planters, filled with substrate. In this way, the vegetation is physically separated from the main façade, preventing thermal bridging and allowing for the continuity of insulation. The prefabricated and modular nature of the system facilitates both construction and maintenance, making it an efficient integration of technological rationality and a high level of biological incorporation into the architectural envelope. A diverse plant palette adapted to the Parisian climate has been applied, with the intention of creating a layered and evolving landscape. In total, 93 plant species are incorporated, including 65 varieties of medicinal, perennial, and herbaceous plants (*Artemisia vulgaris, Mentha, piperita, Valeriana officinalis, Allium schoenoprasum, Iris germanica 'Pacemaker', Eupatorium cannabinum, the climbing rose 'New Dawn', Clematis flammula 'Aromatica', Passiflora caerulea, Asarum canadense, Petasites japonicus, and Geranium pretense*). The variation in plant colors, together with their organization into three vertical layers, creates a dynamic composition. Over time, this living system becomes the most expressive architectural element, continuously transforming in response to seasonal and environmental changes.

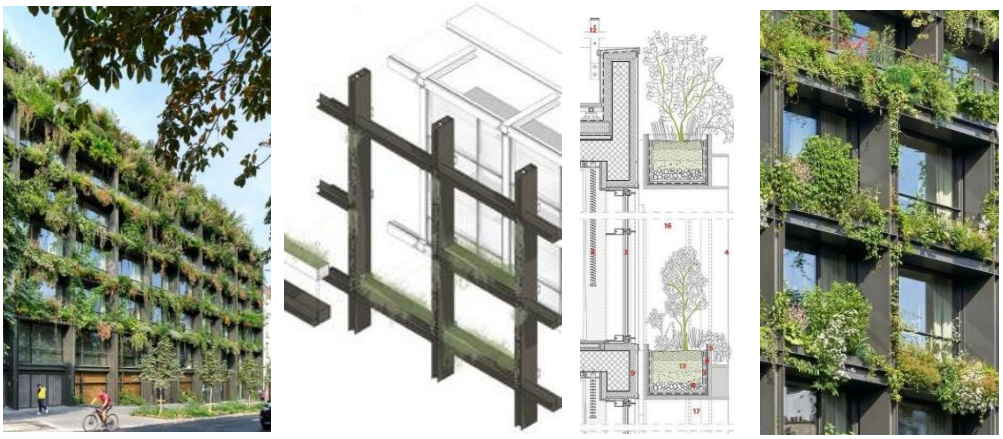


Figure 2. Villa M / Triptyque Architecture

Buildings *SR-1 House* [13] and *Resort in House* [14] are examples of a low-tech approach to the integration of vegetation within a dense tropical urban environment (Figure 3). The greening system is based on a network of suspended planters distributed along the façade, forming a continuous green layer that functions as passive protection against intense solar radiation, while also acting as a visual filter toward surrounding buildings. Unlike buildings with a strictly predefined planting scheme, this approach employs a flexible planting strategy based on a combination of plant species suitable for planter growth. The plant palette consists of a mix of tropical ornamental and shrub species, including plants with abundant foliage, ferns and small trees, enabling the rapid formation of dense vegetation. Such an approach allows for adaptability over time, as well as active user participation in the selection and maintenance of the plants. In climatic conditions characterized by high temperatures and humidity, typical of tropical regions, this type of greening system contributes to

effective solar shading, reduction of façade overheating, improvement of natural ventilation and the creation of a more favorable microclimate. At the same time, it provides a high level of visual and spatial quality, enhancing the overall environmental experience of the building.



Figure 3. a) SR-1 House / SPNG Architects, b) Resort in House / ALPES Green Design

4.2. Planters with climbing support

The façade treatment of the *Consorcio Building* in Santiago represents one of the early and paradigmatic examples of integrating vegetation into the architectural envelope [15]. Due to its westward orientation, the building is exposed to significant heat gains during the summer, which led to the implementation of a double-skin façade system. This system consists of an inner glazed layer and an outer vegetated layer that functions as a climatic buffer. The greening strategy is based on deciduous climbing plants, most likely vine species from the *Vitis genus* or related varieties, which enable seasonal regulation of solar exposure. The vine is climbing along a secondary metal structure, with horizontal support, positioned in front of the glass façade. This provides a continuous green layer of approximately 3,000 m². In contrast to systems that emphasize biodiversity and complex planting, this project employs a reduced planting concept based on a single dominant species, aiming to achieve an efficient and predictable seasonal response. During the summer, the dense foliage provides effective shading and reduces heat gain, absorbing up to 48% less heat, resulting in significant energy savings for cooling. In winter, the shedding of leaves allows sunlight to penetrate the façade, contributing to passive solar heating and improved delighting of the interior spaces.

The *Breathing House* in Ho Chi Minh City, also applies a greening system based on the principle of a “green veil” [16]. Unlike the previous example, which relies on horizontal support, this project uses vertical steel elements along the façade to guide the growth of climbing plants. The vegetation is supported by a series of integrated planters on each floor, enabling vertical development and continuous connection of the

green layer across all levels of the building. This vegetated envelope functions as a diffuse ecological filter, reducing direct solar radiation, enhancing privacy and contributing to the passive regulation of the indoor microclimate. In this project, vegetation is not treated as a decorative element, but as an infrastructural component of the architectural system, actively participating in the building's environmental performance and spatial organization.



Figure 4. Consorcio Building / Enrique Browne, b) Breathing House Breathing House / VTN Architects

5. DISCUSSION AND CONCLUDING REMARKS

The findings of this study indicate that the effectiveness of façade-integrated greenery systems is strongly conditioned by their technical simplicity, adaptability and level of user engagement. In the context of Niš, where residential buildings predominantly rely on individual maintenance and limited institutional support, low-tech and hybrid planter systems demonstrate the highest potential for long-term viability.

A comparative overview of the analyzed examples reveals distinct approaches in terms of system design, vegetation strategy and level of control (Table 1). First, there is a clear inverse relationship between system complexity and resilience in contexts with limited maintenance capacity. High-tech systems, while offering precise control and expressive architectural integration, tend to depend on stable technical management. In contrast, low-tech or hybrid systems, particularly those based on accessible planters, demonstrate greater adaptability and long-term viability in less controlled environments. Second, the role of vegetation varies significantly: from monoculture, performance-driven systems (as in *Consorcio Building*) to biodiverse, evolving landscapes (as in *Villa M*). Planter-based systems occupy an intermediate position, enabling both controlled and user-driven planting strategies. Third, user participation emerges as a key factor in the sustainability of these systems. Buildings that incorporate greenery as a shared responsibility between design and everyday use tend to demonstrate greater durability over time. In this sense, vegetation is not only a

design element but also a medium of interaction, contributing to the formation of a more engaged and environmentally aware residential culture.

Table 1. Comparative analysis of integrated façade planters systems

Project	System type	Vegetation strategy	Technical complexity	User involvement
Edison Lite	Individual façade planters	Highly diverse, Layered planting	Medium	High
Villa M	Individual façade planters on exoskeleton	Highly diverse, Layered planting	High	Medium
SR-1 House Resort in House	Suspended planters	Flexible, user-adaptable	Low	High
Consorcio Building	Large planters with horizontal climbing support system	Monoculture Type of vine	Medium	Low
Breathing House	Large planters with vertical climbing support system	Monoculture Asian climbing plant	Medium	Medium

Given the local climatic conditions, characterized by increasing summer temperatures, pronounced urban heat effects and limited green infrastructure, planter-integrated greenery can play a significant role in passive cooling, façade shading and improvement of microclimatic conditions. These systems enable a gradual and decentralized model of urban greening, aligned with the local socio-economic context.

Based on the findings, the following design recommendations can be outlined:

- Prioritize low-tech, modular planter systems for residential applications;
- Ensure accessibility of planters for maintenance by users;
- Select plant species adapted to local climatic conditions;
- Integrate simple drainage and irrigation solutions;
- Encourage user participation through flexible and adaptable planting schemes;

In conclusion, the integration of greenery into private open spaces represents a pragmatic and context-sensitive approach to sustainable housing development in Niš, with the potential to contribute to broader urban resilience through cumulative, small-scale interventions. However, for such systems to achieve broader impact, it is necessary to establish clearer design guidelines, promote awareness among both professionals and residents and incorporate façade greenery into local planning guidelines as a complementary form of urban green infrastructure. However, this study has several limitations. The analysis is primarily based on qualitative assessment and does not include detailed quantitative performance measurements, such as precise temperature reduction or energy savings. Future research could include simulation-based or empirical measurements within the local context of Niš.

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Research paper

INTEGRATION OF GREENERY IN RESIDENTIAL ARCHITECTURE: A COMPARATIVE CASE STUDY OF SELECTED HOUSES

Hristina Krstić[1], Branislava Stoiljković[2], Nataša Petković[3]

Abstract

The reduction of direct human contact with nature caused by intensive urbanization imposes the need for new approaches to the design of residential spaces in which greenery constitutes an integral part of the architectural composition. The aim of this study is to identify and systematize models of greenery integration in contemporary single-family residential architecture, which enable nature to become an active component of users' everyday life rather than merely an aesthetic addition. The research was conducted using a comparative case study approach through the analysis of four representative projects of contemporary residential architecture: Moriyama House (Ryue Nishizawa), House N (Sou Fujimoto), Garden House (Takeshi Hosaka Architects), and Sixteen Doors House (INC Architecture & Design). First, each project was analyzed in terms of spatial and functional organization, the position and role of greenery within the architectural composition, the relationships between interior and exterior spaces, and the nature of their interrelation. This was followed by a comparative analysis of the selected cases. The results show that the success of integrating greenery into residential space does not depend primarily on the amount of greenery, but rather on the way in which it is incorporated into the spatial composition of the building. Four models of greenery integration were identified—fragmentation of volumes, spatial layering, atrium-centered spatial organization, and openness toward the natural environment—whereby all of them contribute to the blurring of the boundary between interior and exterior, the formation of in-between spaces, and the inclusion of nature in the everyday life of residents. The study highlights the potential for designing residential spaces in which greenery represents an equal constitutive element of architecture and the basis for a higher-quality relationship between humans and nature, achieved through architecture.

Key words: *Greenery; Residential space; Spatial organization; Green space integration.*

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1. INTRODUCTION

Current global trends, characterized by intensive urbanization and increasing construction activity, are gradually leading to a loss of contact between humans and nature. Considering the importance of the presence of natural elements in the immediate living environment for physical and mental health, as well as for the sense of comfort, opportunities for social interaction, and the overall quality of living [1–4], the integration of greenery into residential space has become one of the key issues in contemporary architecture. In this context, greenery is increasingly regarded not merely as a complement to a building or an aesthetic feature, but as an integral and equal component of its spatial organization.

Against this background, the paper investigates the principles through which greenery can be integrated into the architectural composition of residential buildings. It seeks to answer the central research question concerning how the spatial organization of a residential building's architectural composition can enable greenery to become its constitutive element rather than merely an external addition. This topic has been examined in the context of single-family housing, with the possibility of further developing this line of research in the context of multi-family housing. The aim of the research is to identify and systematize different models of greenery incorporation into residential space through the analysis of representative examples of contemporary single-family residential architecture. The paper aims to highlight design approaches that enable the creation of residential spaces in which nature becomes an active component of everyday life and an equal element of the architectural composition.

The research methodology is primarily based on individual case studies and comparative analysis. Four case studies are examined and subsequently compared to identify different architectural approaches to integrating greenery into residential space, enabling the identification of distinct integration models. The case studies include following projects: *Moriyama House* (Ryue Nishizawa), *House N* (Sou Fujimoto), *Garden House* (Takeshi Hosaka Architects), and *Sixteen Doors House* (INC Architecture & Design). The projects were selected according to the criteria of: typological consistency (single-family housing), contemporary character, architectural relevance, availability of project documentation, the presence of a relationship between architecture and nature, and, above all, different ways of integrating greenery into residential space. The limited number of selected projects may be considered a limitation of this research, and the authors acknowledge that a larger sample would provide a more comprehensive basis for analysis. Nevertheless, the number of selected projects is consistent with the qualitative nature of the research and the case study methodology, which emphasizes an in-depth analysis of a limited number of carefully selected and representative examples. The aim of the research is not the statistical generalization of the findings, but rather the identification of characteristic models of greenery integration into residential space through different architectural approaches. The scientific contribution of this research lies in the proposal of a preliminary, rather than definitive, typology of models for integrating greenery into residential space, based on a comparative analysis of the selected case studies. The identified models constitute an analytical framework

that may serve as a foundation for future research and the development of design principles for integrating nature into residential architecture.

The case studies were conducted using interpretative models of selected architectural projects, developed on the basis of the available literature and graphic documentation. The analysis focused on the following aspects: spatial and functional organization, the position and role of greenery within the architectural composition, and the relationships between interior and exterior spaces and their spatial character. Through comparative analysis, characteristic models of greenery integration into residential space were identified, together with their common principles and distinctive features.

2. ANALYSIS

This section first provides a concise overview of the individual analyses of the projects selected for the research, followed by a comparative analysis of the case studies.

2.1. Individual case studies

2.1.1. Moriyama House

Moriyama House (Tokyo, Japan, 2005, designed by Ryue Nishizawa) [5] is a residential house designed to serve both as the owner's home and as rental accommodation [6]. This requirement resulted in an unconventional residential design: instead of a single compact building, the house consists of a series of different volumes scattered across the site, each accommodating one or more functions. Through their combination, these volumes create living spaces for both the owner and the tenants.

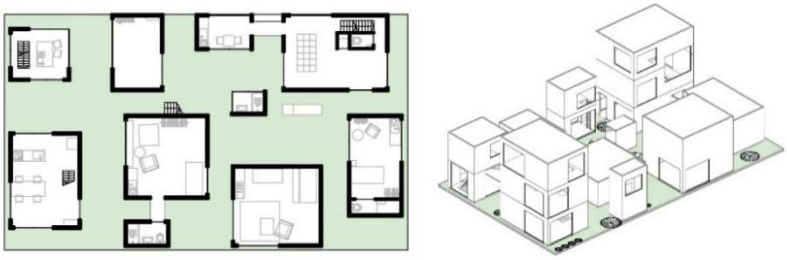


Figure 1. Integration of greenery in Moriyama House (left: plan, right: simplified model). Green space is shown in green. The plan and model sketches were prepared by the authors for this research and are based on their interpretation of the architects' drawings available in published sources.

The volumes are interconnected by green open spaces—gardens—that function both as courtyards and as circulation spaces connecting the rooms distributed among the different volumes (Figure 1). Indeed, the spatial arrangement of the volumes across the site creates a network of gardens and open spaces whose functional significance is equal to that of the enclosed spaces. A strong relationship between the interior and exterior is evident, reflecting the close integration of greenery into the residential environment, achieved through the fragmentation of the architectural composition.

The continuous interweaving of living spaces and greenery is manifested not only visually, but also physically and spatially, to a remarkable extent.

2.1.2. House N

House N (Oita, Japan, 2008, designed by Sou Fujimoto) is a house that was designed, according to the architects, as "a home for two plus a dog" [7]. The project is based on the concept of one volume enclosed within another, or, in other words, on the idea of a layered architectural composition. The composition consists of three volumetric enclosures of different sizes that surround one another. The innermost enclosure defines the primary interior living space of the house, accommodating everyday activities such as the living room and dining area. The middle enclosure extends the interior living space by incorporating functions such as sleeping and relaxation. The outermost enclosure defines the overall footprint and volume of the house, forming a semi-open space positioned at the threshold between the house and the urban environment, or more precisely, between the private and the public realm. Through this gradation of privacy, the three volumetric enclosures define distinct spatial zones within a unified whole, simultaneously enabling both the separation and the interweaving of spaces.

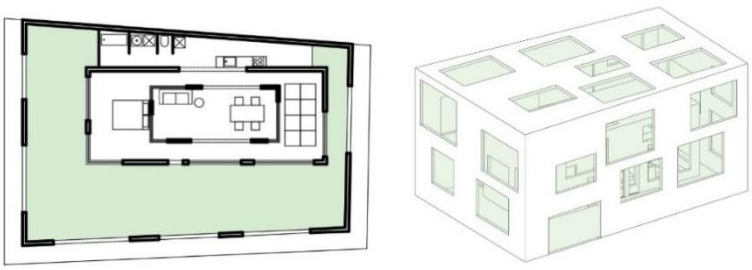


Figure 2. Integration of greenery in House N (left: plan, right: simplified model). Green space is shown in green. The plan and model sketches were prepared by the authors for this research and are based on their interpretation of the architects' drawings available in published sources.

The outermost enclosure shapes a space that can be understood as a "green room"—a semi-open garden integrated into the structure of the house (Figure 2). It represents a natural extension of the living space and a transitional zone between the interior and the city, allowing the occupants to maintain a continuous relationship with the natural environment. Owing to its numerous perforations, the enclosure simultaneously functions as both a protective shell and a transparent membrane. In this way, natural elements become an integral part of the occupants' everyday life while the enclosure also provides a buffer from the noise and intensity of the public realm, creating a comfortable and protected outdoor living environment.

2.1.3. Garden House

Garden House (Yokohama, Japan, 2007, designed by Takeshi Hosaka Architects) is a residential project whose design originated from the clients' desire to live in a house that would provide the experience of living in an open environment [8–9]. The defining characteristic of the architectural composition is its introverted organization and the

centrally positioned courtyard around which the house is arranged (Figure 3). The specific geometry of the site determined the spatial and functional organization of the building, which consists of two linear wings positioned along the site boundaries and connected by an open green space. Throughout the project, open and enclosed spaces are continuously interwoven through the central courtyard, a series of roof terraces, and transparent partitions that blur the boundary between the interior and the exterior. It can be concluded that the open and enclosed parts of the house are unified through the introduction of the courtyard, which becomes the focal point of the architectural composition. The rooms are arranged linearly around the central courtyard, establishing both visual and physical continuity with it. In this project, the courtyard performs a role that differs from its conventional function: rather than functioning solely as an inner courtyard, it acts as an open extension of the interior living space. It can be understood as an open room containing greenery—one of a sequence of interconnected spaces that, through their different functions, collectively form the house.

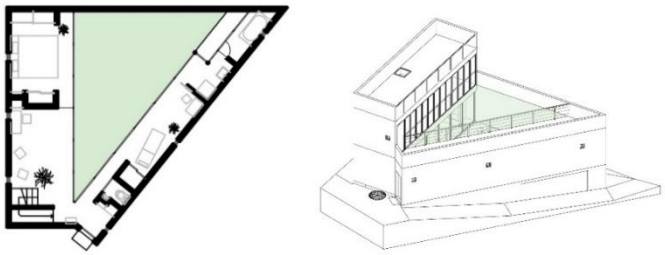


Figure 3. Integration of greenery in Garden House (left: plan, right: simplified model). Green space is shown in green. The plan and model sketches were prepared by the authors for this research and are based on their interpretation of the architects' drawings available in published sources.

2.1.4. Sixteen doors House

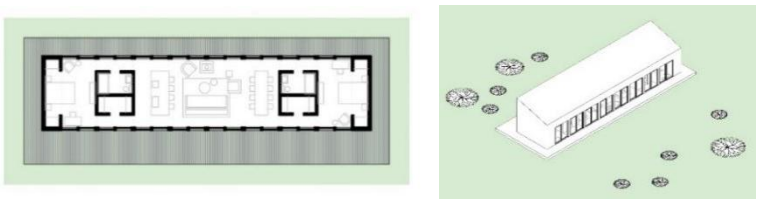


Figure 4. Integration of greenery in Sixteen doors House (left: plan, right: simplified model). Green space is shown in green. The plan and model sketches were prepared by the authors for this research and are based on their interpretation of the architects' drawings available in published sources.

Sixteen Doors House (Hillsdale (NY), USA, 2005, designed by INC Architecture & Design) [10] is a residential project based on the concept of an open-plan spatial organization, in which the living area occupies the center of an elongated volume with a rectangular floor plan, composed of a linear sequence of functional spaces. Two physically separated groups of service spaces, positioned symmetrically with respect to the transverse axis, divide the house into a central living zone and two peripheral sleeping zones. The longitudinal façades are almost entirely glazed, visually connecting the entire interior with the surrounding natural environment. When the large glazed openings are fully opened, a direct physical connection with the exterior is established,

allowing the surrounding landscape to become a natural extension of the interior and an integral part of the living space (Figure 4).

2.2. Comparative analysis across cases

The cross-case analysis reveals that all four projects pursue the integration of greenery into residential space, albeit through entirely different spatial strategies:
(1) The spatial concept of organization in *Moriyama House* is based on the idea of fragmentation, or the decomposition of the architectural composition. Greenery appears as the space between volumes, resulting in a complete interweaving of interior and exterior space, both physically and visually.
(2) The spatial concept of organization in *House N* is based on the idea of space within space. Through the use of layered enclosures, greenery appears as a transitional zone that gradually mediates movement along the interior–exterior continuum.
(3) The spatial concept of organization in *Garden House* is based on the idea of the courtyard. Greenery is positioned as the central organizing element, around which the interior space is developed.
(4) The spatial concept of organization in *Sixteen Doors House* is based on a linear open-plan arrangement of interior spaces, which, through a transparent envelope, communicate with the natural environment in which the house is embedded. Greenery, as part of the surrounding landscape, becomes the dominant element, primarily in visual terms, but also physically through the opening of partitions.

In *Moriyama House*, greenery is not an addition to the residential space, but rather becomes an integral functional element of it (as a means of circulation). Movement between individual programmatic units takes place through gardens and open spaces. In other words, part of everyday life necessarily unfolds outdoors. It can be argued that this is the most radical example of the integration of nature among the analyzed projects, as the boundary between house and garden is almost entirely dissolved.

In *House N*, the open green space is not primarily a circulation zone or a conventional garden space, but rather a transitional space. Fujimoto introduces multiple layers between the city and the interior, with the garden functioning as a protective intermediary zone. Greenery serves to filter the influences of the urban environment and to soften the sharp boundary between the private and the public realm, gradually modulating spatial privacy (from the public realm beyond the site boundary, through a semi-public/semi-private “green room,” to the private interior space).

Garden House presents a different approach. Instead of life extending outward from the interior through open spaces or being connected via them, the entire spatial organization gravitates toward a single central open space. Here, the atrium departs from its traditional role as an inner courtyard and is transformed into an “open room,” which becomes the spatial core of the architectural composition—a place of everyday living as well as the primary point of contact with the exterior environment.

In *Sixteen Doors House*, unlike in the previous projects, greenery is not physically introduced into the spatial structure of the house. Instead, integration with greenery is achieved through a transparent façade: the greenery remains outside, but is visually

incorporated into the interior, while physical continuity with the interior is established by opening glazed façade partitions. Nature becomes the dominant element of the spatial perception of the dwelling.

3. DISCUSSION

The results of the comparative analysis identify several common characteristics shared by the analyzed projects, arising from the ways in which greenery is incorporated and treated within their spatial organization:

(1) All analyzed projects exhibit a high degree of interweaving between greenery and residential space (Table 1). Although the intensity of this relationship varies depending on the spatial organization and the intended use of each house, the presence of green space represents a defining characteristic of every project. This relationship is manifested primarily through physical and visual connections. Such integration is particularly significant, as contact with natural elements, including vegetation and natural daylight, has been shown to enhance health and recovery, while proximity to open green spaces is associated with improved physical and social well-being [11]. Furthermore, contact with nature has been linked to enhanced cognitive functioning [11]. These documented benefits further emphasize the importance of the strong physical and visual integration between greenery and residential space observed across all analyzed projects. From a physical perspective, the highest degree of interweaving is observed in *Moriyama House*, where open green spaces serve as the primary circulation routes between certain rooms. A strong physical relationship is also evident in the other projects: in *House N*, through a semi-open living space that also functions as a transitional zone between the strictly private interior and the public realm; in *Garden House*, through an open space used for outdoor living that simultaneously connects and integrates the enclosed spaces; and in *Sixteen Doors House*, through operable glazed partitions that merge the interior with the surrounding natural environment. Owing to the high degree of transparency of the building envelopes separating the open green spaces from the enclosed interior, a strong visual relationship between greenery and residential space is present in all the analyzed projects. This visual connection is particularly pronounced in *Sixteen Doors House*, where it constitutes the dominant form of interweaving between the interior and the surrounding natural environment.

(2) The boundary between the interior and the exterior is blurred in all analyzed projects. None of the projects exhibits a strict separation between interior and exterior. Instead, these two spatial domains are in a constant interweaving. Rather than establishing a strict separation between enclosed and open spaces, houses create different degrees of spatial continuity through gardens, transitional zones, courtyards, and transparent envelopes. Interior and exterior spaces are therefore continuously interconnected through physical and/or visual relationships, allowing greenery and natural elements to become an integral part of the residential experience. Such an approach reflects Kim's considerations regarding the form of the continuity as a fundamental principle of architecture, which emphasizes, among other aspects, the

establishment of meaningful relationships between architecture and its surroundings [12].
(3) By blurring the boundary between interior and exterior space, greenery causes these two spatial domains to become interwoven and to acquire characteristics of one another, giving rise to a new spatial category within the architectural composition based on ambivalence—the in-between space [13]. In the analyzed projects, these in-between spaces take the form of: gardens between volumes, a semi-open garden, an atrium, and terraces opening onto the surrounding natural landscape.
(4) As transitional spatial categories, in-between spaces enrich the spatial experience while also encouraging a way of living that differs from conventional residential patterns [13].
(5) In none of the analyzed projects is greenery treated merely as an addition to the residential function or as an aesthetic feature of the building. On the contrary, it actively participates in everyday life and constitutes an inseparable part of the spatial concept of the dwelling. The spatial-functional organization of each house reflects the intention to integrate nature into everyday living. This equal treatment of greenery—as a component equivalent to any other residential function—results in nature becoming an integral part of the occupants' daily lives.

Table 1. Characteristics of spatial organization in the analyzed houses

Project	Spatial organization	Green space type	Greenery – building interweaving degree	Dominant type of interior – exterior relationship
Moriyama House	Fragmentation	Network of green spaces	Extremely strong	Visual and Physical
House N	Space within space	Green layer	Very strong	Visual and Physical
Garden House	Atrium	Inner courtyard	Very Strong	Visual and Physical
Sixteen Doors House	Compact building volume	Natural context	Very Strong	Visual

The common characteristics identified across the analyzed projects result from different conceptual approaches (Figure 5a): fragmentation (*Moriyama House*), layered spatial organization (*House N*), an atrium-centered spatial organization (*Garden House*), and the maximum opening of the building toward the surrounding landscape (*Sixteen Doors House*). Common characteristics are reflected in the blurring of the boundary between interior and exterior, the formation of in-between spaces as transitional spatial categories, and the treatment of nature as an integral part of everyday life rather than as a decorative element. The creation of in-between spatial categories—i.e. ambivalent spaces that acquire characteristics of both interior and exterior domains—emerges as one of the key mechanisms for connecting interior and exterior space, that is, habitation and nature. Although the approaches to spatial organization differ and each architectural composition produces a unique spatial and functional outcome, all of the projects are equally successful in establishing a close relationship between greenery and everyday living.

Thus, based on the individual case analyses and the comparative analysis, four dominant roles of greenery can be identified (Figure 5b): (1) Greenery as a circulation space; (2) Greenery as a buffer zone; (3) Greenery as a central space; (4) Greenery as an extension of the interior.

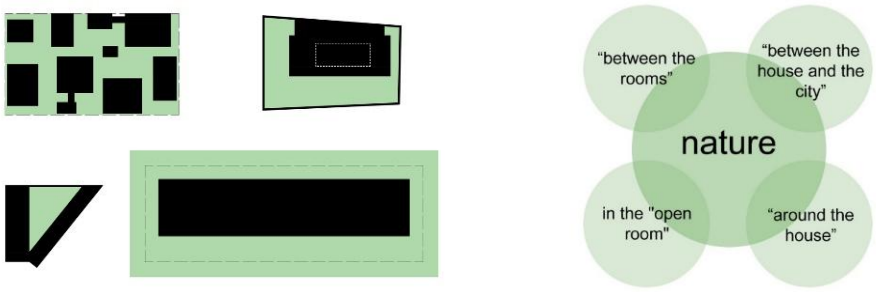


Figure 5. (a) Conceptual approaches: fragmentation, layered spatial organization, atrium-centered spatial organization, opening of the building toward the surrounding landscape; (b) Models of Green Space Integration in the Analyzed Projects.

4. CONCLUSION

Through four different conceptual approaches to the spatial organization of architectural composition—based on decomposition, the layering of spatial structure, courtyard organization, and the transparency of the external envelope—it has been demonstrated that greenery does not have to be treated merely as an external addition to architecture, but can function as an equal constitutive element of residential space. The analyses confirm that the integration of greenery into architectural design can serve as a principle of spatial organization that contributes to a higher-quality relationship between humans and the natural environment. Architecture can act as a medium for this relationship as well as its catalyst. Furthermore, the analyzed projects show that the success of integrating greenery into residential space does not depend primarily on the amount of greenery, but rather on the way in which it is incorporated into the spatial composition of the building.

The research identified four typological models of greenery integration into residential space: fragmentation, spatial layering, atrium-centered spatial organization, and openness toward the natural environment. These models facilitate the integration of greenery into the building's spatial structure and foster a close and meaningful relationship between users and the natural environment.

The identified typological models provide a conceptual framework for the design of residential projects that seek to strengthen the connection between architecture and nature. However, it should be acknowledged that each of the proposed typological models of greenery integration into residential space has practical limitations regarding its applicability in different climatic, cultural, and urban contexts. Therefore, it is necessary to emphasize that further research should examine these limitations in order to assess the applicability and potential adaptation of the proposed models across diverse settings.

Additionally, several other limitations of this study should be acknowledged. The analysis of models of greenery incorporation was conducted exclusively on examples of single-family residential buildings, as well as on a limited number of case studies. Future research should be extended to the field of multi-family housing in order to examine the applicability of the identified models within more complex spatial and functional structures. Moreover, by analyzing a larger number of representative examples, it would be possible to identify additional models of greenery integration into residential space and further improve their typological systematization.

ACKNOWLEDGMENT

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Research paper

MULTIPLE BENEFITS OF COMMUNITY GARDENS IN MULTIFAMILY HOUSING AREAS: RODA-RODA-GASSE, VIENNA

Ivana Bogdanović Protić [1], Ljiljana Vasilevska [2], Jelena Živković [3], Magdalena Slavković [4]

Abstract

Community gardens are increasingly recognized as small-scale but highly effective interventions for improving the quality of life in multifamily housing areas. Inherited housing estates often contain underused or insufficiently activated open spaces, whose spatial, social and environmental potential remains only partially realized. This paper examines the multiple benefits of community gardens in the context of urban regeneration, focusing on the case of the Roda-Roda-Gasse community garden within the Oscar-Helmer-Hof municipal housing estate in Vienna. The research is based on a review of relevant literature and case study analysis, with particular attention to the transdisciplinary planning and participation process through which the garden was developed. The paper analyzes how the implementation of a community garden can contribute to the transformation of an unused green area into an active shared space that supports residents' participation, social interaction, environmental awareness and a stronger sense of belonging. Special emphasis is placed on the social, spatial-functional, environmental, health-related and governance benefits of the project. The findings indicate that community gardens should not be understood only as spaces for gardening, but as participatory tools for the regeneration of residential open spaces and the strengthening of local communities. The Roda-Roda-Gasse case demonstrates that, with adequate institutional support, facilitation and resident involvement, community gardens can become important elements of sustainable and inclusive housing environments. The paper concludes that this model may provide useful guidelines for the revitalization of open spaces in multifamily housing areas with similar spatial and social challenges.

Key words: *community gardens, multifamily housing, urban regeneration, open spaces, quality of life*

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1. INTRODUCTION

The quality of life in multifamily housing areas depends not only on the architectural characteristics of residential buildings, but also on the condition, accessibility and everyday usability of their open spaces. In inherited housing estates built after World War II, open spaces were often planned as important parts of residential comfort, recreation and neighbourhood life. However, long-term problems of maintenance, unclear responsibilities, changing lifestyles and insufficient adaptation to residents' needs often reduce their social, functional and ecological values [1].

Open spaces in multifamily housing areas have a multidimensional role. They provide opportunities for recreation, informal encounters, children's play, contact with nature, visual comfort and everyday outdoor activities. Their quality is therefore related to spatial design, but also to social sustainability, environmental performance and residents' identification with the living environment [1, 2]. When such spaces remain unused or poorly organized, they may become residual areas rather than active components of housing quality.

In this context, community gardens can be understood as small-scale interventions with the capacity to produce wider spatial and social effects. They transform passive lawns or unused green areas into shared places of cultivation, communication, learning and collective responsibility. Although community gardens are sometimes discussed within the broader field of urban agriculture, their relevance for multifamily housing areas is not primarily connected with food production. Their main value lies in the activation of common open spaces and in the creation of social relations around everyday care for the environment [3, 4].

The paper focuses on the Roda-Roda-Gasse community garden, located in the Oscar-Helmer-Hof municipal housing estate in Vienna. This case is particularly relevant because it was developed within Vienna's municipal housing system and is identified as the first community garden in a council housing block of the City of Vienna [5]. The project demonstrates how gardening can be introduced into a collective housing environment through institutional support, facilitation, resident participation and self-organization [5-7]. Recent research on RE:RO:DA also frames Oscar-Helmer-Hof as a post-war municipal housing estate with generous but underused open spaces, infrastructural limitations and social challenges, which confirms the relevance of the case for discussing open-space retrofit and community-based regeneration [8].

The aim of the paper is to examine the multiple benefits of community gardens in multifamily housing areas, using the Roda-Roda-Gasse case as the research platform. The main research question is: How does the implementation of community gardens within urban regeneration projects contribute to improving the quality of life in multifamily housing areas? Following the logic of case-study papers that examine multiple benefits of regeneration measures, the paper first presents the project context, then the implementation process, and finally the main categories of benefits [2]. Methodologically, the paper is based on a qualitative case study approach, combining a review of relevant literature, analysis of available project documentation and secondary research sources related to the Roda-Roda-Gasse community garden. The contribution of the paper lies in systematizing the multiple benefits of community gardens in

multifamily housing areas and in positioning them as participatory, spatial and governance instruments of small-scale urban regeneration.

2. URBAN REGENERATION PROJECT: RODA-RODA-GASSE, OSCAR-HELMER-HOF, VIENNA

The Roda-Roda-Gasse neighbourhood garden is located within Oscar-Helmer-Hof in Strebersdorf, in Vienna's 21st district, Floridsdorf (Figure 1a). Oscar-Helmer-Hof was built between 1960 and 1967 and contains 791 apartments distributed across 102 staircases. It is a municipal housing estate characterized by three- to eight-storey linear residential buildings and relatively generous green open spaces [5, 8] as shown in Figure 1b. The garden is positioned at the edge of the estate, near a busy road, but separated from it by a slope and a pedestrian path.



Figure 1. Roda-Roda-Gasse neighbourhood: a) spatial context; b) open space before regeneration
Source: [8]

The project of community garden started in autumn 2008 as a pilot initiative introduced by Verein Wirbel on a previously unused lawn. The selected plot had an area of about 700 m2 and was chosen in cooperation with Wiener Wohnen, the tenants' advisory board of Oscar-Helmer-Hof, the local customer service centre of Wiener Wohnen and Verein Wirbel. This institutional constellation is important because it shows that the project was not only a spontaneous gardening initiative, but a negotiated intervention within an existing municipal housing framework.

A loan-for-use agreement was concluded between Wiener Wohnen and Verein Wirbel, while the project also received financial support from the City of Vienna through relevant municipal departments. The project paid special attention to the inclusion of women, both in everyday use of the garden and in taking formal roles within the new gardening community. This aspect is relevant for understanding the garden not only as a spatial intervention, but also as a tool for more inclusive participation in shared residential environments.

The first residents were informed through the tenants' advisory board and notices placed in the staircases of the housing estate. After initial information meetings on the future garden site, a group of interested tenants was formed. In 2009, 22 plots of 9 to 15 m2 were prepared and allocated to gardeners; later, the number of plots was increased, and by spring 2010 the garden was cultivated by 25 tenants and their families [5].

The project can be understood as a specific form of urban regeneration because it transformed an underused open space into a socially active and collectively managed place. It did not involve large-scale physical restructuring, but rather a precise intervention that changed the meaning and everyday function of a part of the housing estate. In this way, Roda-Roda-Gasse illustrates how small interventions in open spaces can generate wider effects on community life, spatial identity and residents' relationship with their living environment.

3. IMPLEMENTATION OF COMMUNITY GARDENS WITHIN THE URBAN REGENERATION PROJECT

The implementation of the Roda-Roda-Gasse community garden was based on the activation of unused spatial potential through a participatory and facilitated process. The garden included individually cultivated plots, common areas for sitting and meeting, circulation paths, space for children's movement and areas for storing garden equipment. This spatial organization made it possible to combine individual use with collective interaction.

The plan of the garden shows a clear division between cultivated beds and shared surfaces, which is important for reducing conflicts and supporting different ways of using the space (Figure 2). Some users may primarily cultivate their plots, while others may use the garden as a place for meeting, resting or observing gardening activities. In this sense, the garden was not planned only as a productive area, but as a neighbourhood space with several degrees of participation [7].

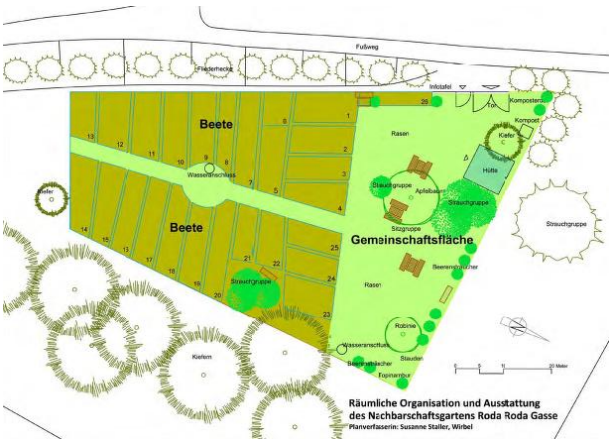


Figure 2. Schematic spatial organization of the Roda-Roda-Gasse community garden, Source: [5]

The implementation process included both technical and social preparation. A fence was installed, a water connection was provided, the area intended for plots was prepared, and paths were covered with wood chips through joint work by the members. All members received a garden pass with the most important rules and a key, which enabled independent access to the garden. The agreed time for garden work was set between 6 a.m. and 9 p.m.

A central feature of the project was the role of facilitation. During the first gardening season, representatives of Verein Wirbel regularly supported the gardeners, helped

with practical questions, organized composting and workshops, and mediated in situations of misunderstanding or conflict. Over time, this support was gradually reduced, which encouraged a transition from external guidance toward stronger self-organization [5, 6].

The project also had a research and learning dimension. The accompanying research examined the process of introducing the garden, its effects on users and neighbours, and the conditions needed for a wider implementation of neighbourhood gardens in Vienna's municipal housing. The methodology included protocol analysis, participant observation, SWOT analysis, interviews with gardeners and relevant actors, short interviews with passers-by, interpretation workshops and content analysis. This makes the case particularly valuable as a documented example for future housing regeneration projects.

The implementation process therefore combined physical, social and organizational dimensions. The physical transformation created a new garden space; the social process created a group of users; and the organizational framework defined rules, responsibilities and support mechanisms. The Roda-Roda-Gasse case shows that community gardens in multifamily housing cannot be reduced to the allocation of land. They require facilitation, governance, shared agreements and continuous communication among stakeholders [5, 6, 7].

4. MULTIPLE BENEFITS OF COMMUNITY GARDENS

4.1. Social benefits

One of the most important benefits of community gardens is the strengthening of social cohesion. Gardening activities create opportunities for residents to meet, communicate and cooperate in an informal setting. In multifamily housing areas, where everyday encounters are often limited to staircases, entrances or circulation areas, a shared garden can provide a more meaningful framework for neighbourly interaction.

The accompanying research on Roda-Roda-Gasse identified the garden's role as a place of social contact as one of the most frequently mentioned effects on individual users. The garden made it possible to create new contacts, maintain existing acquaintances and develop communication gradually, without forcing social interaction. This is important because the garden allows different levels of sociability: residents may participate intensively, occasionally or mainly through quiet individual work (Figure 3).



Figure 3. Everyday use and social interaction in the Roda-Roda-Gasse community garden. Source: [5]

The Roda-Roda-Gasse garden also illustrates the link between community gardening and intercultural contact. The first gardeners and their families had different cultural backgrounds, including Austrian, Bosnian, Egyptian, Indonesian, Iranian and Turkish backgrounds [5]. Such diversity makes the garden a space where social relations can be built through shared activity rather than only through formal neighbourhood programmes. Similar effects have been emphasized in research on community gardens and social cohesion [9, 10, 11].

4.2. Spatial and functional benefits

Community gardens improve the spatial and functional quality of open spaces by transforming underused green areas into active and recognizable places. Many inherited housing estates include large lawns or green surfaces that contribute visually to the residential environment but do not necessarily offer clear possibilities for everyday use. When such areas are reprogrammed as community gardens, their functional value increases substantially.

The Roda-Roda-Gasse project demonstrates how a previously unused lawn can become a shared place with a clear purpose (Figure 4 a, b). The introduction of plots, paths, common areas and regular activities increased the usability of the space and gave it a recognizable identity within the housing estate [7]. The garden also made issues of neighbourhood coexistence visible and negotiable, because themes that existed in the wider housing community could be addressed within a smaller and more concrete shared setting [5, 7].



Figure 4. Spatial and functional benefits: a) activated open space; b) place attachment. Sources: a) [7]; b) [8].

The spatial-functional benefit is closely related to residents' identification with the place. When residents participate in shaping and maintaining a space, they are more likely to perceive it as part of their own living environment. This strengthens territoriality, everyday care and attachment to the neighbourhood [1].

4.3. Environmental benefits

Community gardens contribute to environmental quality by increasing the diversity and intensity of vegetation within housing estates. Even when they are modest in size, they can improve the ecological value of open spaces through planting, soil care,

support for pollinators and the creation of small habitats. Their environmental value is therefore both physical and educational.

This environmental role is consistent with contemporary retrofit approaches in open spaces, where vegetation, soil permeability, biodiversity, shading and water retention are considered together. In the RE:RO:DA study, open-space retrofit is linked to climate resilience and to the creation of social outdoor spaces; community gardens fit this logic because they combine planting with everyday use and collective care [8].

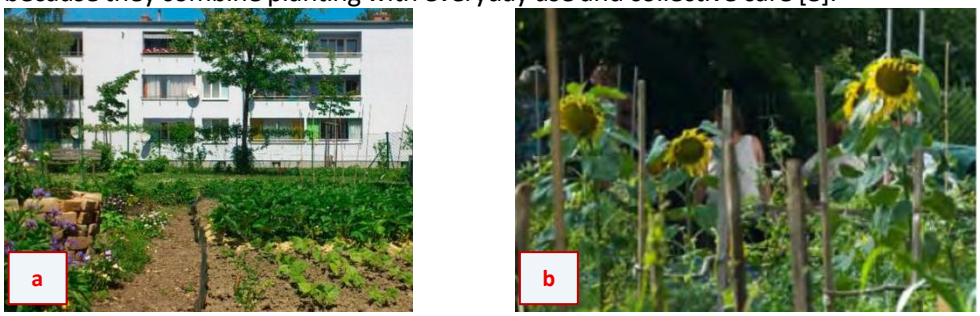


Figure 5. Environmental benefits of community garden a) productive open space; b) urban biodiversity. Sources: a) [8], b) [7].

Residents who participate in gardening gain direct experience of seasonal changes, plant growth, composting, water use and everyday ecological practices. This practical relationship with nature can strengthen environmental awareness more effectively than passive observation of green areas. Research on community gardens emphasizes their role in creating a more active relationship between urban residents and natural processes [12, 13, 14].

In dense urban environments, such spaces may also improve microclimatic comfort by introducing more varied vegetation and reducing the monotony of poorly used surfaces. Urban green spaces are widely recognized as important for health, climate adaptation and the improvement of urban living conditions [15]. Community gardens add an active and participatory dimension to this broader green-space function.

4.4. Health and well-being benefits

Community gardens can positively influence health and well-being by encouraging outdoor activity, contact with nature and everyday relaxation. Gardening involves light physical activity, sensory experience and time spent outside, which can contribute to both physical and psychological well-being.

In the Roda-Roda-Gasse research, gardeners described the garden as a place for meaningful activity, recreation, success experiences, stress relief and contact with nature [7]. Several users connected gardening with memories of childhood or their country of origin, which suggests that the garden can also support emotional continuity and personal identity [5, 7].



Figure 6. Health and well-being benefits of community garden: a) relaxation; b) physical activity; c) children's recreation.
Sources: a) https://donaufeld.wordpress.com/2010/05/31/nachbarschaftsgarten/; b, c) [5].

Studies on community gardening indicate positive effects on psychosocial outcomes, community well-being and health-related behaviour [16]. Contact with nature has also been associated with restoration, stress reduction and improved mental health [17], [18]. For residents of multifamily housing areas who do not have private gardens, community gardens provide an accessible opportunity to engage with nature close to home (Figure 6 a, b, c).

4.5. Participatory and governance benefits

The Roda-Roda-Gasse case is particularly important because it demonstrates the governance dimension of community gardens. Shared gardens require rules, communication, collective decisions, maintenance responsibilities and the ability to resolve everyday issues. These processes can strengthen residents' capacity for self-organization and shared management of common spaces.

The accompanying research identified the transition from external support to self-organization as one of the central themes of the project [5], [7]. The role of Verein Wirbel gradually shifted from leading and organizing toward supporting the gardeners' own structures. This transition is important because long-term sustainability depends on whether the garden community can continue to function beyond the initial project phase [5, 6, 7].

The governance benefit of a community garden is also related to collective resource management. The garden creates a small-scale common resource that must be shared, negotiated and maintained. This makes it relevant to broader discussions on commons and collective management [19]. In the context of multifamily housing, such practices can strengthen the culture of shared responsibility for open spaces.

Mayrhofer's analysis shows that the co-creative process helped participants move towards stronger forms of involvement and self-organization [6, 7]. Such support is important where social diversity, language barriers, lack of initiative or previous negative experiences may limit participation. The project therefore offers useful lessons for regeneration initiatives in housing estates with similar spatial and social challenges.

5. CONCLUSION

The analysis of the Roda-Roda-Gasse community garden shows that community gardens can play an important role in the urban regeneration of multifamily housing areas. Their contribution is multidimensional and includes social, spatial-functional, environmental, health-related and governance benefits. The project demonstrates that an unused green area within a housing estate can be transformed into an active shared space that supports everyday interaction, resident participation, environmental learning, outdoor activity and a stronger sense of belonging.

The Roda-Roda-Gasse case is particularly valuable because it shows that community gardens can be implemented within municipal housing, where spatial, institutional and social conditions may be complex. Its success depends on the combination of available open space, resident involvement, institutional support and professional facilitation. This confirms that community gardens should not be treated as isolated greening interventions, but as integrated tools of urban regeneration.

For multifamily housing areas with underused or neglected open spaces, community gardens can provide a practical and adaptable model of improvement. In the context of Serbian housing estates, where many open spaces face problems of poor maintenance, insufficient use and weak resident participation, the Roda-Roda-Gasse example may offer useful guidelines. These include participatory planning, clear management models, cooperation between housing institutions and residents, and the recognition of open spaces as resources for improving quality of life.

The paper concludes that community gardens can contribute significantly to the creation of more sustainable, inclusive and socially active housing environments. Their multiple benefits make them relevant not only as green spaces, but as planning, design and governance instruments for the revitalization of multifamily housing areas. By clarifying the social, spatial-functional, environmental, health-related and governance dimensions of the selected case, the paper provides a transferable analytical framework for considering community gardens in similar multifamily housing contexts. In this way, they can be positioned within broader retrofit strategies for post-war housing estates, where existing buildings, open spaces and social infrastructures need to be improved together [8].

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Research paper

PARAMETRIC EVALUATION OF TREE LAYOUT FOR GROUND-LEVEL INSOLATION MITIGATION IN AN URBAN COURTYARD

Ivana Bajšanski[1]

Abstract

The spatial configuration of urban blocks influences the exposure of courtyards to increased solar insolation due to building arrangement and tree layout, which can negatively affect the quality of public open spaces. This research investigates the influence of tree layout on ground-level insolation within an urban courtyard surrounded by five residential buildings. The study aims to develop a parametric evaluation workflow for reducing ground-level solar insolation through the strategic placement of trees.

The research was conducted using various software applications such as Rhinoceros 3D, Grasshopper, Ladybug and Galapagos. The existing urban block configuration, consisting of 14 trees and surrounding building geometry, was first analyzed to determine ground level insolation. In order to mitigate ground level insolation, three evaluation approaches for tree distribution were tested.

The first approach employed randomly generated tree positions using the Populate component controlled by seed variation. The second approach utilized a divided surface with predefined tree placement points to prevent canopy overlap. The third approach combined a dense surface subdivision with evolutionary optimization through Galapagos, enabling the algorithm to identify improved tree layouts while indirectly minimizing canopy overlap through fitness evaluation.

The results indicate that evolutionary optimization provides the most effective and interpretable solution for reducing ground-level insolation, while also offering greater control over tree positioning compared to random seed-based methods. The study demonstrates the potential of parametric and data-driven environmental simulations for improving microclimatic conditions in urban open spaces and supporting climate-responsive urban design strategies.

Key words: *Parametric optimization, Urban courtyard, Tree layout, Inoslation, Evolutionary algorithm.*

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1. INTRODUCTION

Urban courtyards represent important semi-public open spaces within dense residential blocks, playing a significant role in providing environmental quality and opportunities for outdoor use [1,2,3]. In many urban blocks, the spatial configuration of buildings often results in unfavourable microclimatic conditions, particularly in terms of ground-level solar insolation. Depending on their geometric proportions, courtyard spaces can be exposed to high levels of solar insolation at ground level [4,5].

One of the key factors influencing ground-level solar insolation is the interaction between surrounding buildings and trees [6,7]. While buildings define the overall enclosure and shading potential of a courtyard, trees introduce a dynamic layer of shading that can significantly modify solar access conditions at pedestrian level [8,9,10]. The spatial arrangement, density, and positioning of trees therefore become critical parameters in creating microclimatic performance.

In recent years, parametric design methods and environmental simulation tools have enabled more advanced approaches to analyzing and optimizing urban spaces [11,12]. Digital tools such as Rhinoceros 3D (3D modelling software) [13], Grasshopper (Rhinoceros plug in, visual programming software) [14], and Ladybug (software for environmental simulations) [15] allow for detailed solar analysis, while evolutionary solvers such as Galapagos [16] enable the exploration of large solution spaces for spatial optimization problems. These computational approaches provide opportunities to systematically test and evaluate different tree layouts in relation to environmental performance criteria.

Within this context, this study focuses on a case study of a single urban courtyard surrounded by five residential buildings. The courtyard has an open spatial configuration, resulting in increased exposure to solar insolation at ground level. The research investigates how different tree layouts influence ground-level insolation and explores how parametric and evolutionary methods can be used to identify configurations that mitigate insolation.

The main objective of this study is to develop and test a parametric workflow for evaluating and comparing tree distribution strategies in order to reduce ground-level solar insolation. By combining environmental simulation with algorithmic optimization, the research aims to contribute to a better understanding of how vegetation design can be used as a tool for microclimatic improvement in dense urban environments.

2. METHOD

In order to evaluate ground-level solar insolation within an urban courtyard under different tree layout configurations, a parametric approach consists of the following phases:

The first phase involves modelling of the urban environment in a 3D software. The 3D model includes:

- surrounding buildings geometries;
- ground surface representing the courtyard area;
- tree geometries representing existing vegetation elements.

The courtyard geometry, consisting of five residential buildings and a central open space, is created into Rhinoceros 3D. Buildings are modelled as sphere solid, non-transparent objects that generate full shadow effects. Trees are modelled as simplified sphered representing canopy influence on solar shading. The ground surface is discretized depending on the selected analysis resolution. All geometric elements are referenced inside Grasshopper, where the parametric definition is developed and linked back to the Rhinoceros environment for visualization and iteration (*Figure 1*).

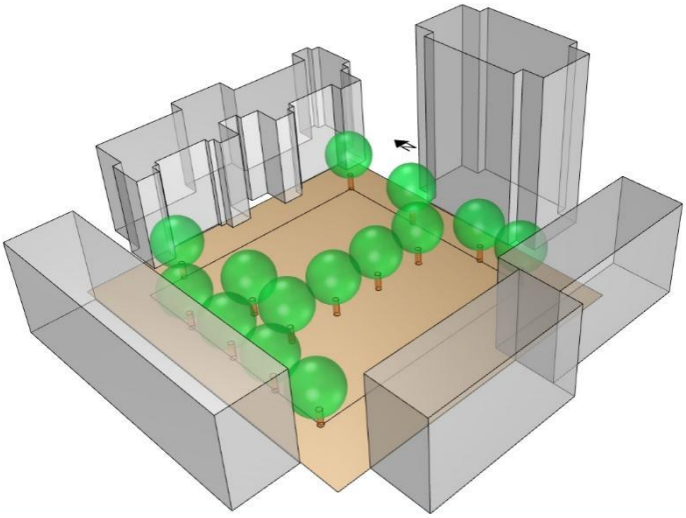


Figure 1. 3D representation of referenced building geometry and existing 14 trees placed in the courtyard. Source: Author.

The second phase refers to the generation of potential trees position. Three different approaches are implemented:

- random distribution using a Populate component controlled by seed variation (*Figure 2a*);
- structured distribution using a divided surface with predefined placement points to avoid canopy overlap (*Figure 2b*);
- dense ground surface subdivision combined with evolutionary optimization to allow flexible positioning and interaction between tree canopies (*Figure 2c*).

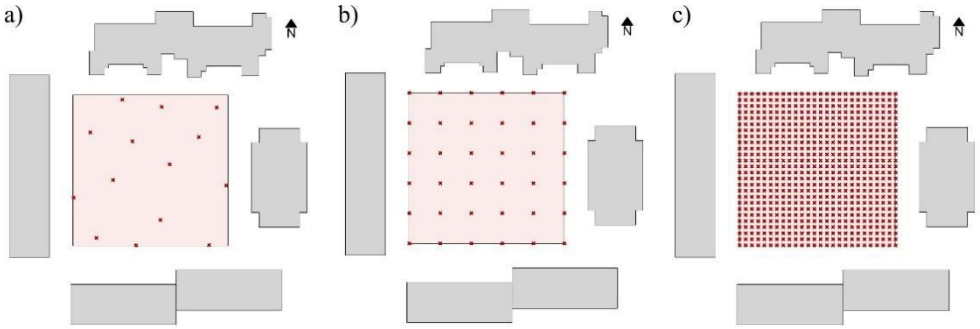


Figure 2. Tree layout configurations obtained with a) random distribution using a Populate component; b) a divided surface with predefined placement points to avoid canopy overlap and c) dense ground surface subdivision. Source: Author.

The third phase is the simulation of ground-level solar insolation using Ladybug. Ladybug uses building geometry, tree shading, and weather data to calculate solar insolation on the ground surface over a defined analysis period. The simulation outputs the average ground-level insolation expressed in kWh/m² for each tested configuration. Weather data for the selected location of Belgrade, Serbia, is imported using a standard EPW file. Ladybug take into account geometry of buildings, weather data and time (from 9pm to 15 pm) and year period (7th July) of analysis set. The Ladybug software calculates the average insolation of a ground surface in kWh/m^2.

The final phase includes the comparison and export of results from all tested configurations. The performance of each method (random, structured, and evolutionary) is evaluated based on the resulting ground-level insolation values, allowing for a comparative assessment of tree layout strategies.

3. RESULTS

The results of the study are evaluated based on the average ground-level solar insolation calculated for all simulation scenarios and compared to the baseline condition with existing placement of 14 trees (2.71 kWh/m²), which serves as the reference value for all comparative analyses (*Figure 3a*).

The random distribution strategy produced the most favorable outcome, with an average insolation value of 2.52 kWh/m² (*Figure 3b*). This corresponds to a reduction of approximately 7.01% compared to the baseline condition.

The structured distribution method, based on predefined placement points designed to avoid canopy overlap, resulted in an average insolation value of 2.54 kWh/m² (*Figure 3c*), representing a 6.27% reduction relative to the baseline. Although slightly less effective than the random distribution, this approach provides more controlled spatial organization and predictability of tree placement.

The evolutionary optimization approach, applied to a densely subdivided surface allowing flexible positioning of tree canopies, achieved an average insolation value of 2.55 kWh/m² (*Figure 3d*), corresponding to a 5.90% reduction compared to the initial condition. While this method enables adaptive optimization of tree locations, the results indicate only marginal improvement over the other tested strategies.

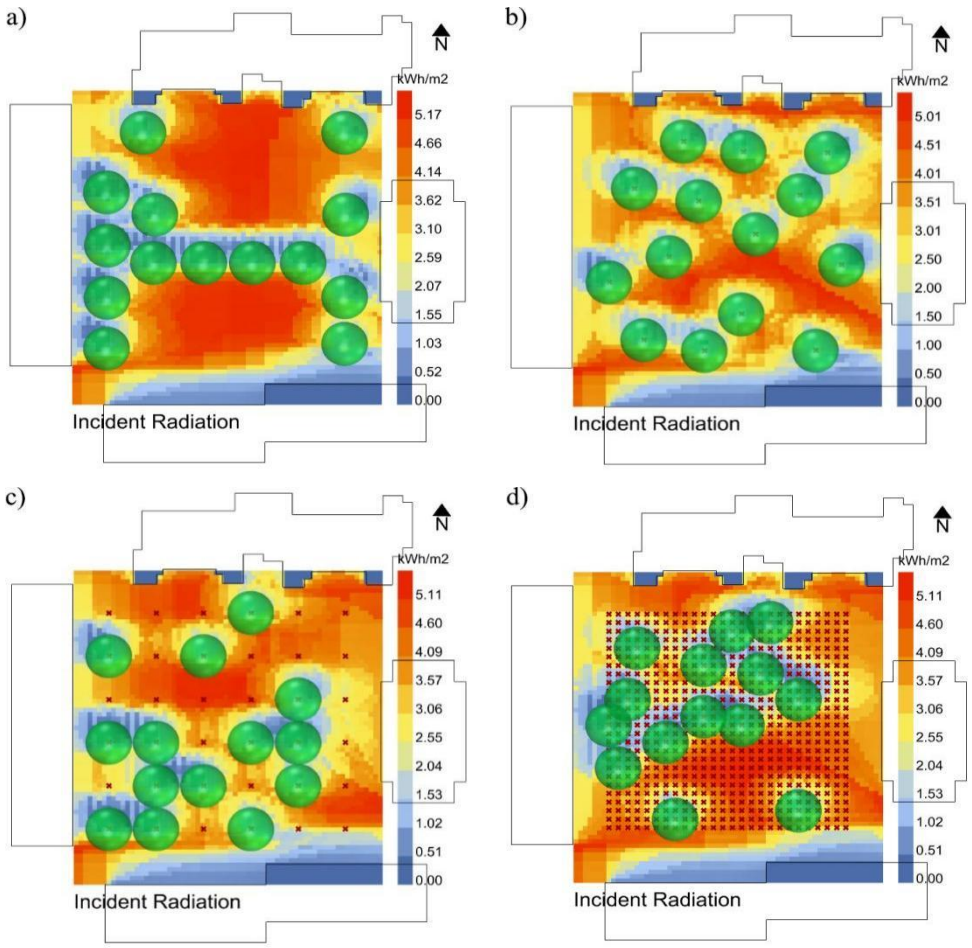


Figure 3. Insolation of tree layout configurations of a: a) baseline tree layout; b) random distribution using a Populate component; c) a divided surface with predefined placement points to avoid canopy overlap and d) dense ground surface subdivision. Source: Author.

In addition to the comparison of mean values, the variability of results was evaluated using both the range (min–max) and the standard deviation (σ) of ground-level solar irradiation values obtained from multiple simulation runs.

The random distribution strategy showed values between 2.52 and 2.61 kWh/m² (*Figure 4a*), with a standard deviation of σ = 0.02 kWh/m², indicating very low dispersion around the mean and a high level of stability across different tree configurations.

The structured distribution method resulted in a wider range of 2.54 to 2.75 kWh/m² (*Figure 4b*), with a standard deviation of σ = 0.04 kWh/m², suggesting moderate sensitivity to spatial configuration and increased variability compared to the random population-based approach.

The evolutionary optimization approach using the Galapagos solver exhibited the largest variability, with results ranging from 2.55 to 3.05 kWh/m² (*Figure 4c*), and a standard deviation of σ = 0.07 kWh/m², confirming a significantly higher dispersion of solutions due to the exploration of a broader and less constrained search space.

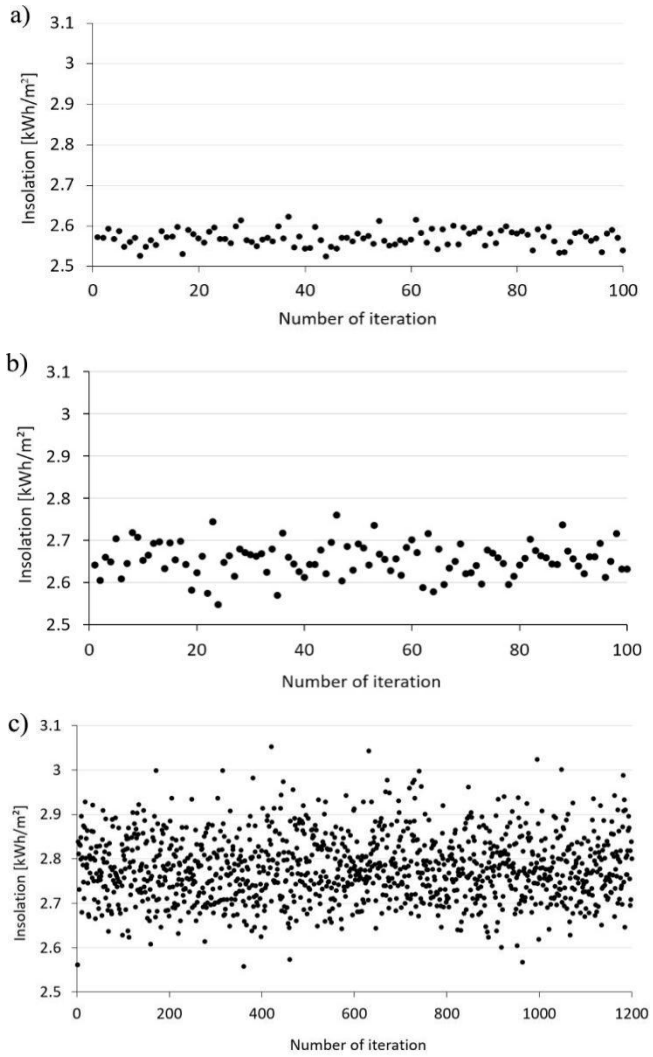


Figure 4. Insolation of ground level obtained with a: a) random tree distribution using a Populate component; b) a divided surface with predefined placement points to avoid canopy overlap and c) dense surface subdivision. Source: Author.

Overall, the comparison of standard deviations clearly indicates a trend of increasing variability with increasing algorithmic complexity. While the random distribution strategy provides the most stable and consistent outcomes, the structured distribution method introduces moderate variability, and the Galapagos-based optimization produces the least stable results despite exploring a larger solution space.

The Galapagos-based configuration is presented as a representative optimized solution generated within a search space. Although it does not yield the best mean performance, it illustrates the spatial characteristics of an evolutionary optimization outcome under the given constraints.

4. CONCLUSION

This study investigated the impact of different tree distribution strategies on ground-level solar insolation in an urban block, with the aim of evaluating both the effectiveness and robustness of generative and optimization-based placement methods.

Three approaches were analyzed: random distribution using a Populate component controlled by seed variation, structured distribution using a divided surface with predefined placement points to avoid canopy overlap, and an evolutionary optimization approach using the Galapagos solver with dense ground surface subdivision to allow flexible positioning and interaction between tree canopies. All methods resulted in a reduction of ground-level solar insolation compared to the baseline condition (2.71 kWh/m²), with mean values ranging between 2.52 and 2.55 kWh/m², corresponding to improvements of approximately 5.90% to 7.01%.

Beyond mean performance, the study highlighted significant differences in result stability. The Population-based method demonstrated the highest robustness, with the lowest standard deviation (σ = 0.02 kWh/m²), followed by the structured distribution approach (σ = 0.04 kWh/m²), while the Galapagos-based optimization exhibited the highest variability (σ = 0.07 kWh/m²). These findings indicate that increasing algorithmic complexity does not necessarily lead to more stable or consistently improved environmental performance within the defined simulation framework.

An important limitation of the evolutionary optimization approach is the difficulty in extracting a single deterministic optimal configuration due to the stochastic nature of the seed-driven process and the exploration of a large solution space. As a result, the study focuses on statistical performance indicators (mean values, range, and standard deviation) rather than a single definitive optimal tree layout.

Despite this limitation, the results provide valuable insight into the trade-off between control, randomness, and optimization in parametric urban design workflows. The findings suggest that simpler methods may offer more predictable and robust performance under similar environmental constraints, while more complex optimization strategies require additional post-processing or constraint refinement to ensure solution stability.

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Research paper

PERFORMANCE-BASED DESIGN IN ARCHITECTURAL EDUCATION: CLIMATE-RESPONSIVE URBAN DESIGN THROUGH ENVIRONMENTAL SIMULATION

Ivana Bajšanski[1]

Abstract

The increasing frequency of extreme heat events in urban environments requires architects and urban designers to develop new competencies for creating climate-responsive cities. In this context, performance-based design (PBD) approaches, supported by environmental simulation and optimization tools, have become an essential component of contemporary architectural education and practice. This paper presents an educational framework implemented within a Master's level architectural course, where students are trained to integrate environmental performance analysis into the early stages of the design process. The course introduces parametric and simulation tools such as Rhinoceros, Grasshopper, Ladybug and Galapagos, Ecotect and City Engine enabling students to evaluate and optimize urban design proposals based on measurable environmental criteria.

Students independently address urban climate-related design challenges and develop parametric models to investigate potential improvements in insolation and outdoor thermal comfort. The projects presented in this study include the optimization of tree placement to reduce insolation in children's playgrounds and the modification of building heights and massing configurations to improve thermal conditions in courtyard spaces while maintaining comparable floor area ratios. Also, outdoor thermal comfort is evaluated under the canopy whose geometry was optimized.

The results demonstrate that integrating PBD methodologies into architectural education enhances students' understanding of the relationship between urban form, vegetation and environmental conditions. Furthermore, the use of simulation and optimization tools supports informed decision-making in the earliest design stages, enabling future architects to identify and mitigate potential environmental problems before implementation. Such educational approaches contribute to the development of professional competencies necessary for designing sustainable, climate-adaptive, and resilient urban environments.

Key words: *Performance-based design, Climate-responsive urban design, Urban design education, Environmental simulations, Parametric modelling.*

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1. INTRODUCTION

Climate change and rapid urbanization have increased environmental challenges in cities, including urban overheating and reduced outdoor thermal comfort [1,2,3]. These issues have highlighted the importance of climate-responsive approaches in urban design. Architects are expected not only to develop spatial solutions but also to understand how their design decisions affect environmental conditions during the design process.

Recent developments in digital design and environmental simulation tools have created new opportunities for integrating environmental performance assessment into architectural practice. Performance-based design (PBD) enables designers to evaluate and compare design alternatives using measurable environmental indicators, supporting more informed design decisions. Tools such as Rhinoceros (3D modelling software) [4], Grasshopper (Rhinoceros plug in, visual programming software) [5], Ladybug (Grasshopper plug in, software for environmental analysis) [6], Ecotect (software for environmental analysis) [7], City Engine (software for procedural modelling of urban areas) [8] and optimization algorithms [9] allow designers to investigate the influence of urban form, vegetation and insolation on outdoor environmental conditions [10,11]. These tools are particularly valuable during the early design stages, when decisions can have a significant impact on the future performance of urban spaces.

As environmental performance becomes a more important part of design practice, architectural education must prepare students with the knowledge and skills needed to apply these methods. The integration of environmental simulation and optimization techniques into course can help students better understand the relationship between design decisions and environmental performance while encouraging a more analytical design approach [12,13,14].

This paper presents an educational framework implemented within a Master's level architectural design course focused on climate-responsive urban design. Using Rhinoceros, Grasshopper, Ladybug and Galapagos, students explore and optimize urban design solutions addressing issues such as insolation and outdoor thermal comfort through vegetation and built form modifications. The paper describes the course methodology and presents representative student projects that demonstrate how environmental simulation and optimization tools can be effectively integrated into architectural education to support sustainable urban design and improve environmental performance in urban spaces.

The findings suggest that integrating performance-based design methods into architectural education can help students better understand the environmental impact of design decisions and develop skills needed to address contemporary challenges in the built environment.

2. COURSE METHODOLOGY

The presented framework was developed within a Master's level architectural course focused on climate-responsive urban design and environmental performance assessment. The primary objective of the course is to introduce students to PBD methodologies and enable them to integrate environmental analysis and optimization into the early stages of the design process.

The course combines theoretical lectures with practical workshops. Students are introduced to parametric modeling and environmental simulation tools, including Rhinoceros, Grasshopper, City Engine, Ladybug, Ecotect and Galapagos. These digital tools allow students to evaluate the environmental performance of urban spaces and test alternative design solutions based on measurable criteria.

At the beginning of the semester, students select a specific urban environmental problem related to urban ground insolation and outdoor thermal comfort. The selected urban design is modeled using Rhinoceros, Grasshopper and City Engine, while environmental simulations are conducted using Ladybug and Ecotect.

Depending on the project objectives, students define performance indicators and optimization criteria that serve as the basis for the design process.

A typical workflow consists of the following stages:

1. Identification of an environmental problem within an urban context.
2. Development of a parametric digital model.
3. Definition of design variables.
4. Environmental simulation and performance evaluation.
5. Optimization.
6. Comparison and assessment of alternative design solutions.

The use of Galapagos enables students to explore multiple design iterations and identify solutions that best satisfy predefined performance objectives. Through this process, students gain practical experience in decision-making and develop an understanding of the relationship between urban form, vegetation, and environmental performance.

3. REPRESENTATIVE STUDENT PROJECTS

The projects cover different topics and address environmental challenges in contemporary urban contexts. However, all projects follow the same methodology based on simulation, performance evaluation and optimization.

3.1 Optimization of tree placement to mitigate insolation in playgrounds

This type of project focuses on reducing insolation in children's playgrounds during the summer period. High levels of insolation often limit the usability of these outdoor spaces and increase thermal stress for users.

Students explore how the arrangement of existing trees can be optimized to mitigate insolation. 3D models were created in Rhinoceros and referenced within Grasshopper. Tree and playground locations are defined as variable parameters, while optimization is carried out using the Galapagos algorithm in combination with randomly generated points and the Populate 2D component. Solar radiation analysis is performed using Ladybug to evaluate the effectiveness of different configurations.

The optimization process identifies tree layouts that minimize insolation, resulting in a 24.4% reduction (from 469.02h to 354.35h) in solar exposure within the defined analysis period (from 21 June to 21 September, from 11:00 to 18:00), while respecting spatial constraints within the site. Convergence was achieved through repeated simulation cycles until no further improvement in the fitness function was observed. Through this exercise, students learn how vegetation can be strategically integrated into urban design to improve outdoor microclimatic conditions. The workflow of this project is presented in *Figure 1*.

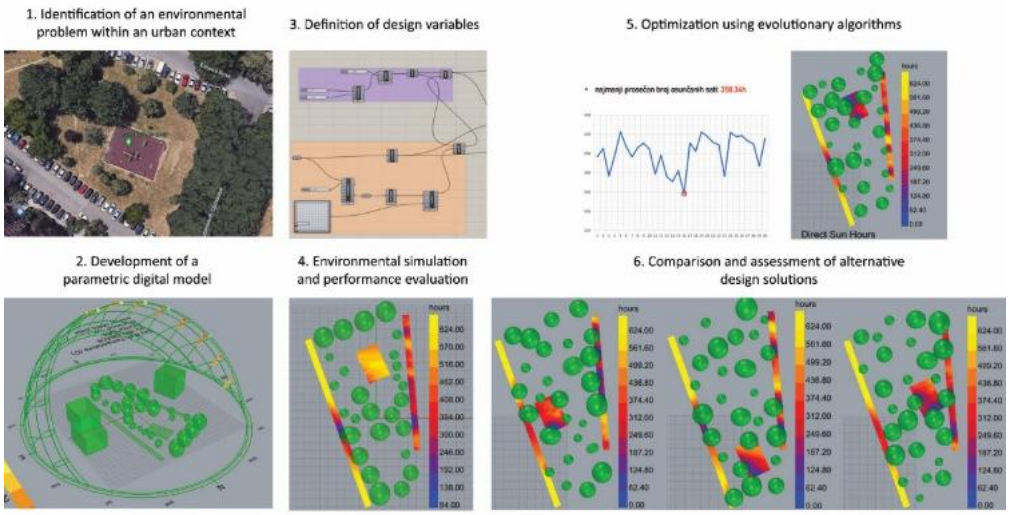


Figure 1. Workflow for optimization of tree placement for mitigating insolation in playground. Project by student Milica Simovski.

3.2 Manual optimization of building heights for mitigating insolation

The second project investigates the influence of building morphology on insolation within urban blocks. Students develop parametric models in which building heights can vary while maintaining approximately the same gross floor area. This constraint ensures that environmental improvements are evaluated without significantly affecting development capacity. 3D models are generated in City Engine while the insolation simulations are performed in Ecotect. Optimization process is manual / semi-automated iterative parameter search with attribute-driven variation in City Engine, involving the generation and evaluation of approximately 50 different 3D urban design configurations.

Through iterative insolation simulations, students explore how modifications in building massing influence shading patterns. The results demonstrate that relatively

small changes in building heights and spatial configuration can significantly improve microclimatic conditions within urban courtyards and pedestrian areas , resulting in a reduction of insolation from 1236.51 kWh/m² (existing urban design) to 1134.62 kWh/m² (improved urban design), which corresponds to an approximate 8.2% decrease.

These projects encourage students to understand the complex relationship between urban density and solar access. The workflow of this project is presented in *Figure 2*.

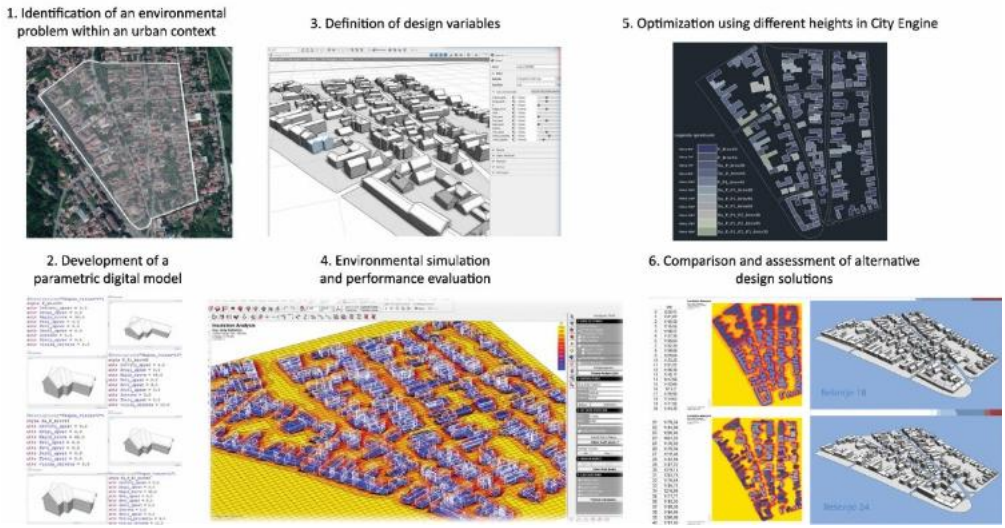


Figure 2. Workflow for the manual optimization of building heights for mitigating insolation. Project by student Marija Esapović.

3.3 Optimization of canopy design to improve outdoor thermal comfort

A third project focuses on architectural shading devices as a means of improving outdoor thermal comfort in public spaces. Students investigate the parametric design of canopies and their environmental performance.

Parametric models created in Rhinoceros and referenced within Grasshopper are used to modify key geometric parameters of the canopy, such as roof opening size, arched opening size, number of side openings, and side opening size. The environmental performance of outdoor thermal comfort is evaluated within Ladybug using the Universal Thermal Climate Index (UTCI), while optimization tool Galapagos is used to identify configurations that maximize shaded areas and improve thermal comfort conditions below the structure. The optimization process was carried out iteratively until no further improvement in the fitness function was observed.

The results show a clear improvement in outdoor thermal comfort, with the average value for all analyzed points decreasing from 28.57°C (existing condition) to 23.95°C (optimized solution), corresponding to an approximate 16.2% reduction in average thermal stress conditions.

This project demonstrates how architectural elements, when designed through PBD parametric workflows, can function as active environmental modifiers in urban outdoor spaces. The workflow of this project is presented in *Figure 3*.

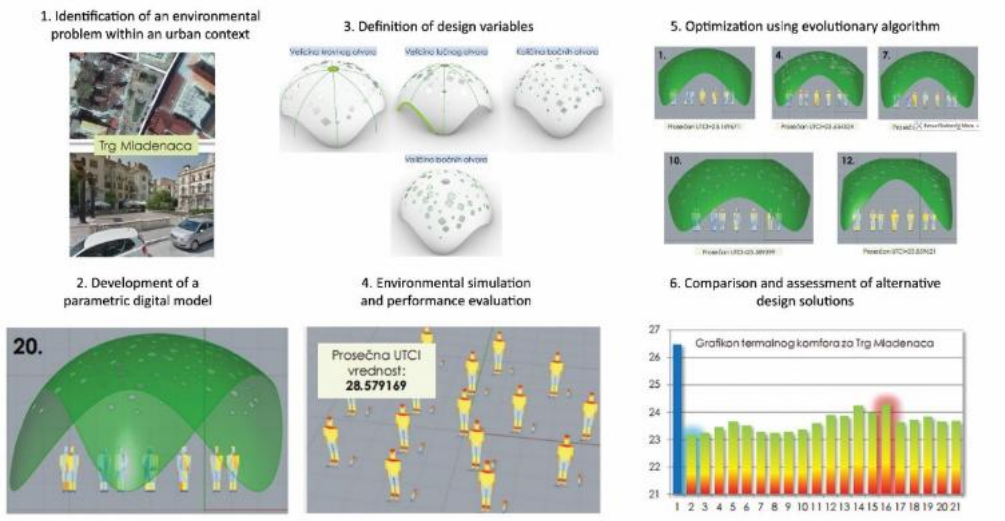


Figure 3. Workflow for the optimization of canopy design to improve outdoor thermal comfort. Project by students Natalija Manja, Aleksandra Gatarić and Aleksandar Lesmajster

4. RESULTS AND EDUCATIONAL OUTCOMES

The implementation of PBD methodologies within the Master's level course has indicated several educational outcomes based on student project work and course observations:

- By applying simulation workflows, students demonstrated engagement with the relationship between design decisions and environmental performance.
- The project approach enabled students to explore a wide range of climate-responsive design strategies while operating within realistic spatial and functional constraints.
- The projects indicate students' ability to apply simulation-based methods in addressing urban design problems.
- The use of evolutionary optimization tools encouraged students to explore the complexity of urban design problems. Rather than searching for a single predefined solution, students explored multiple design iterations and examined trade-offs between environmental performance and spatial constraints.

The results suggest that relatively modest modifications in urban form and vegetation distribution can produce noticeable improvements in key environmental indicators.

The variety of student projects (*Table 1*) also highlights the flexibility of the proposed educational framework. Although projects addressed different scales and topics from urban vegetation and microclimate improvement to building massing and shading performance the same performance-based methodology proved transferable across various design contexts.

Table 1. Integrated workflow for parametric modelling, simulation and optimization for different student projects.

Case study	Design variables	3D modelling tool	Optimization approach	Simulation tool	Outcome
Tree layout	Tree position	Rhinoceros 3D, Grasshopper	Automatic (Galapagos)	Ladybug	Reduced playground insolation by 24.4%
Buildings height	Height variation	City Engine	Manual iterative variation (City Engine)	Ecotect	Reduced courtyard insolation by 8.2%
Canopy design	Geometry parameters	Rhinoceros 3D, Grasshopper	Automatic (Galapagos)	Ladybug	Reduced UTCI by 16.2%

5. CONCLUSION

The presented educational framework highlights the potential of integrating PBD methodologies into architectural education. By combining parametric and procedural modeling, environmental simulation, and evolutionary optimization, students develop design solutions based on measurable environmental criteria rather than intuition alone.

The use of tools such as Rhinoceros, Grasshopper, City Engine, Ladybug, Ecotect and Galapagos are used to explore the relationships between urban form, vegetation, insolation, and outdoor thermal comfort. Through projects, students work through iterative design processes and evaluate alternative solutions during early design stages.

The presented student projects illustrate how environmental simulation can support the development of climate-responsive urban design strategies, including the optimization of tree placement, building morphology and shading configurations. These exercises provide a structured environment for exploring the environmental consequences of design decisions within a performance-based workflow.

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Research paper

A SCALABLE GIS-BASED APPROACH TO MAPPING ECOSYSTEM SERVICE CAPACITY USING CORINE LAND COVER DATA AND BURKHARD MATRIX: APPLICATION ON THE CITY OF NIŠ

Petar Vranić [1], Ivana Petkovski[2]

Abstract

Ecosystem services (ES) represent the benefits that natural and semi-natural ecosystems provide to human societies, yet their spatial distribution remains insufficiently integrated into urban and spatial planning practice in Serbia. This study presents a GIS-based assessment of ES capacity for the administrative territory of the City of Niš, combining CORINE Land Cover (CLC 2018) vector data with the Burkhard matrix scoring framework to quantify and spatially map provisioning, regulating and maintenance, and cultural ecosystem services across 22 land cover classes covering 59,622 ha.

The analysis reveals a pronounced center-periphery gradient, with the urbanized core forming a persistent cold spot of Very Low to Low ES capacity, while forested uplands and heterogeneous agricultural landscapes in the periphery constitute extensive hot spot zones. Total ES capacity is High to Very High across 68.46% of the territory, with only 2.29% classified as Very Low. A key contribution of this study is the full automation of the analytical workflow through a QGIS Python script, making the approach directly transferable to any Serbian municipality without reliance on commercial software and aligned with the EU Nature Restoration Law (2024). Principal limitations include the 25-ha minimum mapping unit, which underestimates ES provision by urban green infrastructure, and the absence of a regionally validated Burkhard matrix for Balkan ecosystem types. Future research should address higher-resolution data integration, field-based score validation, and demand-side ES analysis.

Key words: *ecosystem services, CORINE Land Cover, Burkhard matrix, urban and spatial planning, Niš, GIS, hot spot analysis*

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1. INTRODUCTION

Green infrastructure (GI) together with ecosystem services (ES), are well known as core ideas in spatial and urban planning, and also in land use management. At the EU level, the biodiversity policy and the biodiversity legislation, incl. the EU Nature Restoration Law from 2024 [1], and Mapping and Assessment of Ecosystems and their Services framework (MAES), set up a required ES assessment and mapping, as baseline for decision-making [2]. Furthermore, the EU Green Deal officially folds in climate neutrality by 2050, and it's supposed to cover all essential sectors, too [3]. When Serbia signed the Sofia Declaration in 2020, it agreed to harmonize its growth in line with the Green Agenda for the Western Balkans, which means making Chapter 27 operational [4, 5]. In planning terms, this commitment is directly tied to weaving in ES like climate regulation, water safeguarding, erosion control and biodiversity conservation into spatial and urban planning, where ecosystems move beyond the matters of protections and turn into working infrastructural resources for the green transition [6].

Understanding spatial distribution of ES lets urban planners detect a supply-demand mismatch i.e., underserved population who can have low ES provision [7-10], and support informed decisions in protecting, restoring and designing green spaces in location in need. Thus, high resolution ES data can support identification of hotspots and cold spots in the urban areas informing tailored nature-based solution interventions [8, 11], and co-occurrences and segregation of multiple services for design of multifunctional sites or sites that resolve conflicting objectives (for example, heat mitigation often goes along with runoff retention, and in a few high carbon storage zones, there can be a trade off with other regulating services too) [12, 13]. When services clash, planners can sort out the trade-offs by zoning, conserving particular high-value areas, or creating multifunctional green spaces that serve more than one task. Another alternative is to prioritize services in specific neighborhoods depending on need [12].

Eco-friendly urban concepts such as Nature-based Solutions (NbS), Ecosystem-based Adaptation (EbA), Urban Green Infrastructure (UGI), and Blue-Green Infrastructure (BGI) effectively tackle these challenges. These concepts support urban planning practice that protect and rehabilitates metropolitan ecosystems. GI provides environmental and social ES that protect the environment, enhance public health, and facilitate adaptation to climate change. They decrease air temperature to mitigate urban heat island effects (UHI), filter pollutants, facilitate precipitation infiltration into the soil for urban water management, diminish flooding risk and alleviate pressure on drainage systems, and promote urban biodiversity [13-15].

Mapping and research of ES and GI in Serbia increased in recent years, prominently focusing on Belgrade and Novi Sada, while studies of other urban regions and smaller cities remain inadequately represented in scholarly literature. One of the first studies are related to the conceptualization of GI in Serbian context by [16] who analyzed Belgrade's GI at the residential block level looking at the communal green spaces as instrument for achieving multifunctionality and biodiversity. By applying various landscape metrics, [17] developed a framework for application of GI concepts in planning of urban forests in Belgrade, proving that ES can be quantified. Reference [18]

integrated GI principles studying urban-rural transitions in Novi Sad, Subotica, and Zrenjanin using Voronoi diagrams and landscape graphs to understand ES connectivity.

At the level of individual ES, [19] assessed the potential of ES of ornamental dendroflora in public green areas in Novi Sad. Reference [20] highlighted the potential of NBS tactics like green roofs, rain gardens, porous surfaces as a fundamental element of multifunctional ES in planning of GI of Novi Sad. A study of [21] suggests a geodesign framework for ES integration in planning of GI under uncertainty. Reference [22] makes attempts to quantify carbon sequestration capacity and biomass of urban trees in Topčider park in Belgrade, offering empirical evidence for the assessment of regulatory ES in urban environment.

Even with some progress on the international scene, Serbia still seems to miss standardized, reproducible quantitative tools that can really assess ecosystem service capacity, especially at local and regional level, and then be plugged into the everyday urban and spatial planning practice. Local governments, and also spatial planners, do not really get access to methodologies that are simple enough to carry out in practice, but also at the same time scientifically solid and aligned with the EU framework.

In line with the above mentioned this paper attempt to answer following research question: Is it possible, using publicly available data (CORINE Land Cover - CLC 2018) and standardized expert matrices [23] to develop a spatially explicit assessment of the capacity of ES for an urbanized administrative territory — and to what extent can such an assessment support urban and spatial planning decision?

2. METHODOLOGY

2.1. Study area

The City of Niš, with an area of 596.73 km², has a population of 178,976 in the urban area and 249,816 across the administrative territory, making it the third most populated city in Serbia. Since 2004, Niš has been administratively segmented into five municipal districts: Medijana, Palilula, Pantelej, Crveni Krst, and Niška Banja. In addition to the metropolitan areas of Niš and Niška Banja, the administrative jurisdiction included 68 rural communities. This study examines the entire administrative territory of the city.

2.2. Data

As an input this study used CLC seamless vector database Version 2020 20u1 (dated 02/2020) in ESRI GeoDatabase format. All features in original vector database were classified and digitised based on satellite images with 100 m positional accuracy (according to CLC specifications) and 25 ha minimum mapping unit (5ha MMU for change layer) into the standardized CLC nomenclature (44 CLC classes).

2.3. CICES V5.2 Classification Framework

ES were classified according to the Common International Classification of Ecosystem Services, CICES version V5.1/V5.2. The classification arranges ES in a five-level hierarchy: Section, Division, Group, Class and Class Type, so it is structured yet still flexible, and it supports assessments across different spatial scales, and thematic contexts too. 14 CICES V5.2 classes were assessed grouped into three sections: Provisioning services, Regulating and Maintenance, Cultural services.

2.4. Quantification method: Burkhard Matrix — expert based ecosystem service capacity assessment

The Burkhard matrix approach, first proposed by Burkhard et al. in 2009, and later updated in 2012 and 2014 [23-25], produces semi quantitative scores from 0–5 for each pairing of land use/land cover type and ES class (0 - No relevant capacity, 1 - Low capacity, 2 - Relevant capacity, 3 - Medium capacity, 4 - High capacity, and 5 - Very high capacity). In this study, the matrix spans 14 ES classes across the three CICES sections, and 22 CLC land cover classes identified as relevant to the land cover composition of the Niš administrative area, based on the CLC classes that were present in the dataset, which results in 308 assessed CLC × ES combinations (Figure 1). Each CLC class gets its own scoring pattern, meant to show provisioning, regulating and cultural capacity.

CLC land cover classes / ES classes	Crops	Livestock	Wild foods	Timber	Energy biomass	Freshwater	Global climate regulation	Local climate regulation	Flood protection	Erosion regulation	Water purification	Pollination Biodiversity	Recreation & aesthetic	Cultural heritage
Continuous urban fabric	0	0	0	0	0	0	1	1	0	0	0	0	1	0
Discontinuous urban fabric	0	0	1	0	0	0	1	2	1	1	0	1	2	1
Industrial or commercial units	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Road and rail networks and associated land	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Airports	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mineral extraction sites	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Construction sites	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Green urban areas	1	0	1	0	0	0	2	3	2	2	1	2	4	2
Sport and leisure facilities	0	0	0	0	0	0	1	2	1	1	1	1	4	1
Non-irrigated arable land	4	1	1	0	2	1	1	1	1	2	1	2	1	2
Vineyards	4	0	2	0	1	1	2	2	1	3	1	3	3	4
Fruit trees and berry plantations	4	0	2	0	1	1	2	2	1	3	1	4	2	3
Pastures	1	4	2	0	2	1	2	2	2	3	2	3	2	2
Complex cultivation patterns	3	2	2	0	2	1	2	2	2	3	2	4	2	3
Land principally occupied by agriculture	2	2	3	1	2	2	3	3	3	3	3	4	3	3
Broad-leaved forest	0	0	3	4	3	3	5	4	4	4	4	4	4	4
Coniferous forest	0	0	2	5	4	3	5	4	4	4	4	3	3	3
Mixed forest	0	0	3	4	3	3	5	4	4	4	4	5	5	4
Natural grasslands	0	2	3	0	2	2	3	3	3	3	3	5	3	3
Transitional woodland-shrub	0	1	2	2	2	2	3	3	3	3	3	3	3	3
Inland marshes	0	0	2	1	1	3	4	3	5	3	4	5	3	3
Water courses	0	0	0	0	0	4	2	2	3	2	3	3	3	2

Figure 1. Evaluation matrix, Source: author

For the ES estimates per LULC class, several sources were blended, such as statistical data, model outputs, expert judgement, interview results, and also monitoring information, all of it gathered and then synthesized at a European scale. The method basically supports a kind of swift sorting of which ES could be delivered in an area, while

still being adaptable enough to ingest a whole set of evidence [25]. It's also worth noting that the original matrix model, plus the ES estimates within it, were refined step by step through tests and small corrections to individual ES estimates [24,25].

Here, the original matrix was applied as is, no regional recalibration is conducted, partly to keep the workflow reproducible, and partly to enable comparisons across studies. This is a deliberate Tier 1 methodological choice [26] even if it also brings a drawback: the scores were not cross checked against local ecosystem conditions in the Balkan biogeographical region. The approach also has well known weak points connected to uncertainty in expert judgements, and to differences between different scorers, which was already highlighted by [27] and [28].

2.5. CLC-to-CICES Mapping and GIS Implementation

Each CLC class present in the Niš administrative territory was mapped to its corresponding CICES V5.2 classes based on the Burkhard scoring matrix. Scores were then aggregated into three section-level composite indicators — Provisioning, Regulating & Maintenance and Cultural, computed as arithmetic means across all services within each section, preserving the 0–5 reference scale. The entire workflow was implemented in QGIS 3.x using the Python console.

3. RESULTS

The analysis of the vector layer identified a total of 402 polygons covering an area of 59,622.17 ha, spread across 22 CORINE Land Cover (CLC) classes. The landscape seems mostly deciduous forests, taking up 29.25% of the total area (17,439.75 ha), then come complex cultivation patterns with 19.31% (11,515.83 ha), and non-irrigated arable land at 19.07% (11,368.13 ha). Put together these three classes cover more than two-thirds of the study area, so it really points to a predominantly rural and forested character.

Urban fabric makes up around 7.54% of the territory, while water bodies and wetlands stay marginal at just under 1%. When it comes to provisioning ES there is this striking 88.53% of the whole area that ends up in the High and Very High groups, which suggests quite a strong ability of the Niš hinterland to provide those provisioning types of services like food production, timber, and freshwater (Table 1).

Table 1. Provisioning ES

Class	Min value	Max value	No. Polygons	P (ha)	Share (%)
Very Low	0	0.466	66	6150.22	10.32
Low	0.466	0.932	2	298.05	0.5
Medium	0.932	1.398	7	385.17	0.65
High	1.398	1.864	202	23416.47	39.27
Very High	1.864	2.33	125	29372.26	49.26
Total			402	59622.17	100

Regulating services look a bit less one sided in space, because around 58% of the area is labeled as High or Very High, while almost 29% drops into the Low to Medium

band, so overall it implies there is some real spatial heterogeneity in how climate regulation, water purification, and erosion control are delivered (Table 2). Cultural services somewhat mirrors that, with 58.55% of the area gathered in the higher value categories, meaning the recreational, aesthetic, and heritage potential is actually embedded within the varied land cover mosaic (Table 3). The overall ecosystem service value supports what has been said, with 68.46% of the study area put in the High or Very High group, while just 2.29% lands in the Very Low categories, which feels close to what we would expect from urbanized and somewhat degraded land surfaces (Table 4).

Table 2. Regulating and Maintenance ES

Class	Min value	Max value	No. Polygons	P (ha)	Share (%)
Very Low	0	0.866	20	1363.34	2.29
Low	0.866	1.732	77	15951.85	26.75
Medium	1.732	2.598	86	7696.87	12.91
High	2.598	3.464	161	16490.52	27.66
Very High	3.464	4.33	58	18119.59	30.39
Total			402	59622.17	100

Table 3. Cultural ES

Class	Min value	Max value	No. Polygons	P (ha)	Share (%)
Very Low	0	0.9	20	1363.34	2.29
Low	0.9	1.8	74	15806.55	26.51
Medium	1.8	2.7	85	7547.2	12.66
High	2.7	3.6	174	17182.18	28.82
Very High	3.6	4.5	49	17722.91	29.73
Total			402	59622.17	100

Table 4. Total ES

Class	Min value	Max value	No. Polygons	P (ha)	Share (%)
Very Low	0	9.6	20	1363.34	2.29
Low	9.6	19.2	43	4583.72	7.69
Medium	19.2	28.8	58	12856.58	21.56
High	28.8	38.4	228	22962.1	38.51
Very High	38.4	48	53	17856.43	29.95
Total			402	59622.17	100

4. DISCUSSION

Figure 2 shows clear but also consistent spatial patterns for ES capacity across the four assessed dimensions. There is a prominent contrast between the central urban core, and the surrounding rural and forested landscapes.

Provisioning ES capacity seems to have the sharpest spatial polarization. Cold spots—areas with Very Low to Low provisioning capacity (0.00–0.67) are mostly

grouped in the central, and south-central part of the study area, and these line up with the urban fabric of the city of Niš plus its immediate peri-urban zone. These cold spots end up forming a spatially contiguous patch, it stretches along the Nišava river corridor, running roughly east-west. On the other hand, hot spots of High to Very High provisioning capacity (1.66–2.33) are more common across the northern, western, and southern edges of the study area. There, forested land and agricultural cover basically dominate the scene.

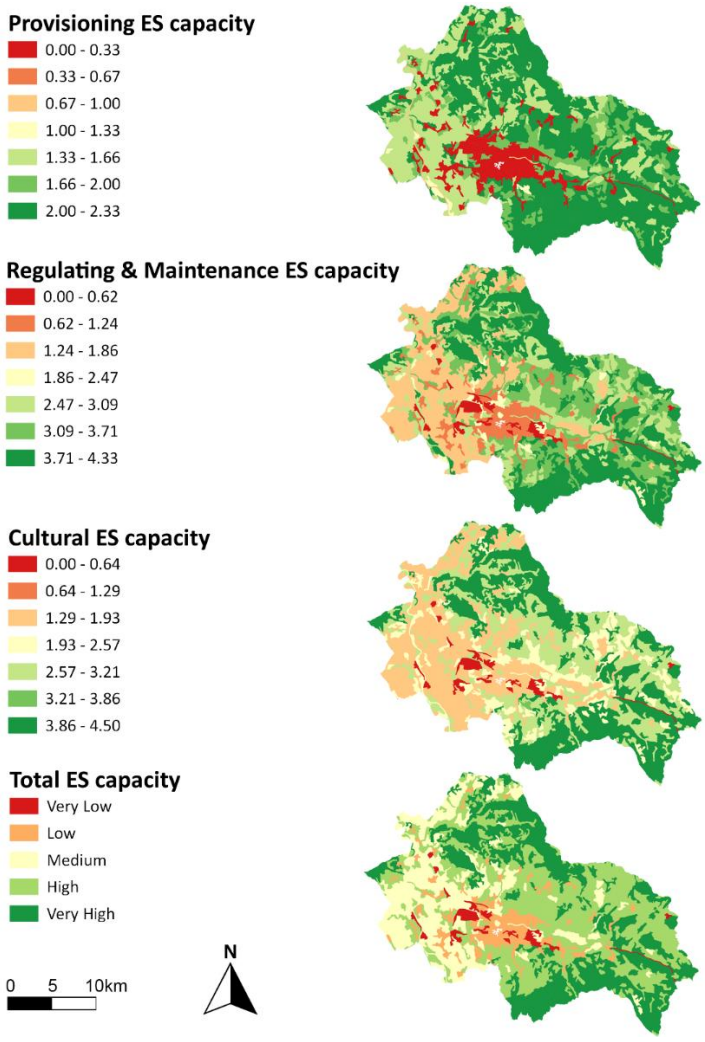


Figure 2. Spatial distribution of ES capacities, Source: author

When it comes to Regulating and Maintenance ES capacity, the displays are a bit more gradual and also rather spatially diffuse, not as sharply set out. Those cold spots stay anchored over the urban core, but they're noticeably less pronounced than what you see in the provisioning dimension. The shift from the lower to higher values moves

outward in a centrifugal gradient, and the strongest regulating capacity (about 3.71–4.33) sits mainly along the northern and southeastern forested uplands. There is also this intermediate area, not too high, not too low, moderate capacity (around 1.86–2.47) that shows up as a wide transitional belt, wrapping around the urban cold spot. This is probably tied to heterogeneous agricultural patterns, and mosaic land cover types.

For Cultural ES capacity, the overall spatial story follows the regulating pattern quite closely, though the details differ. Cold spots are locked to the urbanized central zone, and hot spots (3.21–4.50) appear along the forested northern and southern edges of the study area. The cold-spot zone seems slightly more extensive than in the regulating services, so cultural ES provision might be more sensitive to land cover fragmentation—especially in that peri-urban transition belt, where things tend to break up and mix.

The total ES capacity basically brings together all three dimensions and reaffirms the bigger spatial setup. The urban core functions as the main cold spot across the whole study area, it is labeled mostly as Very Low to Low, while the nearby forested and semi-natural landscapes create this wide hot spot ring, classified as High to Very High. There is also a clear secondary cold spot in the southeastern part of the study area, it looks like it could be tied to intensively managed cropland, or maybe smaller local settlement clusters.

In general, the spatial assessment shows that a center–periphery gradient is the key organizing principle for ES capacity in the Niš area, with the built-up fabric staying a persistent multi-dimensional cold spot, and the forested uplands essentially becoming the main hot spot area for every ecosystem service category that was checked.

5. CONCLUSION

This study shows that mapping ES capacity with CORINE Land Cover data and using the Burkhard matrix, can be a reproducible approach that's also low cost and policy relevant. It works for Serbian municipalities that don't have access to commercial GIS tools, or high-resolution spatial datasets. The results point to a clear center–periphery gradient which is consistent: the urban core keeps showing Very Low to Low ES capacity, across every dimension that was checked. Meanwhile, forested and semi-natural peripheral areas are basically the main hot spots for provisioning, regulating, and cultural services. Deciduous forests and mixed agricultural landscapes are the top ES providers, and together they span almost half of the study area.

From a methodological point of view, the fully automated QGIS based workflow developed here is directly transferable to any other local government unit in Serbia that has CLC data, and it gives a scalable baseline for ES monitoring at national level, still staying inside the MAES framework and the EU Nature Restoration Law (2024) in a pretty straight way. Still, there are two main limitations. First, the 25-ha CLC minimum mapping unit tends to systematically underestimate ES capacity in urban green infrastructure which is a bit problematic. Second, the Burkhard matrix, which was originally calibrated for ecosystems in northern and central Europe, has not been regionally validated for Balkan Forest types including communities that are typical for the Nišava basin. In particular, to our knowledge, there is currently no regional

adaptation of the matrix for the Western Balkans or for Serbia, so this remains an open methodological gap in the literature.

Future research should consider four directions. First, attempt for higher-resolution land cover inputs, like Urban Atlas or even local orthophoto imagery, so the green infrastructure details don't get flattened. Second, field work for validation and then recalibrate Burkhard scores across Balkan ecosystem types, because the local reality is never exactly the "same" everywhere. Third, build dynamic ES models that actually consider ecosystem condition and degradation, instead of assuming that structurally identical land cover classes are, somehow, functionally equivalent in practice. Fourth, bring in demand-side analysis using socioeconomic data, so you can run a more complete supply–demand ES assessment rather than only describing supply in isolation.

Also, making ES capacity mapping a mandatory step inside urban and spatial planning process would turn these results into planning tools one can use right away. That means the detected hot spot zones get explicit protection, and not just vague recommendations about avoiding land-use conversion.

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LITERATURE

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Research paper

IMPLEMENTATION PATHWAYS OF NATURE-BASED SOLUTIONS IN THE URBAN REGENERATION OF MULTIFAMILY HOUSING: A COMPARATIVE STUDY OF TURIN AND ZAGREB

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Abstract

This paper explores the application of Nature-based Solutions (NbS) in the urban regeneration of multifamily housing areas dating from the second half of the 20th century, shifting the focus from traditional energy-efficiency frameworks to holistic eco-social performance. While previous studies often focus on spatial scales of NbS, this research provides an original scientific contribution by evaluating and comparing the institutional, managerial, and socio-economic implementation pathways in Western European and post-socialist transition contexts. Using a qualitative comparative analysis of two contemporary case studies funded under EU Horizon frameworks – as exemplars of Mirafiori Sud (Turin, Italy) and Sesvete (Zagreb, Croatia), the paper examines how varying urban planning paradigms affect the deployment of blue-green infrastructure within urban regeneration of housing areas. Findings indicate that while Western European contexts benefit from stable public funding and institutionalized co-design processes that mitigate risks like green gentrification, post-socialist environments rely heavily on bottom-up community initiatives that face structural, legislative, and property-ownership constraints. The paper concludes with actionable recommendations for integrating NbS into the urban planning practice of Serbia, demonstrating that cross-border model adaptation is essential for building climate-resilient cities.

Key words: *urban regeneration, multifamily housing areas, nature-based solutions, Western European pathways, post-socialist pathways*

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1. INTRODUCTION

In the contemporary era of intense climate change and rapid urbanization, the regeneration of multifamily housing areas built during the post-WWII period has emerged as a critical priority for European urban policies [1, 2, 3]. In South-Eastern Europe, and specifically in Serbia, these inherited estates comprise nearly 80% of the total multifamily housing stock, currently facing severe physical degradation, uncontrolled densification, loss of public space identity, and compromised ecological comfort [4, 5].

Traditional regeneration schemes have historically focused on narrow technical solutions, such as structural retrofitting and thermal insulation of building facades. While these measures reduce energy consumption, they fail to address broader ecosystem-level challenges like the urban heat island effect, localized pluvial flooding, and social isolation. In this context, Nature-based Solutions (NbS) serve as an integrative umbrella concept that harmonizes ecological performance with community resilience [6, 7, 8, 9, 10, 11].

This paper advances the current discourse by comparing two distinct European implementation pathways of NbS within inherited multifamily housing areas: the Western European welfare-driven model (Mirafiori Sud, Turin, Italy) and the post-socialist transitional model (Sesvete, Zagreb, Croatia). By identifying the structural barriers and success factors of these pathways, the study delivers practical insights for local planning frameworks in transition economies.

2. METHODOLOGY AND THEORETICAL FRAMEWORK

This study employs a qualitative comparative case-study methodology, evaluating empirical data from the EU-funded *proGIreg* (Productive Green Infrastructure for Post-industrial Urban Regeneration) project [12]. The selection of the specific case studies, Mirafiori Sud in Turin and Sesvete in Zagreb, is scientifically justified by two main criteria: 1) their shared programmatic foundation within the same European framework, and 2) their contrasting planning cultures which represent distinct European socio-political paradigms. Structurally, both areas function as large-scale residential and post-industrial zones that exhibit morphological similarities to Serbian modernist multifamily housing estates, such as generous open public spaces that currently suffer from ecological underperformance and climate vulnerability.

However, a critical contextual distinction must be highlighted: while Mirafiori Sud reflects a planned expansion of industrial worker housing, the spatial configuration of Sesvete represents a post-socialist transitional phenomenon where market-driven densification brought the multifamily housing fabric into direct contact with degraded brownfields. Despite these divergent spatial geneses, both areas function as critical testing grounds for NbS. While Turin and Zagreb cannot capture the entire complexity of their respective macro-regions, they serve as illustrative examples of contrasting Western European and post-socialist planning contexts. Their selection reflects the intention to compare two case studies developed within the same EU-funded

framework and addressing similar urban regeneration challenges, while differing primarily in their institutional and planning contexts, thereby enabling a meaningful comparison of NbS implementation pathways.

The theoretical framework integrates ecosystem services with urban governance theories to analyze how spatial interventions translate into socio-ecological benefits [7, 8, 9, 10, 11, 13] . To systematically dissect the implementation pathways, the comparison evaluates three core analytical pillars:

- Institutional governance structures: Examining the degree of local government backing and formal policy integration.
- Community co-design involvement: Assessing how local citizens and civil society are engaged in the life-cycle of the NbS.
- Property-ownership dynamics: Evaluating how land-tenure fragmentation and transitional legislative frameworks impact spatial execution.

3. CASE STUDIES: NBS IMPLEMENTATION IN THE URBAN REGENERATION OF MULTIFAMILY HOUSING AREAS

To evaluate the empirical pathways of nature-based urban regeneration, this study analyzes two dynamic implementation models developed within the international *proGIreg* framework [12]. Executed between June 2018 and 2023 under the European Commission's Horizon 2020 programme, this research-driven initiative focused on developing self-sustaining and market-ready business and governance setups for NbS. Rather than treating blue-green infrastructure as isolated spatial elements, the project was anchored in an integrated co-design methodology that brought together local citizens, local governments, academic institutions, businesses, and non-governmental organizations. The following sub-sections examine how this standardized European methodology materialized under two contrasting socio-political planning environments: Turin and Zagreb.

3.1. Mirafiori Sud, Turin: Exemplifying the western European pathway

The implementation of NbS in Turin focused on the post-industrial residential district of Mirafiori Sud within the *proGIreg* initiative [12, 14, 15, 16] . This area, characterized by social housing estates and adjacent degraded industrial plots, suffered from the urban heat island effect, social vulnerability, and a lack of functional green infrastructure.

The regeneration strategy prioritized a highly structured, co-design approach involving local governments, research institutions, and citizens. On a structural level, the interventions included the installation of green walls on public school and residential buildings, which acted as thermal buffers and local climate regulators. Simultaneously, the project introduced innovative urban gardens on contaminated soils by applying safe, human-made technosols (Fig. 1).

From a governance perspective, Turin established a top-down institutional framework that legally integrated local citizen associations into the long-term management and maintenance of these spaces [14].



Figure 1. Mirafiori Sud. a) Co-design activities displaying five implemented proGIreg NbS in Turin Living Lab (RWTH); b) Community-based urban garden, Source: https://progireg.eu/turin/

Quantifiably, these NbS interventions resulted in a microclimate cooling effect, reducing local peak summer temperatures by up to 3.5 °C through enhanced evapotranspiration [16] . More importantly, the institutional model successfully prevented green gentrification by ensuring that the primary beneficiaries of the new green amenities remained the low-income residents of the existing public housing stock. The Turin experience therefore illustrates that the long-term success of NbS depends not only on the quality of the spatial interventions themselves, but also on the institutional capacity to ensure their long-term implementation and maintenance.

3.2. Sesvete, Zagreb: Exemplifying the post-socialist transitional pathway

Representing the post-socialist transitional context, the settlement of Sesvete in Zagreb served as a "front-runner" site within the same *proGIreg* framework [12, 17, 18, 19]. Sesvete possesses a spatial morphology shaped by a combination of mid-to-late 20th-century residential blocks, generous but unmaintained open spaces, and abandoned industrial complexes.

This morphological entanglement is not a product of deliberate socialist spatial synthesis, but rather a consequence of transitional planning collapse. Originally

established on the urban periphery in accordance with the CIAM principles of functional segregation, the 'Sljeme' meat-processing complex became landlocked inside a dense matrix of multifamily and individual housing blocks due to uncontrolled post-1990s residential sprawl.

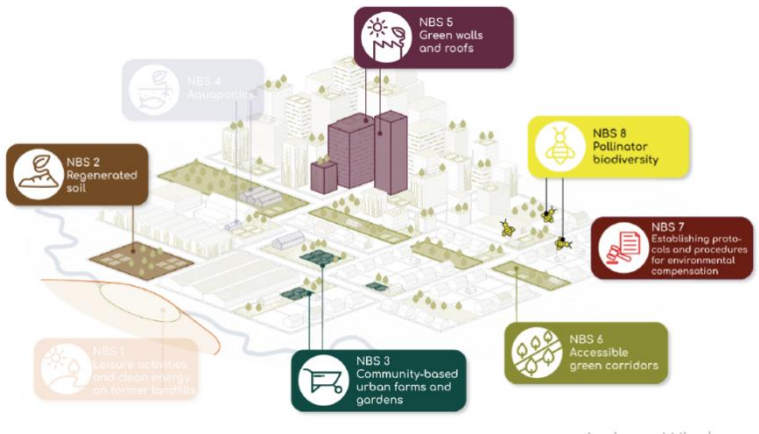






Figure 2. Sesvete. a) Co-design activities displaying four implemented proGIreg NbS in Zagreb Living Lab (RWTH), b) Green wall as a part of the modular urban farm; c) Urban gardens next to the former meat processing factory 'Sljeme', Source: https://progireg.eu/zagreb/

Unlike Turin's institutional approach, the driving force in Zagreb was bottom-up, led by local NGOs and civil society organizations that promoted the ecological transformation of the neighborhood. Physical interventions focused on utilizing unpaved open spaces through therapeutic gardens, restored water corridors, and urban micro-forests for storm-water management (Fig. 2).

The governance architecture in Zagreb faced significant friction due to the rigid administrative legacy of the post-socialist transition. The project encountered unresolved land-ownership disputes and a lack of flexible municipal protocols for co-managing public land with citizens. Despite these barriers, bottom-up initiatives stimulated a gradual adaptation of local planning tools. Environmentally, the interventions transformed paved surfaces into active green sinks, increasing local pluvial storm-water retention by more than 60% and demonstrating the potential of community-led green infrastructure.

4. RESULTS AND DISCUSSION

The key similarities and differences between the Turin and Zagreb case studies are synthesized in Table 1, providing a comparative overview of their governance structures, spatial characteristics, and ecological outcomes.

Table 1. Comparative Matrix of NbS Implementation Pathways

Analysis Criteria	Western European context: Mirafiori Sud,Turin	Post-Socialistc context: Sesvete, Zagreb
Socio-Political Context	Established planning system; mature welfare state; stable public-private-civic partnerships.	Post-socialist transition; fragmented institutional management; legacy bureaucratic inertia.
Origin of Spatial Entanglement	Deliberate capitalist synthesis: Planned expansion of social housing (FIAT) in close structural proximity to the industrial complex.	Transitional anomaly: Rigid socialist functional zoning encroached and "swallowed" by post-1990s unregulated residential sprawl.
Scale and Type of Urban Vacancy	Post-industrial brownfield undergoing continuous, state-led structural economic restructuring.	Landlocked industrial brownfield (Sljeme factory) trapped within an un-amenitied residential matrix.
Dominant Spatial Scale & NbS	Building and block scale; highly localized interventions (green walls, technosol urban gardens).	Neighborhood and district open spaces (therapeutic gardens, urban forestry, water corridors).
Governance Architecture	Institutionalized top-down support fully integrated with structured citizen co-design frameworks.	Bottom-up NGO-led initiatives (e.g., Zelene i plave Sesvete) driving gradual, reactive planning adaptation.
Primary Implementation Barrier	Long-term social equity management; preventing green gentrification and displacement.	Complex land-ownership disputes; legislative gaps; lack of municipal protocols for public-land co-management.
Key Ecological KPI	3.5 °C reduction in local peak summer temperatures via enhanced evapotranspiration.	60% increase in local pluvial storm-water retention capacity through unpaved zones.

The empirical evidence synthesized from Turin and Zagreb demonstrates that nature-based urban regeneration is fundamentally a socio-political and managerial challenge, rather than a purely technical one. While both front-runner sites successfully deployed blue-green infrastructure under the same European framework, their institutional pathways diverged significantly based on their legacy planning cultures.

4.1. Comparative analysis of governance pathways

The quantitative and qualitative indicators [14, 15, 16] show that the Turin case illustrates a Western European planning pathway characterized by institutional predictability, whereas the Zagreb case [17, 18, 19] reflects a post-socialist planning pathway operating within a more fragmented administrative and institutional landscape.

The systemic divergence between these two implementation pathways is deeply rooted in the historical genesis of their spatial and institutional configurations. In the case of Turin (Mirafiori Sud), the proximity of the industrial giant (FIAT) and social housing blocks was a product of deliberate, state-backed capitalist synthesis designed to optimize production and labor welfare. Consequently, when the deindustrialization phase arrived, the mature institutional planning machinery of Turin was structurally capable of orchestrating a top-down, continuous regeneration strategy. By embedding NbS into long-term municipal protocols and public-private-civic partnerships, the local government acted as the primary risk-mitigator. This top-down integration enabled stable citizen co-management agreements, ensuring that building- and block-scale interventions (such as green walls and technosol gardens) were systematically protected from real estate speculation and green gentrification.

Conversely, the post-socialist transitional model in Zagreb (Sesvete) demonstrates a reverse spatial logic. The landlocked presence of the 'Sljeme' industrial brownfield within a dense multifamily housing environment does not reflect intentional socialist mixed-use design, but rather a transitional phenomenon. Following the collapse of rigid socialist functional zoning in the 1990s, an institutional vacuum allowed unregulated, market-driven residential sprawl to encroach upon and eventually 'swallow' the industrial periphery. Operating within this fragmented administrative and legislative landscape, the local municipality lacked the flexible, formalized protocols required to co-manage public assets with citizens.

Thus, the entire operational burden of NbS deployment was shifted onto bottom-up civil society organizations (e.g., 'Zelene i plave Sesvete'). Consequently, the grassroots implementation of NbS in Sesvete functions as a reactive, ad-hoc remedial mechanism. Instead of unfolding within a continuous, state-backed urban strategy, these green interventions represent a civic reclamation of a brownfield vacancy trapped inside a residential zone by the institutional failures of the transition era. However, this institutional inertia inadvertently fostered high grassroots agility. Bottom-up initiatives proved capable of reclaiming and transforming large, unpaved urban vacancies at a neighborhood scale much faster than rigid bureaucratic structures, turning vulnerable, paved surfaces into active green sinks that increased local pluvial storm-water retention capacity by over 60%, even though their long-term legal security remains fragile.

4.2. Applicability to the Serbian planning paradigm

The structural realities of Serbian multifamily housing estates such as Novi Beograd, Liman in Novi Sad, or Bulevar Nemanjića in Niš, possess immense spatial capital due to their modernist, generously dimensioned open layouts [4,5,20]. However, domestic professional practice continues to operate within a narrow building-level energy-efficiency framework, focusing almost exclusively on partial facade thermal insulation measures [21].

The comparative analysis offers two critical directions for the Serbian paradigm:

The strategic value of public open spaces: Serbian estates' morphology is ideally suited for neighborhood-scale, unpaved ecosystem interventions similar to the Zagreb model. Reclaiming degraded public open spaces, parking lots or transit areas into active

green sinks and rain gardens represents a highly cost-effective way to boost local pluvial storm-water retention by up to 60%.

The institutional bottleneck: To prevent these interventions from falling into decay, Serbia cannot rely solely on the financial resources of fragmented housing communities. It requires the introduction of flexible municipal protocols—inspired by the Turin model—that legally and financially support co-management models between local authorities and residents. Crucially, this institutional shift should leverage recent domestic legislative tools, such as the amendments to the Serbian Law on Planning and Construction, which formally introduce the framework for 'Green Infrastructure'. Aligning local governments' protocols with these statutory mechanisms is essential for anchoring community-led initiatives within a stable, institutionalized framework.

This study has certain limitations that should be acknowledged. The analysis is based on two case studies developed within the same European project framework and therefore does not aim to generalize the findings to all Western European or post-socialist planning contexts. Rather, the selected cases illustrate contrasting implementation pathways that provide transferable insights for comparable urban environments. Future research could expand the comparative sample by including additional cities and quantitative performance indicators to further validate the identified governance patterns.

5. CONCLUSION AND RECOMMENDATIONS FOR THE SERBIAN PLANNING PRACTICE

The comparative analysis of Mirafiori Sud in Turin and Sesvete in Zagreb demonstrates that the successful urban regeneration of inherited multifamily housing areas through NbS is fundamentally a governance and legislative challenge, rather than a purely spatial or technical one [22]. While the Turin case highlights the benefits of institutionalized co-design and secure land-tenure frameworks, the Zagreb case illustrates how post-socialist transitional contexts rely heavily on vulnerable bottom-up community dynamics that must continuously navigate structural, administrative, and property-ownership constraints.

These findings offer highly actionable lessons for contemporary urban planning practice in Serbia, which shares a comparable post-socialist spatial and institutional legacy. To successfully integrate NbS into the regeneration of Serbian multifamily housing estates, three strategic recommendations are proposed:

- Institutionalization of co-design protocols: Serbian local governments must transition from purely formal public hearings to binding, long-term co-design frameworks, legally recognizing civil society organizations as legitimate partners in the co-management of public spaces to ensure the long-term spatial and economic viability of NbS.
- Addressing ownership and governance barriers: Planning instruments must develop flexible legal mechanisms that enable temporary or permanent ecological interventions within fragmented ownership

structures, overcoming barriers that commonly hinder regeneration efforts in post-socialist housing estates.

- Diversification of funding and policy integration: Future urban regeneration projects in Serbia must move away from ad hoc, project-dependent financing, explicitly integrating NbS into local strategic documents, capital investment plans, and urban planning regulations.

Ultimately, this study confirms that cross-border model adaptation is not a matter of copy-pasting technical blueprints, but of re-engineering local governance structures. For Serbian cities to become climate-resilient, the planning paradigm must evolve to support eco-social performance, ensuring that the regeneration of post-WWII multifamily neighborhoods directly empowers and protects the communities that inhabit them.

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Review paper

NATURE-BASED SOLUTIONS IN LOCAL STRATEGIC AND PLANNING FRAMEWORKS: THE PERSPECTIVE OF THE CITY OF NIŠ, SERBIA

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Abstract

Nature-based Solutions (NbS) are increasingly recognized as important elements for addressing environmental, social, and climate-related challenges in urban areas. By integrating green and blue infrastructure into the urban fabric, NbS contribute to climate adaptation, human well-being improvement and biodiversity benefits, particularly within public open spaces (POS) in multi-family residential neighbourhoods. Successful implementation of NbS, however, depends not only on physical interventions but also on supportive governance, planning, and regulatory frameworks.

This paper examines the treatment of NbS within the local governance and urban development framework of the City of Niš, Serbia. The study analyses key strategic and statutory planning documents, including the Urban Development Strategy, Development Plan, General Urban Plan, and Plans of General Regulation, with a particular focus on their implications for the (re)integration of POS in multifamily residential areas. The research aims to identify the opportunities and limitations that the existing local framework creates for NbS implementation.

The findings indicate that NbS principles are increasingly embedded in local strategic and planning frameworks through measures promoting green and blue infrastructure, green roofs and facades, minimum green-space requirements, and common-use open spaces in residential developments. At the same time, implementation is constrained by weak monitoring systems, the absence of a functional green-space cadastre, insufficiently elaborated planning standards, and market-driven development. The study highlights the need for stronger institutional capacities, improved monitoring mechanisms, clearer implementation guidelines, and greater public awareness to support the effective integration of NbS into urban development. The findings also point to the importance of further legislative and policy support at the national level to ensure a more consistent and sustainable application of NbS in Serbian cities.

Key words: *Strategic Development Documents, Urban Plans, Integration of Nature-based Solutions, City Level*

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1. INTRODUCTION

Nature-based Solutions (NbS) is the umbrella concept of ecosystem-based approaches that addresses crucial societal and environmental challenges of urban development. According to the International Union for Conservation of Nature (IUCN), NbS are “actions to protect, sustainably manage and restore natural and modified ecosystems, which address societal challenges effectively and adaptively, providing human well-being and biodiversity benefits” [1]. These solutions are also considered to be one of the key measures of disaster risk reduction and climate change adaptation and mitigation in the New Urban Agenda [2].

NbS imply restoring natural elements of blue and green infrastructure into the urban landscape, as well as renaturing paved surfaces. Therefore, NbS play a vital role in designing public open space (POS) within multi-family residential areas, offering sustainable, resilient and affordable solutions to challenges such as climate change adaptation [3] and improving public health and well-being [4]. The application of NbS can help minimize vulnerability to risks such as heat stress, air pollution and urban flooding [5,6], while also creating safe, inclusive and ecologically diverse environments. Such resilient and vibrant communities with NbS elements are favoured in contemporary urban planning and design concepts for reclaiming POS in residential areas [7].

Regarding the treatment of NbS in national legislation of the Republic of Serbia, it can be stated that the existing general framework fits well into the context of NbS, and provides good grounds for their application in POSs. The standing *Law on Planning and Construction* [8] does not explicitly mention "Nature-based Solutions" but refers to “Biodiversity-based solutions" and “Green infrastructure”, while the *Law on Environmental Protection* provides a framework for the management of green areas [9]. Furthermore, the *Rulebook on the Content, Method and Procedure of Creating Spatial and Urban Planning Documents* [10] mandates incorporation of green space regulations into urban planning documents of lower rank, as well the inclusion of green areas data into urban design projects. This conceptual commitment is further supported in the *Sustainable Urban Development Strategy of the Republic of Serbia until 2030* [11], which prioritizes NbS within its framework for urban development, and proposes certain priority measures that are directly or indirectly linked to NbS implementation in POSs within multi-family housing.

This paper investigates how NbS concept is incorporated into local planning and governance frameworks in Serbia through the case of the City of Niš. By analysing the city’s regulative and strategic framework related to NbS, the overall objective of this research is to explore the treatment of NbS in strategic and planning documents of the city, in order to determine the potentials and limitations for the implementation of NbS in POS (re)integration at the neighbourhood level.

This study employs empirical research and a review of relevant literature, with a methodological framework based on descriptive and analytical approaches. The research involves a comprehensive review of local-level data, including strategic frameworks and statutory planning documents, to examine how the concept of NbS is addressed within residential areas of the City of Niš. The analysis of these policy and

planning documents provides insight into the contextual factors influencing NbS implementation, and assesses the extent to which the existing planning framework supports the sustainable development of POS within multifamily housing areas. The synthesis of study findings is used as a basis for discussing the opportunities and constraints for NbS implementation in residential POSs within the specific context of Niš, and in the broader planning and governance framework of the Republic of Serbia.

2. NATURE-BASED SOLUTIONS IN STRATEGIC DEVELOPMENT DOCUMENTS

2.1. Urban Development Strategy of the City of Niš and the Municipalities of Svrljig, Merošina and Gadžin Han

When reviewing green infrastructure in the Analytical part, the *Strategy* [12] acknowledges the issue of the lack of greenery in urban blocks, which is devastated and used as parking. Furthermore, it points to the planned increase in green areas and open spaces at the level of the entire urban settlement (to 15.7% of the construction area).

By harmonizing the goals and measures from the EU and national policies, a framework for sustainable and integral territorial development of urban areas was established, with a set of localized goals suited to the local context. Goals, specific goals and measures relevant for NbS are summarized in Table 1.

Table 1. Goals and measures relevant for NbS in the Urban Development Strategy of the City of Niš and the municipalities of Svrljig, Merošina and Gadžin Han

Goal 2. Promoting clean and fair energy transition, green and blue investments, climate change adaptation and mitigation, risk prevention and management, and sustainable urban mobility	
Specific goal 2.4. Adaptation to climate change and disaster risk prevention, strengthening resilience to climate change, taking into account an ecosystem-based approach	
Measure 2.4.5.	Developed or improved green infrastructure to adapt to climate change
Specific goal 2.7. Strengthening the protection and preservation of nature, biodiversity and green infrastructure, and reducing all forms of pollution	
Measure 2.7.1.	Green and blue infrastructure

According to the Map of priority areas of intervention in the *Strategy*, the green infrastructure appears to be planned outside the urban area, while no NbS elements are discussed for zones of multi-family housing. Furthermore, none of the established strategic projects in the document relate to the NbS. However, a list of priority ideas is given in the Annex of the Strategy. One of them refers to NbS, and includes roof gardens and gardens in neighbourhood greenery. Another idea includes a project to reduce the carbon footprint of buildings and create green roofs and facades in Niš.

2.2. Development Plan of the City of Niš 2021-2027

The *Development Plan* [13] establishes four priority development directions tailored to the local context. The importance of NbS is acknowledged within “Development direction 2. Territorial development and environmental protection”. Table 2 summarizes the relevant priority goal and measure dealing with the NbS.

Table 2. Goal and measure related to NbS in the Development Plan of the City of Niš 2021-2027

Development direction 2. Territorial development and environmental protection	
Priority goal 2.5. Preserve the potential of adaptation and mitigation measures established at the national level until 2030, by increasing resistance to climate change in priority sectors and establishing response in risky and emergency situations in urban and rural settlements	
Measure 2.5.4.	Prescribes the creation of green and blue infrastructure in Niš territory, and emphasizes the investment in green infrastructure in public spaces.

Within the framework of this measure, it is planned to create interconnected ecosystems and incorporate green infrastructure, as well as prepare guidelines for defining green and blue infrastructure and nature-based infrastructure. In line with these guidelines, two studies will be prepared: (1) a study of the initial condition of the green areas of the urban and rural core with the cadastre (including protected properties), and (2) a study of adaptive measures to climate change for greenery, green and blue infrastructure and nature-based infrastructure, with ecosystem management measures to increase resistance and reduce the sensitivity of people and the environment to climate change (EbA approach), and strategic planning of the network of natural and semi-natural areas. These results will serve as a basis for the preparation of the Plan of General Regulation, and the integration of the obtained Plan into the cadastre, which is one of the services of the Geographical Information System of the City of Niš. Following that, this measure implies investments in green infrastructure (vertical gardens, green roofs, city parks, green network, green bridges, green corridors for wildlife, underground parks, urban wetlands, public spaces, streets and squares...).

Two performance indicators are provided to measure the results in the application of this measure: the number of study-planning-analytical documents that define blue and green infrastructure, and the number of pilot projects with blue and green infrastructure. As no monitoring of the achievement of goals defined in the *Development Plan* is carried out in the City of Nis, the effects of this measure are unknown even five years after the *Development Plan* was adopted. The cadastre of green areas has also not been formed to date.

3. NATURE-BASED SOLUTIONS IN URBAN PLANNING DOCUMENTS

3.1. General Urban Plan of Niš 2010-2025

Although this *General Urban Plan* (GUP) [14] and its four amendments and supplements do not mention the term NbS, greenery is discussed in detail within the framework of spatial and environmental protection. GUP states that the importance of greenery in Niš is reflected in the function of satisfying sanitary-hygienic-recreational conditions. According to the GUP, greenery in residential areas, in addition to greenery involving individual single-family plots, includes block greenery as an integral part of extended housing function. GUP states that the use of block greenery allows for close and everyday contact between residents and vegetation. In addition to aesthetic and decorative significance, landscaping of open space must also have functional significance.

3.2. Plans of General Regulation of City Municipalities

3.2.1. Plan of General Regulation of the City Municipality Medijana

Given the extreme densification of urban fabric in the post-socialist period, particularly in the most densely developed territory of the city municipality Medijana [15,16], attempts were made to improve the quality of urban living by increasing the share of green surfaces. In 2021, in the *Third Modifications and Additions of Plan of General Regulation of the City Municipality Medijana* (PGR) [17], all prior provisions in the Plan relating to green areas were repealed, and new regulations were provided. In Chapter 2.0. Building Rules, Section 2.3. Individual Building Rules, the minimum percentage of green areas is set at 25% of the plot area, out of which 10% of the plot area is green areas in direct contact with the ground. This applies to all land uses with a share of green areas smaller than 25%. Soon afterward, additional PGRs of city areas also introduced the same rule concerning the share of green areas in residential zones.

This was the first PGR to initiate the implementation of NbS and further elaborate the term "green areas", which was later applied in PGRs of other city municipalities. The term "green areas" refers to all types of green surfaces and tall greenery, and aside from ground-connected greenery also involves green roofs, green facades as well as greenery above underground floors. However, only green spaces with direct ground contact are evaluated as 100% contributing greenery, while the Plan prescribes that other types of green surfaces are to be assessed at a reduced percentage:

- Green roof: 50% of the roof area covered with greenery is valued in the calculation;
- Green facade: 50% of the facade area covered with greenery is calculated;
- Greenery above underground floors: 50% of the required green area in the calculation.

Regarding tall greenery, it is defined that one tree is valued as 5.0 m² of greenery, but it is not precisely stated whether tall greenery also needs to be in direct contact with the ground, or not. This implies that this rule is open to misinterpretation, and may even result in trees with smaller canopy span that are placed in planters. Additionally, in the PGR of Medijana city municipality, the type of tall greenery is not pre-defined and may refer to any tree species. This issue was addressed in following PGSs of city municipalities Pantelej and Palilula.

3.2.2. Plans of General Regulation of City Municipalities Pantelej and Palilula

The analysed PGRs of city municipalities Pantelej and Palilula involve: *Sixth Modifications and Additions of the PGR of the City Municipality Palilula – Phase I* [18], *Second Modifications and Additions of the PGR of the City Municipality Palilula – Phase II* [19], *Second Modifications and Additions of the PGR of the City Municipality Pantelej – Phase I* [20], *Third Modifications and Additions of the PGR of the City Municipality Pantelej – Phase II* [21], and *Third Modifications and Additions of the PGR of the City Municipality Pantelej – Phase III West* [22].

These planning documents take on a comprehensive approach to implement various types of green infrastructure in POSs in the area covered by the Plans.

Regarding the overall landscaping of neighbourhoods, it is advised to use a large number of autochthonous (native) and allochthonous (exotic) species, both conifers and deciduous species in the form of trees, ornamental shrubs, climbing plants, hedges, flowerbeds and lawns. The PGRs of the city municipality Pantelej go a step further to provide a table "Typology of Greenery" that defines the type and density of particular greening elements that are implemented in parterre greenery, green roofs, vertical greenery and tree lines. Regarding the type of trees, the two PGRs for city municipality Pantelej even define the type of seedling, its diameter and the spacing of the trees, as well as the ratio of trees and shrubs on the plot.

All PGRs for Pantelej and Palilula also state that in the case of new construction, vertical extension of structures and reconstruction, resulting in the increase of more than three single residential units, one tree sapling should be provided for each apartment within the plot/complex, or on public and other land within the boundaries of the Plan, in line with the conditions of the relevant public utility company.

The PGRs for city municipalities Pantelej and Palilula further elaborate on the construction of green roofs and define the greenery that is to be used when implementing this type of green infrastructure. The use of extensive green roofs is prescribed, which are primarily designed as decorative surfaces that also provide environmental benefits, have limited access for maintenance only, and do not enable recreational activities. This type of green roofs is selected because they are easier, cheaper and faster to install, and require very little maintenance. Regarding the type of greenery that may be planted, it involves low plants that are highly resistant to dry climate conditions, such as grass, dwarf shrubs and flowering plants, and even some medicinal and perennial herbs, depending on the accessibility of the roof area. Regarding green facades, the PGRs for city municipalities Pantelej and Palilula define climbing plants as the type of greenery to be used, at a density of three seedlings per meter long.

It is also important that the *PGR of the City Municipality Pantelej – Phase I* was the first plan to introduce a new land use "Mixed-use Zone with Larger Green Areas", where business and residential uses are dominant urban functions. The PGR states that many important building rules for this land use, such as the share of POS, will be determined through further elaboration, implying elaboration at the lower levels of urban planning. Regarding green areas, building rules prescribe mandatory share of greenery of at least 30% of the plot/complex area, which is also to be determined through further urban elaboration of the site in lower-ranked planning documents.

3.2.3. Management Solutions and Digital Solutions in Plans of General Regulation

The intent to implement green infrastructure has revealed the crucial weakness of all Niš's PGRs, which relates to the provision of POS that would accommodate such green surfaces. Therefore, the PGRs for city municipalities Pantelej and Palilula prescribe mandatory provision of "undeveloped area in common use" of all residents where various leisure activities are carried out, for plots containing more than three independent housing units. These undeveloped areas do not include green areas, traffic areas, parking lots and pathways. The minimum share of undeveloped area in common

use is prescribed at 20% of plot area, of which 15% should be in open space. The remaining 5% of undeveloped area in common use are related to common rooms within building volume, which can be located on any floor.

This rule could provide good grounds for setting up building-oriented POSs and common POSs for a cluster of buildings, if it referred to open spaces at the parterre level. However, aside from areas in direct contact with the ground and areas in the parterre, it is envisioned in the Plans that the "undeveloped area in common use provided in open space" should also involve open terraces and walk-through roofs. Open terraces and walk-through roofs as options for areas in common use are preferred by the developers as they enable higher index of plot occupancy and more lucrative investments, but such design solutions limit public access. Areas in common use involving open terraces and walk-through roofs mostly imply shared spaces that enable access to local tenants only, resulting in semi-public or semi-private character of open space, and reducing the role of such spaces to environmental benefits alone. This issue gains importance in light of the next rule defined in the Plans, which refers to shaping of these spaces. Namely, it is suggested that undeveloped area in common use should be functionally defined as zones for relaxation, children's play, socializing, recreation, etc., and, if planned at the parterre level, should be connected to green areas, traffic areas and pathways. This rule clearly indicates the need to implement POS in residential developments having both social and environmental function, but in market-driven residential schemes it actually leads to privately owned public space (POPS) models having only environmental function.

Niš is characterized by a low share of parks and recreational areas available to citizens. The creation of a cadastre of green areas is necessary in order to provide a more detailed insight into the typology, structure and extent of green areas in the city. In this regard, the development and implementation of a unified geographic information system (GIS) in public and utility companies and the city administration is recommended, as digital solutions can help improve the city's green areas and overall environmental protection.

4. DISCUSSION: POTENTIALS AND LIMITATIONS FOR THE IMPLEMENTATION OF NATURE-BASED SOLUTIONS IN NIŠ

At the local level of Niš, the importance of NbS is acknowledged in the *Development Plan* as the strategic document of urban development, within a measure that promotes the creation and of green and blue infrastructure, as well as the investments in green infrastructure in public spaces. The proposed development of the cadastre of green areas for the urban and rural core is a noteworthy initiative, but its realization needs to be accelerated. The creation and use of such digital solution within the city's GIS system would be a great enhancement for NbS implementation. The measure relating to green infrastructure is further supported at the strategic level, as the *Urban Development Strategy* also prioritizes roof gardens and gardens in neighbourhood greenery.

Enhancing urban planning at the local level in PGRs by increasing the share of green surfaces to 25% for residential land use, out of which 10% in direct contact with the

ground, is a step forward in creating quality POS with NbS elements. These efforts are further enhanced by prescribing mandatory provision of "undeveloped area in common use" for multi-family housing.

Although the significance of NbS implementation is highlighted in the strategic document of urban development, effects of the measure related to green and blue infrastructure is unknown. Monitoring on the progress of goals defined in the strategic documents is identified as a one of the key issues impeding progress of NbS implementation at the local level. It is therefore necessary to begin the process of monitoring and evaluation grounded in the *Development Plan*, and further incorporated in other legal acts. This requires a significant shift in perception of local decision-makers and institutional departments that are the carries of implementation actions, as well as the improvement of inter-departmental cooperation.

Despite the efforts to increase the minimum percentage of green areas in PGRs of the City of Niš, in residential zones and in mixed-use zones with larger green areas, which favour the implementation of various NbS elements, this regulation needs to be further elaborated depending on the particular urban context in order to avoid misuse. The share of green areas that is in direct contact with the ground of only 10% of plot area may be suitable for the regeneration of highly urbanized areas, but must be significantly higher in new developments. Furthermore, setting the context properly will also help with the choice of NbS elements that would be appropriate for a particular urban area.

When reviewing the management solutions to accommodate NbS in POSs, the PGRs mandate a minimum share of undeveloped common-use areas, including open spaces. However, the inclusion of terraces and roofs into these open spaces limits accessibility, making them semi-private. While the rules emphasize both social and environmental functions of common-use areas, in market-driven developments they primarily result in privately owned public spaces (POPS) with only environmental benefits.

Finally, an important limitation deals with low awareness of general population on the significance of NbS in local communities in cities such as Niš. Further educational actions and raising awareness are needed at city level, to promote the benefits of NbS implementation to all relevant stakeholders in reclaiming neighbourhood's POSs: decision-makers, carries of implementation actions, residents, users and the general population, as an instrument for the broad adoption of NbS.

The example of Niš also reveals that some enhancements of the legislative, strategic and planning frameworks are needed at the national level. Although the national legislative framework favours NbS implementation, it is necessary to introduce this globally-known term into Serbian legislation and regulations on urban development in order to enable the sustainability and permanence of NbS elements. Furthermore, it is essential to set criteria and standards for NbS application, and establish clear guidelines for implementation, which would streamline the process for all stakeholders, particularly urban planners and carriers of implementation. Additionally, local governments in the Serbia must be legally bound to monitor performance indicators in achieving the goals defined in the *Sustainable Urban Development Strategy*. In terms of NbS implementation, the key performance indicator is the surface of urban area

designated for POSs or parks, which is linked to the “Indicator 11.7.1. Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities”. The calculation of SDG Indicator 11.7.1. is not yet being monitored in Serbia at the national level due to the lack of local data.

5. CONCLUSION

The analysis of the strategic and planning framework of the City of Niš indicates that the principles of NbS are increasingly being incorporated into local urban governance and planning, although their application remains partial. Strategic documents recognize the importance of green and blue infrastructure, climate adaptation, and ecosystem-based approaches, while planning documents provide concrete mechanisms for the implementation of NbS elements, including green roofs, green facades, increased green-space requirements, and common-use open areas within multifamily housing developments. These provisions demonstrate significant potential for the (re)integration of POS at the neighbourhood level through NbS.

However, several limitations continue to hinder their effective implementation. These include the absence of systematic monitoring and evaluation, the lack of a functional green-space cadastre, insufficiently elaborated planning standards, and the tendency of market-driven development to prioritize semi-private open spaces over accessible public spaces. The findings suggest that, while the existing local framework provides a solid foundation for NbS implementation, stronger institutional capacities, clearer implementation guidelines, improved monitoring mechanisms, and greater public awareness are needed to fully realize the environmental and social benefits of NbS in residential neighbourhoods.

Furthermore, the case of Niš highlights the need for additional legislative and policy support at the national level to ensure a more consistent and effective integration of NbS into urban development practice across Serbia.

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Research paper

MULTIFUNCTIONAL SOLUTIONS FOR RECLAIMING PUBLIC OPEN SPACES IN MULTI-FAMILY HOUSING: GELLERUP NATURE PARK

Jelena Živković[1], Tamara Mladenović[2]

Abstract

Multifunctional solutions (MFS) are increasingly taking a central role in contemporary urban planning as a response to the challenges of sustainable development. The idea that multifunctional public open spaces (POS) can contribute to sustainable urban development is based on the assumption that they bring a broader range of ecological, social, and economic benefits to urban area, and as such their application is of particular significance for multi-family housing regeneration. This is especially important in the context of climate change and the growing developmental challenges, where POS are expected to simultaneously provide benefits for both people and nature.

Based on the theoretical framework that recognizes the space, time, use and service dimensions of urban open space multifunctionality, this paper presents the case study of Gellerup Nature Park in Aarhus, Denmark as an outstanding example of the revitalization of neglected public open spaces through a multifunctional approach that simultaneously addressed the ecological, socio-cultural, and economic aspects of sustainability. The implemented solutions were developed through participatory process and involved a multilayered approach in which ecological and social interventions were interconnected. The aim of the paper is to explore the context, process and modalities of MFS application in Gellerup multi-family housing estate and to highlight environmental and social benefits that this approach may bring to multi-family residential areas.

Key words: *Public open space, multifunctional solutions, multi-family housing, sustainable development, citizen participation*

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1. INTRODUCTION

The idea that *multifunctional open spaces* may support sustainable urban development is based on the assumption that they bring a wider spectrum of environmental, social and economic benefits to urban areas [1, 2]. The application of this concept is especially important in residential public open spaces (POS) that are nowadays expected to provide a variety of benefits for both people and nature [3].

This issue is additionally relevant today, when vast underused, neglected, and unsafe public green open spaces of modernist multi-family housing represent a systemic problem faced by cities worldwide [4,5]. Although they may be beneficial to nature, if they do not have value and meaning to residents, they usually enter into a negative loop of negligence, thus contributing to the overall environmental and social decline of the area. To convert this negative process, there is a need for a complex, democratic, and multi-scale view of how POS may be used and perceived, that takes into account the variety of needs, interests, and meanings that people contribute to the place [3]. In this respect, a multifunctional approach and deriving solutions open new possibilities to reclaim POS in multifamily housing areas. In addition, current climate change debates recognize that POS have the potential to offset the impacts of climate change, and suggest integration of this new climate function into their planning and regeneration. In this regard, large green areas typical for inherited modernist residential complexes offer a great potential to make this possible [6,7].

In order to explore *how the revitalization of the neglected public open spaces in modernist housing area can be achieved and their potential activated through implementation of multifunctional solutions (MFS)*, the Gellerup Nature Park in Aarhus, Denmark, was chosen as an officially recognized example of good practice. Learning from this case may bring valuable insights to how multifunctional approach to POS planning and design may contribute to urban sustainability and regeneration. After introducing the theoretical framework on *multiple dimensions of POS multifunctionality* that was previously developed by authors [3], this paper uses case-study methodology to explore the context, process and modalities of MFS application in Gellerup multi-family housing estate in order to highlight environmental and social benefits that this approach may bring to multi-family residential areas.

2. THEORETICAL FRAMEWORK: UNDERSTANDING THE MULTIFUNCTIONALITY OF PUBLIC OPEN SPACES

Urban open spaces are physically un-built areas within a city's territory and integral parts of the urban structure [8]. Well-planned, designed, and maintained, they contribute to urban life through various functions, such as movement, recreation, gathering, and water management, alongside "non-urban" activities like agriculture, forestry, and nature conservation. In the pursuit of sustainable urban development, creating multifunctional public open spaces (POS) is highly promoted, assuming they simultaneously bring a wider range of benefits. This is especially relevant in residential areas, where sustainability depends on how people perceive and value these

spaces.However, the interpretation and application of multifunctionality in urban planning and design can vary.

Here we present a theoretical framework on POS multifunctionality, previously developed by the authors [3], which addresses different dimensions of this concept. Within this framework, multifunctionality is understood as a spatial feature that helps solve multiple problems and achieve diverse benefits, linking it directly to sustainable development. To harmonize the ecological, socio-cultural, and economic aspects of sustainability, we propose a multidimensional conceptualization. Based on theoretical analysis, we recognize key dimensions that link multifunctionality to space, time, use, and land services, and elaborate on how each contributes to sustainability.

The SPACE dimension refers to how different functions are distributed horizontally and vertically, determining the spatial scale of multifunctionality (from the city-wide level to specific locations). Diversifying the range of activities attracts more people, fostering sociability and social sustainability. Concurrently, enhancing an area's appeal boosts local economies, investments, and property values in surrounding neighborhoods. The level of sociability depends on the spatial configuration of the POS (dispersed or concentrated) and how individual spaces are linked. Furthermore, the ecological value of green POS can be protected by showcasing their natural beauty, enabling their active use, and integrating them into the daily lives of residents.

The TIME dimension refers to the temporal distribution of functions, which can be synchronic or diachronic: Diachronic multifunctionality involves the scheduling of different functions across different times. This supports the continuity of socialization for various user groups throughout the day or seasons, contributing to social sustainability. Synchronic multifunctionality refers to the co-occurrence of different functions at a single moment. This makes a place highly attractive to diverse users simultaneously, concentrating people and increasing opportunities for social interaction and communication. Both modalities provide direct and indirect economic benefits by making the space more vibrant and appealing.

The USE dimension focuses on providing possibilities for both people and other living beings to use space in different ways, which is heavily shaped by urban design. Social benefits are generated by diversifying activities; as more users are attracted, the chances for social interaction rise. While adding new uses to green public spaces helps residents connect with and appreciate nature, planners must note that intensifying use can either enhance or compromise the ecological value of a POS.

The SERVICE dimension refers to the capacity of natural or built land to provide tangible and intangible goods, services, and amenities to people and nature. Multiplying land functions and services helps reveal the diverse values of nature, supporting the protection of natural features in urban environments. At the same time, improving environmental comfort and aesthetics through ecosystem services increases the use and sociability of space, helping construct a positive identity for the area.

How all these dimensions of multifunctionality can be achieved in practice will further be explored through the case study of Gellerup Nature Park in Aarhus, Denmark.

3. METHODOLOGY

To investigate how multifunctional solutions (MFS) can be deployed to reclaim neglected public open spaces (POS) within modernist housing estates this study adopts a qualitative, exploratory single-case study research design. The case study method is particularly suited for this inquiry as it allows for an in-depth, contextual investigation of a contemporary phenomenon within its real-world setting, where the boundaries between the phenomenon and the context are highly integrated. The case (Gellerup Nature Park) was selected as an exemplary case of strategic urban regeneration using purposive sampling based on the following criteria: a) Typological relevance (modernist housing estate), b) Multifunctional POS development for sustainability; c) Institutional recognition (validated as an international benchmark, nominations and awards).

Data were gathered from multiple sources, facilitating data triangulation: a) Project and design documentation (EFFEKT and SLA); b) Policy and strategic regeneration frameworks (issued by the Aarhus Municipality and Brabrand Boligforening), c) Peer-reviewed journal articles analyzing impacts of the Gellerup regeneration project. The collected qualitative and spatial data were analyzed using deductive thematic analysis, in which the thematic coding was structured around the four dimensions of POS multifunctionality established in the authors' previous theoretical framework.

4. CASE STUDY OF MULTIFUNCTIONAL GELLERUP NATURE PARK DEVELOPMENT

Gellerup Nature Park in Aarhus, Denmark was selected as a good practice case of reclaiming POS in multifamily housing areas by applying multifunctional solutions in all dimensions: through the USE of SPACE in different ways and scales, simultaneously or during a certain period of TIME, as well as through providing landscape SERVICES. The result is a new urban space that by activating and linking the existing green areas, reconnects residents, thus creating a new positive image of the area.

4.1. Urban brief

Gellerup Nature Park was developed between 2014 and 2021, through a public-private partnership, aiming to bring „new life“ to modernist social housing blocks with large neglected and underused public spaces. The project was commissioned by Brabrand Boligforening, the Municipality of Aarhus, and Realdania, and designed by EFFEKT and the landscape architecture office SLA. Built in 1960’the Gellerup neighbourhood is one of the largest social housing projects (13ha) with more than 10 000 residents [9, 10]. The proposed park serves as a prototype for transforming similar residential estates, guiding their transition from modernist 'machines for living' into humane, nature-based communities[11].The project aimed at increasing social cohesion and biodiversity, addressing climate issues and economic factors, and at improving the well-being of the residents of the surrounding blocks. The park’s planning and design prioritized enhancing safety, promoting diverse activities, and fostering sociability through cross-cultural exchange [11](Fig. 1).

4.2. Issues detected

The construction of this social housing settlement was initiated in 1960' by the state of Denmark. Over time, it became a symbol of the fragmentation of both urban space and society. The neighborhood faced social and ecological challenges, resulting in the need for sustainable urban regeneration and revitalization of its public spaces. The neighborhood suffered an increased rate of crime, poverty, and unemployment. In addition to social problems, the neighborhood faced environmental problems. The original urban design of the area, with cascading courtyards, made green spaces inaccessible, underused, and neglected (Fig.2). Before the implementation of the new project, a limited variety of plant species had been recorded, indicating a significantly reduced biodiversity in the area [11]. The need for nature-based solutions was recognized, and the Gellerup Nature Park project became the answer to the question of how to integrate nature into the urban environment to provide multifunctional use and landscape services, thus harmonizing ecological, social, and economic aspects of sustainability.

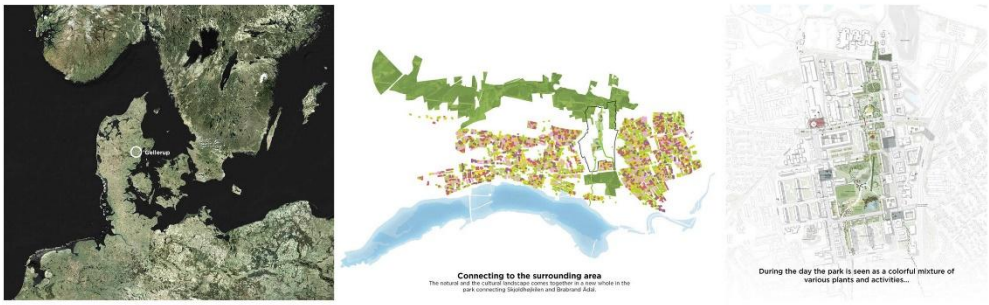


Figure 1. Gellerup Nature Park, a) Gellerup location, b) Gellerup Park connecting the city, c) Site plan. Source: https://www.effekt.dk/gelleruppark



Figure 2. Social housing from the 60s, a) Modernist blocks before the Gellerup Park intervention. Source: https://www.effekt.dk/gelleruppark

4.3. Multifunctional solutions implemented

The competition for the Gellerup Nature park was announced in 2014, and the first prize was awarded to EFFEKT architects + SLA landscape firm. Their concept was based on the multi-scale „return to the natural environment", by imitating the natural terrain that existed in this area before the modernist interventions (landscape cascades) and by introducing multifunctional use of both built and green spaces. [9]

Developed under a broad regeneration program by Brabrand Boligforening and Aarhus Municipality, the park's plan brought together experts in architecture, urban planning, sociology, and social development [11]. The 2018 "Bootcamp Gellerup 2.0" engaged experts and researchers to establish core values for the Gellerup-Toveshøj neighborhoods [12], while JAJA Architects and WE Architecture managed the wider urban redesign. Essential to this process was citizen participation, giving residents a platform to debate and propose ideas for the park's design and functions. The project was developed through three phases: 1) an extensive participatory process with the local community; 2) an architectural and landscape design phase; and 3) Implementation of the new natural environment together with citizens, gardeners, and biologists.

Design for projects' multifunctionality was developed by addressing two main issues: a) Ecology and climate, and b) Social cohesion and wellbeing.

Design for Multifunctionality: Ecology and Climate.

The ecological and climate interventions of the project refer to the design of a new landscape, featuring gentle and natural slopes, suitable for walking. The new terrain brings the feeling of being in a real natural environment [9]. The design also introduced water streams and lakes, which, apart from their aesthetic contribution, collect excess rainwater as a landscape SERVICE.



Figure 3. Ecology and nature in Gellerup, a) Landscape - from modernist cascades to natural slopes b) Natural-ecological multifunctional POS c) Ladscape before and after d) Meadows and hills, biodiversity. Source: https://www.effekt.dk/gelleruppark

Part of the water pools are in the form of cascades, taking on the possibility of height differences inherited from the previous modernist landscape design. The gradation in the "naturalness" exists: while some water reservoirs are implemented as natural lakes, others are shallower and in the form of water mirrors, providing a place

for rest, play and education. Moreover, to enhance biodiversity, over 160 new plant species were planted, including more than 2000 trees. This led to the appearance of over 23 new animal species that have found their living space in this park, including rabbits, foxes, squirrels, and wild bees [11]. Significant microclimate optimization was also a by-product of this form of park's multifunctionality.

The new natural environment offers the possibility of play, rest, walking, and educating the youngest, in addition to mitigating climate change related disasters, such as heavy rainfall and floods. The park functions as a dynamic location that attracts visitors and contributes to the development of local businesses (Fig. 3)

Design for Multifunctionality: Social cohesion and wellbeing.

To improve social cohesion, the park integrates playgrounds, sports courts, outdoor gyms, gardens, and cultural facilities, creating a "social nature" that enhances neighborhood quality of life [13]. The new Gellerup Park offers the possibility of partaking in a wide variety of activities, planned for a variety of users. Multifunctionality of SPACE is achieved at both area and location level. Although various activity areas are dispersed in space and can be alternatively used over TIME, every part of this park is multifunctional; regardless it is a green or paved area, a path or a field. Symbolic entrance portals foster a sense of belonging, while new, deliberately curved paths connect the park with the surrounding areas, providing better accessibility and enabling a greater degree of USE. The green areas are equipped with places for sitting, picnicking, and socializing with neighbors. Built structures are also multifunctional in their form: for example, the concrete benches along the walking paths “emerge” out of the terrain, which makes them suitable for skates or children to play.

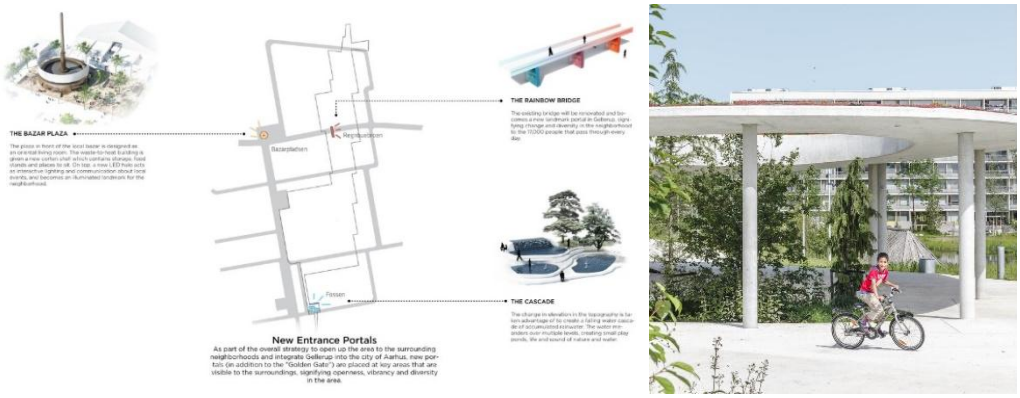


Figure 4. Design for social wellbeing in Gellerup: a)Spatial diagram – Bazar Plaza, New Entrance Portals, The Cascade, The Rainbow Brigde, b)Pavillions.Source: https://www.effekt.dk/gelleruppark

The space is decorated with murals, and the existing “Rainbow Bridge” was also restored as a local symbol. The new multifunctional pavilions provide gathering places, and "Bazarpladsen" - Bazar Plaza is equipped with food stands and space for sitting and socializing, while at the same time serves as storage and offers possibility of converting waste into energy. The entire space can be used even at night because it is lit by a circular LED "halo" (Fig. 4). Citizens actively support livability of the Park by organizing various temporary activities, cultural events, and happenings (Fig. 5). Consequently, the

increase of feeling of belonging and pride of being part of the Gellerup community was detected after implementation [11].



Figure 5. Gellerup Park summer neighbourhood activities, Source: https://skraeppebladet.dk/2024/7/sommersjov-i-gellerup-gratis-glaede-for-hele-familien/[n] , https://skraeppebladet.dk/blad/2024-04/gellerup-nu/paa-udkig-i-byparken-efter-sommerfugle-og-insekter/[n]

4.4. Benefits and recognition

Gellerup Park is globally recognized as an exemplary model of residential urban regeneration. Its innovative nature-based design and participatory process earned a nomination for the EUmies Awards 2022 [14] and a feature in the Simon Architecture Prize 2022 [15] for measurably improving safety and social cohesion. Additionally, the project won the European Garden Award 2019/2020 [16] and was nominated for the Green Cities Europe Award 2022 [11] for its climate adaptation. Multiple academic studies [5,17,18] further validate these substantial social and ecological benefits, confirming its success.

Key ecological and socio-cultural benefits achieved through different dimensions of Gellerup park multifunctionality are summarised below:

Table 1. Benefits of Developing Different Dimensions of Multifunctionality in Gellerup Park

		BENEFITS	
		Ecological	**Socio-cultural**
DIMENSIONS OF MULTIFUNCTIONALITY	**Space**	The project integrates nature into the urban area through a new landscape, featuring gentle and natural slopes, water streams and lakes, meadows and hills, making natural elements accessible, while supporting biodiversity.	Benefits are achieved at both area and location level by providing places for people to meet and interact. New paths connect the park with the surrounding areas providing better accessibility .
	Time	Areas of the park are planned as multifunctional, regardless of whether they are green or paved, supporting different activities over time while preserving the ecological value of the space.	Citizens are involved in the life of the park and organize various temporary activities, meetings and cultural events. This diachronic increase of the use of space supports continuity of socialisation.
	Use	The new landscape, with water bodies and gentle and natural slopes suitable for walking, offers opportunities for play, rest, and education for the youngest and reveals natures beauty and value.	The park offers playgrounds, courts, outdoor exercise areas, gardens and greenhouses, and meeting points that attract different users. Sitting, picnicking, and socializing with neighbors is encouraged.
	Service	Water streams and lakes support collecting excess rainwater as a landscape service, while also mitigating the effects of climate disasters, such as heavy rainfall and floods, and enabling significant microclimate optimization.	The project activated and linked the existing green areas, reconnecting residents and creating a new positive image of the area, inducing a greater degree of feeling of belonging .

5. DISCUSSION AND CONCLUSION

Implementing multifunctional solutions through public open space planning and design may bring *multiple benefits to both people and nature*, which is of special importance for reclaiming public open spaces in multi-family housing areas. Diversification of activities enhances attractiveness, use and sociability of POS, while the multiplication of land functions reveals values of Nature, thus supporting the protection of natural elements in the city. When delivered through the engagement of residents, these solutions contribute to building social capital in the neighbourhood.

The Gellerup Park case study serves as an outstanding example of how multifunctional solutions can revitalize neglected public open spaces in modernist urban fabrics, unlocking their potential for climate adaptation while enhancing both the neighborhood environment and residents' well-being. Our research reveals several key insights that form the basis for this contribution. First, the case study demonstrates that when dealing with the vast amounts of underused green open spaces typical of modern urbanism, alongside the urgent need for climate adaptation, all four dimensions of multifunctionality—*time, space, use, and service*—should be integrated into POS development. This approach better connects people with nature and helps harmonize the ecological, social, and economic aspects of sustainability, allowing natural elements and processes to be revealed, appreciated, and utilized for a variety of purposes.

The research also shows that multifunctional solutions can be applied *at different spatial scales and in different types of public spaces*. They are relevant for courtyards, parks, plazas, and communication paths, in which proposed uses and services can be combined for different activities, such as recreation, play, movement, community gathering, wildlife habitat setting, landscaping, and climate adaptation functions. The study reveals that, while multifunctional solutions can be implemented at a single POS location level, the best results are achieved when a systemic view is applied and when they form a part of strategic urban regeneration interventions, aiming to address and harmonize complex environmental and social goals.

Finally, this case highlights the importance of *good communication and collaboration* between public, private, and third sector, including local residents, in all phases of planning, design, delivery and management of multifunctional POS. Through mixed public-private collaborations and extensive participatory process with the local community, the new design of the park was proposed and delivered to enable new uses provided on a permanent and temporary basis, as well as new landscape services aimed to manage water, reconnect people with nature and attract diverse users, thus creating situations in which urban life may flourish.

Taking all this into account, it can be concluded that a multifunctional approach to public open space revitalisation yields diverse environmental and social benefits conducive to multi-family housing regeneration. Understanding POS multifunctionality through a multidimensional lens—incorporating time, space, use, and service dimensions—is essential for its successful application in specific urban scenarios. Future research should investigate the pathways and factors that shape how these multifunctional solutions are implemented across varied urban contexts.

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Research paper

OPTIMIZING URBAN NATURE-BASED SOLUTIONS THROUGH ARTIFICIAL INTELLIGENCE: PROSPECTS FOR THE CITY OF NIŠ

Ljiljana Vasilevska[1], Petar Vranić[2], Tigran Haas[3]

Abstract

Modern smart city concepts are evolving from techno-centric models focused on raw data collection toward ecologically sustainable urban ecosystems. The primary challenge of contemporary urbanism lies in mitigating climate change impacts, particularly the urban heat island (UHI) effect and air quality degradation. This paper explores the potentials of optimizing urban Nature-based Solutions (NbS) and green infrastructure through Artificial Intelligence (AI) and Urban Digital Twins (UDT) as advanced analytical tools. A theoretical framework is established by integrating concepts of intelligent Nature-based Solutions, IoT-based environmental monitoring, digital twin technologies, and generative urban design. Through a comparative analysis of global best practices -specifically Barcelona, Helsinki, and Vienna, the research identifies how AI-supported decision-making can improve environmental monitoring, optimize green infrastructure placement, enhance mobility management, and increase the efficiency of municipal services. The second part of the paper focuses on highlighting the prospective opportunities and open possibilities for the city of Niš, exploring how these global methodologies could address critical local issues such as summer thermal stress and winter air pollution. Rather than proposing an immediately deployable technological solution, the paper develops a conceptual framework for the gradual introduction of AI-assisted ecological planning adapted to local institutional and infrastructural conditions. While a systematic institutional framework for AI urban implementation currently does not exist in the local context, this study highlights the importance of early-stage exploratory research. Such academic inquiry is essential for bridging theoretical data science and local urban planning practice, positioning AI strictly as an analytical assistant for ecological optimization rather than a replacement for human expertise.

Key words: *Artificial Intelligence, Smart Cities, Nature-based Solutions, Digital Twin, Niš.*

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1. INTRODUCTION

Accelerated urbanization and the climate crisis have created an urgent need to transform traditional cities into more resilient and sustainable systems. The first generation of smart cities was frequently criticized for technological determinism, where success was measured by the sheer volume of installed cameras, sensors, and free Wi-Fi zones [1]. However, the contemporary paradigm frames technology strictly as a tool, while the ultimate goal remains sustainability—cleaner air, reduced energy consumption, and an enhanced quality of life for citizens [2].

In this context, Nature-based Solutions (NbS) and green infrastructure are recognized as vital components for reducing urban vulnerability [3, 4, 5]. Integrating vegetation systems, green roofs, and urban forests directly impacts the mitigation of urban heat islands, stormwater management, and biodiversity preservation [3, 5]. Yet, traditional green infrastructure planning often suffers from a lack of empirical, real-time data, leading to the suboptimal placement of greenery.

The emergence of Artificial Intelligence (AI) and Urban Digital Twins (UDT) introduces entirely new capabilities [6, 7, 8]. AI enables the concurrent analysis of numerous variables, identifying hidden spatio-temporal patterns that elude human observation [1]. The objective of this paper is to analyze how these advanced tools can be leveraged to simulate and optimize ecological interventions, with a specific focus on prospective implementation possibilities in the city of Niš.

2. THEORETICAL FRAMEWORK AND METHODOLOGY

This section establishes a tripartite methodological framework that integrates urban ecology with computational design. It systematically links IoT-driven environmental monitoring, digital twin simulation techniques, and generative spatial optimization to form an adaptive matrix for smart urban planning [6].

2.1. The concept of intelligent Nature-based Solutions (INbS)

By bridging ecological engineering and information-communication technologies, the concept of Smart or Intelligent Nature-based Solutions emerges. In this model, green areas are no longer static spatial elements but dynamic systems monitored by a network of IoT sensors [7]. Sensors gather data regarding soil moisture, ambient temperature, and pollutant concentrations, enabling automated resource management (e.g., smart irrigation) and predictive maintenance of urban greenery.

2.2. Urban Digital Twin as a simulation laboratory

An Urban Digital Twin is a digital, working copy of a city or its subsystem, powered by real and continuous data streams [8]. Unlike static 3D models, a digital twin integrates infrastructure, traffic, microclimate, and greenery data into a unified analytical environment [9]. Its core value lies in the capacity to execute "What-if" scenarios.

Through machine learning, a digital twin can simulate the impacts of various urban planning decisions before any physical intervention occurs [6]. For example, planners can virtually route traffic or simulate multi-year tree canopy growth to evaluate their cumulative cooling effects and energy savings within a matter of minutes.

2.3. Generative urbanism and spatial optimization

Generative Design uses AI algorithms to explore thousands of spatial configurations based on predefined parameters [9, 10]. Planners input constraints such as parcel boundaries, traffic accessibility, and environmental standards. The algorithm then generates a spectrum of optimal solutions that balance ecological goals (e.g., maximizing solar exposure and greenery coverage) with structural parameters.

3. TRANSFERABLE PLANNING APPROACHES FROM EUROPEAN SMART CITY PRACTICE

This section reviews selected European smart city initiatives to identify planning approaches and AI-based methodologies that may inform future ecological planning in Niš. The selected cities are not intended as direct benchmarks, but as mature examples from which transferable principles can be adapted to local environmental and institutional conditions. The selected cities represent complementary and well-documented examples of AI-supported urban planning, illustrating different yet interconnected domains of smart urban development: Barcelona in environmental sensing and digital twins, Helsinki in AI-supported mobility management, and Vienna in predictive infrastructure management. Together, these examples provide transferable planning approaches that are particularly relevant to the environmental and institutional context of Niš.

3.1. AI-based planning approaches in Barcelona, Helsinki, and Vienna

Barcelona's model demonstrates the importance of open data architecture. Among other data, the Sentilo platform links temperature, noise, air quality, and parking occupancy data, allowing municipal services to coordinate interventions seamlessly [11]. Through its supercomputing digital twin, the city simulates pedestrian dynamics and maps micro-accessibility to support its "15-minute city" paradigm, preventing ecosystem fragmentation and urban decay by restructuring traffic into localized "Superblocks" [12].

In Helsinki, AI addresses traffic congestion by optimizing multimodal transport in real time through the Whim application and the Mobility-as-a-Service (MaaS) framework [13]. By accurately synchronizing public transit, micro-mobility, and shared fleets, the system increased public transit usage by 12% while reducing private car reliance by 9%. This synchronized transit minimizes dependence on private vehicles, freeing asphalt surfaces that can be repurposed into green micro-locations, urban parks, and permeable spaces.

Vienna utilizes predictive maintenance within its Smart City Wien strategy to prevent public utility failures [14]. By deploying acoustic and pressure sensors across its water and energy grids, machine learning algorithms can detect microscopic structural degradations up to three weeks before a potential rupture occurs. From a sustainable urban management perspective, this approach reduces unnecessary street excavation, lowers greenhouse gas emissions from heavy machinery, prevents clean water loss, and minimizes material waste.

Taken together, these examples illustrate that AI can support urban ecological planning at multiple scales—from neighborhood-level interventions and mobility management to city-wide infrastructure monitoring. Rather than relying on a single technological solution, successful implementation depends on integrating complementary digital tools that address different environmental challenges within a coherent planning framework.

Although these initiatives differ in their technological focus, they share a common planning philosophy: AI is employed not as an end in itself, but as a decision-support tool that enhances environmental performance, resource efficiency, and the long-term resilience of urban systems. This common perspective provides the conceptual basis for considering how similar planning principles could be adapted to different local contexts.

As a synthesis of these examples, Table 1 summarizes how different AI-based planning approaches translate technological capabilities into ecological and functional benefits, highlighting transferable principles that may inform future urban interventions.

Table 1. AI-Based Planning Approaches in Selected European Cities

City	Technological Platform / Model	Primary Ecological and Functional Benefit
Barcelona	*Sentilo* open platform & supercomputing digital twin	Pedestrian flow mapping and "15-minute city" optimization via Superblocks.
Helsinki	*Whim* application & MaaS (*Mobility-as-a-Service*) system	Synchronization of public transit, reducing private car usage by 9% and cutting CO2 emissions.
Vienna	*Smart City Wien* predictive maintenance sensor network	Early detection of microscopic damages in water supply and energy grids.

Despite their technological sophistication, the success of these cities does not primarily stem from AI itself, but from the integration of AI within coherent planning institutions, environmental policies, and long-term urban strategies. Technology alone does not create sustainable cities; rather, it enhances planners' and decision makers' capacity to implement evidence based interventions within a clear ecological and governance framework.

4. DISCUSSION: AN APPLICATION FRAMEWORK FOR THE CITY OF NIŠ

Building upon the transferable planning approaches discussed in the previous section, this chapter explores how AI-based methodologies could be adapted to the specific urban context of Niš. Rather than proposing a fully operational deployment scheme, it presents a conceptual framework that identifies priority application areas

and potential implementation pathways under existing local institutional and infrastructural conditions. Given the current capacities, implementing AI through pilot projects and localized interventions appears more realistic than the immediate development of a comprehensive city-wide Urban Digital Twin.

As an initial implementation step, pilot applications could focus on selected urban areas characterized by pronounced environmental challenges, including the central urban area, densely built residential neighborhoods affected by the urban heat island effect, and major traffic corridors with persistent congestion. The proposed framework would primarily rely on publicly available satellite imagery, municipal air quality monitoring data, traffic counts, GIS databases, and environmental sensor data where available. Its implementation would require interdisciplinary cooperation among the City Administration of Niš, relevant public utility companies, urban planning institutions, and academic and research organizations, including the University of Niš. Such a phased approach would enable the gradual validation of AI-supported planning methods before considering the future development of a comprehensive Urban Digital Twin.

This implementation pathway reflects the current institutional capacities while creating opportunities for future integration of environmental monitoring, spatial analytics, and AI-assisted decision support into everyday urban planning practice. In this way, the proposed framework is intended to serve not as a fixed technological model, but as a flexible planning concept that can gradually evolve in parallel with the development of local data infrastructure, institutional cooperation, and digital governance capacities.

4.1. AI- driven Nature-based Solutions placement against urban heat islands

During summer heat waves, highly sealed areas within the urban core and dense commercial zones of Niš experience substantial thermal stress due to the urban heat island effect, whereas peripheral green areas display significantly lower baseline temperatures. Training machine learning models on land surface temperature (LST) data derived from satellite imagery could assist planners in pinpointing precise thermal hotspots and micro-locations where green interventions would yield the highest environmental relief [15].

Instead of traditional, arbitrary landscaping, generative urbanism simulations could test how targeted green corridors, vertical greenery on public buildings, or localized pocket parks within the dense city center could potentially reduce local surface temperatures by approximately 2–3°C under favorable conditions. This data-driven approach theoretically optimizes ambient cooling, mitigates localized thermal stress, and reduces building energy consumption required for air conditioning during extreme heat waves.

Crucially, this computational approach is of significant value during the initial phases of urban planning, where predictive modeling can guide the allocation of land-use zones and the optimal distribution of public areas. Furthermore, this method serves as an essential tool in urban regeneration processes [16] within inherited, highly built-up environments. By simulating ecological thresholds beforehand, planners can prevent excessive construction density, control population concentration overgrowth, and

ensure that infrastructural re-development does not compromise the local microclimate.

4.2. Predictive air quality management and smart forestry

Winter seasons in Niš are heavily impacted by critical spikes in particulate matter ($PM_{2.5}$ and PM_{10}), particularly within high-density residential zones characterized by low aeration and a prevalence of individual heating units. Traditional monitoring networks provide only descriptive, historical records of pollution. By utilizing AI algorithms to synthesize historical emission patterns, real-time climate telemetry, and terrain topography, the city can transition to a predictive environmental model [17].

In terms of functional application, this framework is highly relevant for urban forestry management and local ecological zoning. Predicting severe pollution accumulation 24 hours in advance allows municipal authorities to optimize the operational scheduling of public infrastructure. More importantly, long-term predictive data allows urban planners to strategically locate and design multi-layered green buffer strips and specific tree-canopy structures that maximize the bio-filtration of airborne particulates. This approach embeds environmental analytics directly into municipal public health strategies, transforming static park planning into an active micro-climate defense system within endangered residential areas.

4.3. Ecological traffic optimization and green corridor integration

Primary traffic arteries and chronic congestion points across the urban matrix serve as major localized sources of greenhouse gases and acoustic pollution. Implementing AI-driven computer vision systems at strategic intersections presents an analytical opportunity to mitigate these footprints. By analyzing vehicle counts and queue lengths in real time, traffic signals can dynamically adjust green light phases based on actual volume, minimizing vehicle idling and reducing exhaust emissions directly at major bottlenecks [18].

In terms of urban design, this computational approach is invaluable for developing Sustainable Urban Mobility Plans (SUMPs) and planning linear green infrastructure. Real-time and predictive traffic load mapping provides planners with empirical data to justify the conversion of redundant asphalt surfaces into permeable green shoulders, linear parkways, and pedestrian zones. Instead of treating transport infrastructure as an ecological dead zone, AI analytics enable the seamless integration of transit networks with urban green corridors. This reduces the fragmentation of urban ecosystems and minimizes the ecological footprint of transport networks inside the inherited urban fabric.

4.4. The role of an Urban Digital Twin as an integrative core

The localized AI applications described above—thermal mapping, predictive air quality modeling, and traffic flow optimization—should not operate as isolated, fragmented software systems. Instead, the ultimate prospective goal for a city like Niš would be their gradual synthesis within a unified Urban Digital Twin (UDT) framework.

An Urban Digital Twin serves as the integrative computational core that merges real-time environmental telemetry with 3D spatial geometry [19].

In the context of nature-based solutions, this platform acts as an interactive simulation laboratory where cross-sectoral impacts can be analyzed simultaneously. For instance, instead of evaluating a traffic intervention solely by its impact on vehicle speed, the digital twin allows planners to instantly visualize how altering traffic patterns correlates with reductions in particulate matter concentrations and localized surface cooling within neighboring green pockets. This technological integration transforms urban planning from a reactive process based on static, historical records into a dynamic, predictive science capable of evaluating complex socio-ecological feedback loops before any physical resources are deployed.

4.5. Critical reflection on the local institutional framework

It is critical to emphasize that a systematic, institutional, or regulatory framework for the deployment of AI or Urban Digital Twins in urban planning and public utility management currently does not exist in Niš or at the national level. The concepts outlined above remain prospective, theoretical suggestions based on global engineering methodologies.

However, exploratory academic papers of this nature are highly significant for several reasons. First, they establish the necessary theoretical groundwork and bridge the gap between advanced data science and practical urban design. Second, they prevent techno-centric path-dependency by defining ecological and human-centric priorities *before* physical technology procurement begins. Finally, they demonstrate how localized academic research can lay the foundation for future data-driven policy, ensuring that upcoming smart-city initiatives are driven by rigorous scientific parameters rather than commercial technology trends.

5. SOCIO-TECHNICAL, INSTITUTIONAL LEGAL, AND ETHICAL CHALLENGES

Implementing AI-driven ecological urbanism is not merely a technological acquisition; it introduces profound governance and ethical complexities. To successfully ground these conceptual models in reality, several critical challenges must be addressed concurrently:

- **Data Quality and Institutional Fragmentation**: The predictive accuracy of any AI or digital twin model depends entirely on high-quality, up-to-date data. Currently, spatial, utility, and environmental datasets in Serbia are fragmented across various public enterprises, municipal secretariats, and directorates. Overcoming this socio-technical barrier requires the establishment of strict, open data-sharing protocols and clear institutional accountability for maintaining cross-sectoral data integrity [20].
- **Privacy and the Ethical Boundary of Urban Surveillance**: To optimize traffic flow and environmental metrics, smart city frameworks require a continuous spatio-temporal data stream, which naturally raises legitimate public concerns regarding citizen surveillance. The ethical boundary is crossed when a municipality collects

excessive personal data, uses it for unannounced tracking, or fails to define transparent retention limits. To align with the European Union's *AI Act* and local data protection regulations, cities must enforce anonymized edge computing. For instance, AI-driven traffic cameras do not need to capture license plates or facial biometrics; they only require vehicle counts, velocities, and queue lengths processed locally at the intersection level, thereby safeguarding citizen privacy [21].

- **Algorithmic Bias and the Preservation of Urban Identity**: AI algorithms are not inherently neutral tools; they optimize exclusively for the specific parameters and mathematical goals defined by their programmers. If an algorithm is tasked solely with maximizing real estate floor-area ratios or traffic throughput, it will inevitably generate a mathematically perfect yet unlivable space. AI completely lacks empathy, historical context, and an understanding of cultural heritage—elements that comprise the historical and cultural identity of an inherited urban fabric. Therefore, AI must strictly serve as an expert analytical assistant, while final evaluation, value-based synthesis, and holistic decisions remain the sole responsibility of human urban planners [22].

6. CONCLUSION

The integration of Artificial Intelligence and Nature-based Solutions represents a paradigm shift toward data-driven, climate-resilient urban planning. Global examples confirm that technology is most effective when deployed to address tangible urban and environmental challenges rather than serving as a political showcase. For the city of Niš, utilizing exploratory scientific modeling and pilot testing targeted AI concepts—such as predictive green infrastructure placement and dynamic traffic management—offers a realistic pathway toward mitigating severe microclimatic and air pollution challenges. A phased implementation based on pilot projects and interdisciplinary institutional cooperation represents the most feasible approach for introducing AI-supported ecological planning under current local conditions.

The proposed framework is intended to support evidence-based decision-making by integrating environmental data, spatial analysis, and AI-assisted planning simulations into the planning process. Although its practical implementation will depend on the gradual development of local digital infrastructure and institutional capacities, the framework provides a realistic foundation for future research, pilot applications, and interdisciplinary collaboration in climate-resilient urban planning.

Ultimately, the success of a smart city is not measured by its digital sophistication, but by the clean air, green spaces, and sustainable living environment it secures for its citizens. Accordingly, the future of smart cities should be understood less as a technological project than as an ecological and human-centered planning paradigm, in which digital intelligence supports—rather than replaces—the professional judgment of urban planners.

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Research paper

NEIGHBOURHOOD IMPROVEMENT DISTRICTS AS A GOVERNANCE MODEL FOR PUBLIC OPEN SPACES IN LARGE HOUSING ESTATES: LESSONS FROM HAMBURG AND OPPORTUNITIES FOR SERBIA

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Abstract

Large housing estates (LHEs) built during the socialist period remain a dominant element of post-socialist cities in Central and Eastern Europe, accommodating a significant share of urban populations. Despite their originally high-quality planning – characterized by high-density housing and extensive public open spaces (POS) – these areas have undergone profound transformations during the post-socialist transition. Overall transformations have contributed to the reduction, degradation, and unclear governance of POS, creating long-term management challenges. Contemporary POS governance increasingly emphasizes collaborative approaches, including Public-Private-People Partnerships (PPPP) and area-based instruments such as Business Improvement Districts (BIDs) and Neighbourhood Improvement Districts (NIDs). These models introduce collective financing and shared responsibility for neighbourhood improvements, offering potential solutions for fragmented post-socialist governance contexts. This paper analyses the Neighbourhood Improvement District (NID) model and assesses its applicability to the management of POS in inherited LHEs in Serbia. A comparative case study approach is applied, focusing on Steilshoop (Hamburg), where the NID model has been implemented, and Krive Livade (Niš), representing a typical Serbian socialist-era housing estate with unresolved ownership and fragmented institutional responsibilities. Findings indicate that the NID model relies on an enabling legal framework, clearly defined property ownership, and structured stakeholder cooperation. The study concludes that full implementation of the NID model in Serbia is not currently feasible; however, selected principles could be adapted through hybrid Public–Private–People governance arrangements.

Key words: *Neighbourhood Improvement District (NID), Public Open Space (POS), POS management, Large Housing Estate (LHE), Serbia*

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1. INTRODUCTION

Large housing estates (LHEs) built during the socialist period remain a defining feature of post-socialist cities in Central and Eastern Europe, accommodating a substantial share of the urban population—around half of all residents in many cities and in some cases, such as Bucharest, over 80% [1]. Developed according to the principles of modernist urban planning, these neighbourhoods combined high-density housing with generous public open spaces (POS) and extensive green areas. The transition from a centrally planned to a market-oriented economy in the 1990s triggered rapid institutional, legal, and ownership transformations that fundamentally changed the governance of urban land and housing.

One of the most significant consequences of these changes has been the gradual transformation of public open spaces within LHEs. Processes such as housing privatization, land restitution, infill development, commercialization of ground floors and others have contributed to the fragmentation and reduction of green spaces, the introduction of vehicular traffic into previously pedestrian environments, and the privatization or informal appropriation of public land [2,3]. As ownership structures became increasingly fragmented, both within residential buildings and across the open spaces between them, the allocation of responsibility for the management and maintenance of POS became increasingly problematic. Consequently, the quality and long-term sustainability of POS in inherited LHEs represent one of major challenges for contemporary urban development in post-socialist cities.

These challenges have renewed interest in innovative governance models capable of ensuring the long-term management of public open spaces. Rather than relying exclusively on local governments, contemporary approaches increasingly promote collaborative governance based on partnerships between public authorities, private stakeholders, and local communities. Within this context Business Improvement Districts (BIDs), i.e., Neighbourhood Improvement Districts (NIDs), have emerged as promising governance mechanisms that combine collective financing with institutional cooperation to improve the quality of neighbourhood environments.

The aim of this research is to identify the main characteristics of Neighbourhood Improvement District (NID) model, and to examine the possibilities for applying this governance approach to public open spaces of inherited LHEs in Serbia. The paper analyses the Steilshoop housing estate in Hamburg as one of the first residential neighbourhoods implementing the NID concept, which illustrates the complexities of managing public open spaces within a fragmented ownership structure and through collaborative governance mechanisms. Particular attention is given to differences in legal frameworks and land ownership structures that influence the feasibility of introducing a similar model in the Serbian context.

2. METHODOLOGY

The paper examines the Neighbourhood Improvement District (NID) model to identify its key characteristics and assess its potential for application in the management of public open spaces in inherited LHEs in Serbia. It first provides an

overview of POS governance models, before focusing on the NID model based on collaboration between public authorities and private property owners.

For the purposes of this study, two case studies were selected: Steilshoop in Hamburg, Germany, where the Neighbourhood Improvement District (NID) model has been implemented, and Krive Livade in Niš, Serbia, representing a typical socialist-era large housing estate facing unresolved governance and ownership challenges.

The Steilshoop case is analysed to identify the institutional prerequisites for implementing the NID model, including the legal framework, land ownership structure, organizational arrangements, stakeholder responsibilities, and financing mechanisms. To assess the transferability of this model to the Serbian context, the study examines the legal and institutional framework, together with the ownership structure of land in inherited large housing estates in Serbia. Ownership analysis is based on cadastral data obtained from the Republic Geodetic Authority of Serbia (RGA) and examines land ownership, property rights, and the distribution of management responsibilities within the study areas. The comparative analysis identifies institutional gaps and opportunities for adapting selected NID principles within the current Serbian governance system.

3. POS MANAGEMENT ORGANIZATIONAL MODELS

Public open space (POS) management can be organized through three main governance models: state-centred, market-centred, and community-centred [4]. These models differ in the way responsibilities for coordination, regulation, maintenance, and investment are allocated among stakeholders and are equally relevant for residential public open spaces. In practice, these governance models rarely operate independently. Contemporary POS management increasingly relies on hybrid arrangements that combine public, private, and community actors.

In the state-centred model public authorities are responsible for POS planning, provision, and maintaining, with limited involvement of private or voluntary actors [5].

The community-centred model delegates management responsibilities to community organizations, resident associations, and other non-profit groups. The model is closely associated with participatory governance, co-production of public services, and the growing role of civil society in urban management.

The market-centred model transfers management responsibilities, though not necessarily ownership, from the public sector to private actors. Management may be delivered through service contracts, outsourcing arrangements, or development agreements. The primary objectives are to improve efficiency, reduce costs, and introduce specialized expertise. Public-private partnerships (PPPs) represent a common form of market-centred governance.

Market-centered models include Business Improvement Districts (BIDs), where private stakeholders collectively finance improvements through mandatory levies. BIDs are commonly described as self-financing districts established at the initiative of property owners or local businesses. Operating within a legal framework defined by state legislation and authorized by local governments, they are responsible for delivering supplementary public services within designated urban and suburban areas

[6]. Governed by voluntary boards of directors, BIDs typically undertake activities such as street maintenance, public safety, infrastructure improvements, and urban design initiatives, thereby contributing to the overall quality and attractiveness of urban environments [7]. Originally developed in the United States, BIDs have been widely adopted across Europe and have also influenced urban regeneration initiatives in Serbia [8,9]. The BID concept has subsequently been adapted to residential neighbourhoods through the Neighbourhood Improvement District (NID) model, first implemented in Steilshoop, Hamburg. The literature indicates that successful implementation of BID/NID models depends not only on financial mechanisms but also on clearly defined ownership structures and an enabling legal framework.

4. CASE STUDY STEILSHOOP NID, HAMBURG

4.1. Urban Context

Steilshoop is a large housing estate located in the north-east of Hamburg, developed during the 1970s as part of the "urbanity through density" concept [10]. With approximately 6,380 dwellings and more than 14,000 residents, it is one of Hamburg's largest post-war housing developments. Around 75% of the housing stock was originally constructed as publicly subsidized housing with rent controls and income-based occupancy restrictions.

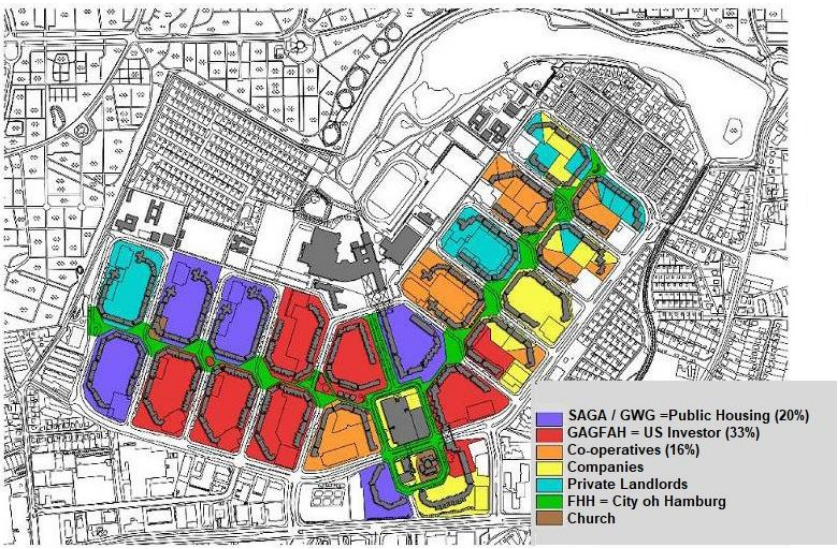


Figure 1. Property relations in Steilshoop, Source: http://archive.northsearegion.eu/ivb/projects/details/&tid=82&back=yes

Despite relatively high housing standards, extensive open spaces, and early community participation initiatives, Steilshoop gradually experienced social and physical decline, accompanied by the deterioration of its public spaces [11].

In 1990s Steilshoop was designated as an urban regeneration area under German federal legislation. More than €13 million of public funding was invested in upgrading

public spaces, community facilities, playgrounds, schools, sports facilities, and parts of the central pedestrian zone. Shortly after the regeneration programme ended, problems re-emerged, particularly regarding the negative image of the neighbourhood and the maintenance of public spaces in the central area [12].

Following the privatization of public housing companies in the early 2000s, the ownership structure became increasingly fragmented. The privatization of GAGFAH, one of the main public housing providers and owner of approximately 34% of the housing stock, significantly transformed the ownership structure, which is now divided among public housing associations, private companies, cooperatives, and individual owners [12].

4.2. Legal and Institutional Framework

Hamburg was the first German federal state to introduce legislation for Business Improvement Districts (BIDs) in 2005 - The Law on Strengthening Retail, Service, and Commercial Centres [12,13,]. Following amendments to the Federal Building Code in 2007 - new paragraph regarding private initiatives in urban development - federal states were authorized to adopt legislation supporting private initiatives in urban development. Hamburg subsequently introduced legislation enabling the transfer of the BID concept to residential areas through the Neighbourhood Improvement District (NID) model - the Law on Strengthening Residential Neighbourhoods through Private Initiatives in 2007. The law applies in two spheres: (1) innovation in retail, service, and commercial centres (*Innovationsbereiche* - innovation areas), and (2) the quality of housing and living in residential neighbourhoods (*Innovationsquartiere* - innovation quarters). The law regulates the following provisions: establishment of NID, task operators, application procedure, steering committee, implementation, monitoring, levy collection, and use of funds. Similar to BIDs, NIDs rely on mandatory contributions from property owners, a formal voting procedure, and a limited implementation period. Activities may include public space improvements, enhanced cleaning, landscaping, security measures, playgrounds, local services, and neighbourhood marketing [14].

The NID process can be divided into four stages: (1) initiation, (2) preparation of a business and financing plan, (3) formal application, audit, and approval by public authorities, and (4) collection of the levy and NID implementation [15]. While local authorities provide expertise and ensure consistency with public interests, property owners initiate and finance the process. A dedicated management body oversees implementation, while a steering committee supervises activities. NIDs are time - limited and may only provide services additional to those already delivered by public authorities [15].

4.3. NID Implementation

In 2006, major property owners initiated discussions on improving the neighbourhood's image. Simultaneously, Hamburg's Ministry of Urban Development proposed establishing Steilshoop as a pilot NID project and offered co-funding for

public-space improvements [12]. A steering committee was established in 2007, bringing together commercial property owners, municipal representatives, and external experts. Between 2007 and 2010, the committee held more than 30 meetings focused on place-making and place-keeping strategies. As comprehensive redevelopment projects proved financially unfeasible, priority was given to the maintenance of the central pedestrian zone. The analysis identified two major problems: fragmented responsibilities between the public and private sectors (approximately 60% public and 40% private land ownership), and insufficient communication among stakeholders [12]. To address these issues, a coordinated maintenance strategy was introduced. Stakeholders agreed to clarify responsibilities, improve cooperation, coordinate maintenance activities, and involve residents more actively. The pilot period resulted in a business plan for the residential area, including key actions such as upgrading the pedestrian zone, improving communication among residents, owners and stakeholders, developing a marketing campaign to enhance the area's image, and improving local cleansing and maintenance services [16]. Most actions were implemented within existing public and private budgets, without substantial additional funding.

The initiative showed that significant improvements could be achieved through better coordination rather than major new investments. However, it also revealed limitations, including reluctance among property owners to support mandatory levies, complex communication due to fragmented ownership and multi-level decision-making, and reliance on individual commitment and long-term cooperation. After the pilot phase ended in 2011, Steilshoop continued to operate, supported financially by one of the main real estate funds and in 2012, it officially became the first HID (Housing Improvement District) in Germany and Europe [13,16].

5. POSSIBILITIES FOR APPLICATION IN SERBIA

The Steilshoop case demonstrates that the implementation of the BID/NID model requires an enabling legal framework, but is initiated by local property owners and residents. Accordingly, the following section examines the legislative framework in Serbia and ownership structure of public open spaces in LHEs , using the Krive Livade neighbourhood as a case study.

5.1. Legal framework

Unlike Germany and the City of Hamburg, where the establishment of the NID model is supported by a dedicated legal framework, Serbia lacks specific legislation governing neighbourhood-based improvement districts. Instead, the legal basis for public open space management is dispersed across several laws regulating institutional responsibilities, land status, financing mechanisms, and public–private partnerships.

The Law on Planning and Construction [17] distinguishes "areas of public use" and "areas of other use". "Areas of public use" are designated by the planning document for the arrangement or construction of public purpose facilities or public areas and they refer to publicly owned land. The development of construction land is

financed through development contributions, land rents, land sales or exchanges, conversion of lease rights into ownership, and other legally prescribed sources. Regarding multi-family housing, the law distinguishes (1) residential complex, (2) residential block, and (3) condominium. Land ownership and responsibility for POS management are clear only in the case of condominiums, which are a relatively new form of construction in Serbia. In the case of inherited residential complexes/blocks, the ownership and management responsibilities are still unresolved. The law also defines the term "land for regular use of the building", as the land under the building and the land around the building, which meets the requirements for a construction plot and which, becomes a cadastral plot through the procedure carried out in accordance with the law.

The ownership, use, financing, and maintenance of land for the regular use of residential buildings are regulated by the *Law on Housing and Building Maintenance* [18], which defines the rights and obligations of apartment owners and housing communities in this regard. The maintenance of public green spaces and the cleanliness of public areas are defined as communal activities under the *Law on Communal Activities* [19].

The *Law on Restitution of Seized Property and Compensation* [20], regulates the return of confiscated property and compensation for property nationalized after 1945, including undeveloped construction land in public ownership, while excluding land occupied by public areas or designated for public facilities from restitution.

Public-private partnerships and concessions are regulated by the *Law on Public-Private Partnerships and Concessions* [21], which establishes the legal framework for PPPs and defines the rights and obligations of the contracting parties.

Although NIDs rely on public-private cooperation, they differ from conventional PPPs governed by Serbian law, as they are statutory area-based governance and financing instruments rather than contractual arrangements. NIDs may also be viewed as a Public-Private-People Partnership (PPPP), bringing together public authorities, property owners, businesses, and local communities. However, the collaborative dimension of PPPP should be distinguished from the legal and institutional mechanisms that enable NIDs to operate.

5.2. Land ownership in inherited LHEs: The Case of Krive Livade, Niš

Krive Livade neighbourhood in Niš was selected as a case study to investigate land ownership in inherited LHEs in Serbia. As part of the city's largest socialist-era housing estate, it illustrates how fragmented ownership and unresolved property rights impede the integrated management of public open spaces. As in other inherited LHEs, the large-scale privatization of housing was carried out during the 1990s, while the restitution process has yet to be fully completed. As a result, housing ownership is now predominantly private, whereas the legal status of open spaces remains unresolved. The land beneath residential buildings is designated as separate cadastral parcels that remain predominantly under public ownership, despite the fact that nearly 100% of the apartments are privately owned. The land for regular use of the buildings has not been formally established. Consequently, apartment owners hold ownership rights only over

their individual units and have no legal rights to either the land beneath the buildings or the surrounding land. In addition, the legal status of ground-floor commercial premises formerly held under social ownership remains unresolved.



Cadastral parcels (built / unbuilt) forming part of public open spaces

Type of right to the land	Ownership type
ownership / right of use	state RS
ownership / right of use	private / state RS
ownership / right of use / leasehold right to construction land	public / state RS
ownership / right of use	public /state RS
ownership / right of use / holder	public / state RS / private
ownership	public
ownership / holder	state RS
ownership / right of use / holder	state RS / private
ownership / right of use	state RS
ownership	private
ownership / holder	public / state RS / private
ownership / holder	public / state RS / mixed
ownership / holder	public / state RS / social

Cadastral parcels not forming part of public open spaces (fully built-up or fenced)

Land use	Type of right to the land	Ownership type
residential 100% plot coverage	ownership	public
non-residential 100% plot coverage	ownership	public
public service(kindergarten) enclosed plot	ownership / right of use / holder	public / state RS / private

Figure 2. Property relations on land in Krive Livade, Source: Authors, based on data from the Republic Geodetic Authority (RGA)

Most of the neighbourhood's public open spaces are located on two large cadastral parcels characterized by multiple forms of ownership and different types of land rights (Figure 2). While the northern parcel is entirely under public ownership, the southern parcel is characterized by a complex ownership structure, including different types of land rights (ownership, right of use, and holder) and ownership forms (public, state, and private). The remaining public open spaces also exhibit a complex ownership structure.

Responsibility for the construction and maintenance of open spaces lies within the public sector but is institutionally fragmented. The maintenance of greenery is carried out by the municipal public utility company, while the development, upgrading, and furnishing of public areas fall under the jurisdiction of the Directorate for Construction.

The ownership pattern illustrates the fragmented and unresolved legal status of both built and unbuilt land within LHE, creating a major obstacle to the establishment of integrated models for the management of public open spaces. The division of responsibilities among different public bodies further complicates the coordinated management and long-term improvement of POS.

5.3. Serbian pathway towards NID

Given the absence of dedicated NID legislation in Serbia, a phased implementation strategy appears to be the most appropriate approach. The first phase should focus on strengthening institutional cooperation among municipalities, housing communities, public utility companies, and major property owners, while establishing voluntary pilot neighbourhood management bodies. The second phase should test the applicability of the NID concept through pilot projects supported by a combination of municipal

funding, voluntary property-owner contributions, EU programmes, and corporate social responsibility initiatives. These pilots should be systematically evaluated against criteria such as governance performance, maintenance quality, financial sustainability, and resident satisfaction. Based on these evaluations, dedicated legislation could establish statutory NIDs with clearly defined governance, financing, participation, and levy mechanisms, supporting evidence-based implementation across Serbia.

6. CONCLUSIONS

An analysis of the Steilshoop case in Hamburg and the current legal framework of the Republic of Serbia indicates that the full statutory NID model cannot currently be implemented in Serbia due to the absence of dedicated legislation. Furthermore, the fragmented ownership structure and complex property rights to POS in inherited LHEs make it difficult to clearly allocate rights and responsibilities for their maintenance and improvement.

In Hamburg, the NID is a legally regulated statutory neighbourhood governance and financing instrument through which property owners collectively finance and manage neighbourhood improvements within a defined area. Although Serbia's Law on Public-Private Partnerships and Concessions provides a general framework for cooperation between public and private actors, it does not establish a legal basis for neighbourhood-based improvement districts or mandatory area-based contributions from property owners, which are the core financing mechanism of the NID model. Despite these limitations, several NID principles could be implemented under the existing legal framework through a hybrid PPPP model, based on a contractual partnership between the public and private sectors, while residents („People“) would participate through housing communities, neighbourhood associations, public consultations, participatory budgeting, and monitoring, thereby contributing to decision-making, implementation, and oversight of neighbourhood improvements. Pilot projects could serve to test the feasibility and effectiveness of the NID concept in Serbia. However, its full implementation would require dedicated legislation establishing NIDs with clearly defined governance, financing, and participation mechanisms.

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Research paper

CITIZEN ENGAGEMENT IN RECLAIMING PUBLIC OPEN SPACES IN MULTIFAMILY HOUSING: CASE OF BLOCK 37, NEW BELGRADE

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Abstract

The revitalization and enhancement of public open spaces contribute to sustainable urban development by transforming neglected areas into vibrant community hubs and welcoming green spaces, thus bringing benefits to both people and nature. Citizens play an increasingly vital role in achieving this goal, especially within multifamily housing areas where vast, underused and neglected public open spaces reflect the systemic problems of how these spaces are planned, designed, and managed. This shift requires supporting citizen participation in the planning and design processes, as well as encouraging local communities to actively engage in the transformation of their residential environments. Literature recognizes that citizens' active participation, meaningful engagement, and the effectiveness of their initiatives depend on a variety of factors, but little is known about how these factors operate in a specific development setting. Understanding this is especially important in the context of post-socialist development in which institutional and organizational barriers to formal public participation exist.

This paper explores potential for the engagement of citizens in reclaiming public open space in the context of Serbia as a post-socialist country, where inherited mass housing estates face the challenges of densification and degradation of common open spaces. By employing a case study methodology and action research approach, the paper presents and critically analyses a best-practice example of citizen engagement in the revitalization and protection of public open spaces in Block 37 in New Belgrade. It explores the context, process, actors, and results of the residents' engagement to identify engagement modalities, thereby highlighting the factors of effectiveness to help improve urban planning and public open space management. The results indicate that both pro-active and re-active modalities of citizen engagement are important, and that trust, good community organization, the role of expert-citizens, and the use of digital technologies were the key factors of success.

Key words: *public open space, citizen engagement, multifamily housing, New Belgrade*

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1. INTRODUCTION

While quality public open spaces (POS) are globally recognized as a key component of resilient and sustainable urban development, the existence of vast, underused and neglected common spaces— typical of modernist housing blocks —highlights the systemic problem of how these spaces are planned, designed, and managed [1,2].

At the same time, even when not in active use, public open spaces hold significant value for residents of multifamily housing estates, who perceive them as an essential factor in their quality of life. Consequently, POS-related issues can motivate residents to engage in their protection, enhancement, activation, and maintenance, through both formal and informal channels[3].

Having this in mind, in both theory and practice, citizens are recognized as an important factor in reclaiming public open spaces, especially at the local level. Studies have shown that when citizens are actively involved in their management, sense of ownership and stewardship is enhanced [4]. Citizen engagement accelerates positive change, enhancing environmental adaptability and boosting overall resilience [5,6]. But, it is also acknowledged that their engagement and the effectiveness of the results depend on variety of factors, which Landa-Oregi et al. [5] classify as individual, collective and institutional.

However, little is known about how these factors operate in a specific urban and development context. This is especially important in the context of post-socialist countries, such as Serbia, in which democratic institutions are not fully developed, and where many barriers to formal public participation exist. Inherited multi-family housing estates, largely built during the socialist period, are often degraded and fail to meet residents' needs, while the key barriers to effective citizen participation in Serbia include administrative complexity, insufficient institutional capacity, and limited awareness of participatory rights among residents [7].

And yet, some examples of best- practice in citizen engagement exist, which, within this limiting institutional context, manage to produce effective results and enhance the quality and meaning of residential public open spaces. In this paper, Block 37 in New Belgrade will be analyzed as such a practice example of citizen engagement.

The aim of the paper is to identify the modalities and highlight the factors that support effective citizen engagement for reclaiming POS in multifamily housing in the context of Serbia. To accomplish this goal, the study employs a case study methodology and action research approach to explore the context, process, actors and results of community engagement in the case of Block37.

2. THEORETICAL FRAMEWORK FOR UNDERSTANDING CITIZEN ENGAGEMENT IN RECLAIMING PUBLIC OPEN SPACES

In contemporary urban planning, citizen participation is recognized as basis of inclusive and sustainable urban development. It encompasses a spectrum of engagement, ranging from consultation to co-design, co-decision-making, and self-management of common spaces [1]. In relation to public open spaces, it is assumed

that citizen participation and engagement represents a central prerequisite for the successful (re)creation, revitalization, and long-term management of POS, particularly within multi-family residential neighborhoods[7,3].

From the relational socio-spatial perspective [8], public open spaces are understood as socially produced and continuously transformed spaces "*whose quality, usability, and sustainability depend on everyday practices, needs, and values of their users*" [1]. Within this framework, citizen participation and engagement forms are not limited to consultation during formal planning procedures but encompasses a broader spectrum of collaborative processes that link planning, design, implementation, and maintenance [1]. They relate to formal, NGO-mediated and grassroots activities [7] reflecting the key actors in these processes: public institutions and officials, NGO's and local communities.

Citizen engagement in POS regeneration transforms underutilized areas into vibrant hubs by shifting power to local residents. This inclusive "bottom-up" approach ensures public spaces reflect community needs, tackling environmental challenges through protection and enhancement of green spaces, while fostering a strong sense of ownership and care [3]. In this way linking citizen engagement with POS management enables cities to develop spaces that enhance social cohesion and identity while concurrently promoting ecological regeneration and green infrastructure growth [6, 7]. Besides community based policy innovations, technological advancements are also recognized as pivotal in achieving effective POS management [4].

Effective engagement of citizens depends on numerous factors, which Landa-Oregi et al. [5] classify as individual, collective and institutional. *Individual factors* are grouped into four categories: personal contribution, self-benefit, pressure, and personal characteristics. *Collective factors* fall under the category of collective interactions and encompass community-centered motivation, sense of belonging, sense of place, human connection. Finally, *institutional factors* are classified into process clarity, process design, administrative or legal factors and accessibility factors. The authors suggest that personal interest, personal knowledge and human connection stand out as the most relevant factors. Furthermore, they identify emerging factors, including trust, transparency, power structures, information, communication, safety and digital divide, anticipating that their significance will increase in the coming years.

Community engagement theories link personal, collective, and institutional issues, emphasizing that trust among actors is fundamental to their willingness to take action. Additionally, they acknowledge that motivation depends on outcome expectancy, suggesting that positive outcomes from past projects foster continuous citizen engagement in the future [9].

3. METHODOLOGY

To examine the modalities and success factors of citizen engagement in reclaiming public open spaces (POS) within a post-socialist context, this study employs a qualitative case study methodology combined with an action research approach. The research focuses on Block 37 in New Belgrade, a modernist superblock that provides an empirical example of shifting pro-active and re-active community initiatives.

The methodological framework consists of three main components:

a) Case Study Design: The study analyzes the evolution of citizen engagement by investigating four interrelated dimensions: context, process, actors, and results - to map the shift from informal community interventions to organized institutional resistance and subsequent formalization.

b) Content and Document Analysis: A comprehensive review of regulatory, planning, and media documents was performed to build a reliable timeline of events. This includes formal urban planning documents, legal regulations, institutional programs and project designs (all specified in case-study), digital materials from public media, and the official "Blok 37" association platform as a key source of citizen-led data.

c) Action Research and Field Observations: The action research approach was facilitated by the direct, long-term involvement of one of the co-authors (P. Jovanović) as an active resident and one of the initiators of the Block 37 community actions. This insider perspective allowed for deep, longitudinal tracking of the project's life cycle and provided direct access to community dynamics. These insights were documented through meeting minutes, field notes and photo-documentation.

We analyzed the gathered qualitative data against the established theoretical framework. This combination of insider action research and external document analysis provides a critical reflection on the effectiveness of grassroots spatial reclamation in restrictive institutional environments.

4. CITIZEN ENGAGEMENT IN PRACTICE: CASE OF BLOCK 37, NEW BELGRADE

Block 37 is a modernist neighborhood (17 ha, 5658 NR) is located in the central area of New Belgrade, as a part of the so called Third region. It is one of the oldest superblocks in New Belgrade, which beside residential buildings also houses the elementary school and kindergarten. During time, Block kept its initial urban structure, characterized by a *large central open space* planned for sport, rest and play [10] (Fig.1). Following the post-socialist changes in ownership and maintenance, during the last decade of 20th, this space became devastated and underused.

The need for a better housing environment motivated residents to take action to improve and protect their public spaces. In following section, different phases of community engagement in reclaiming POS in Blok 37 will be presented in chronological order to identify modalities and highlight factors that contributed to positive social and spatial changes in the area. The case will be reviewed in relation to context, process, actors, and results of community engagement, while special focus will be placed to formation of Local civic organization “Blok37” as an authentic initiator, mediator and actor in protecting and managing POS.

4.1. Community Actions as Basis for Public Open Space Reconstruction

During 2010’s the local community initiated the improvement of the existing POS. Residents spontaneously arranged and equipped their own gathering places with a table and two benches made out of used mater, and created an open-air gym.



Figure 1. Block 37 before (left) and after reconstruction (right). Source: Google maps

Then in 2016. the Municipality of New Belgrade initiated the reconstruction of the largest playground in Block 37. The project was planned in accordance to valuing modernist heritage and keeping the continuity of urban planning character of New Belgrade - as stated in Master Plan of Belgrade 2021 (MPB 2003) [11] and Master Urban Plan of Belgrade (MUPB 2016) [12]. It was designed and implemented by public utility company KP "Zelenilo-Beograd", and delivered through the annual Program of Arrangement and Maintenance of Parks, Green and Recreational Areas. The new open space design project fully took into account the initial re-arrangements initiated by local residents. POS improvement included the reconstruction of sport playgrounds and the arrangement of the new multifunctional and accessible playground. Besides that, spontaneously built benches with tables and outdoor gym were replaced by new made from more consistent materials [13] (Fig. 2 & 3).



Figure 2. Tables and benches and gym in open space are located where local residents previously arranged and used spaces for these purposes. Photo: P. Jovanović



Figure 3. Sports playground and gym in public open space. Photo: P. Jovanović

4.2. Community Re-action and Public Open Space Protection

The epilogue of the POS reconstruction project (2016) was raising citizens awareness on how they can actively contribute to the quality of life in their neighbourhood. This came especially into fore when in summer 2021. the location that was previously planned for solving the parking problem was “overnight” converted into eight floors high business and commercial building.

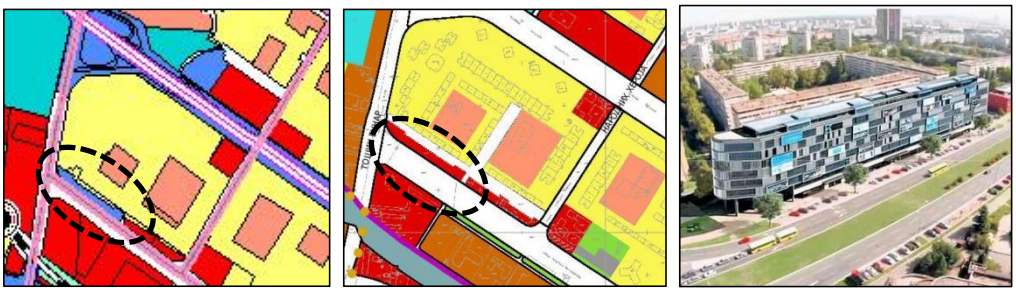


Figure 4. Changes in land use along Bul. Milutina Milankovića street. Left: traffic surface in MPB 2003/2007, Middle: Commercial use in GRP-CB 2016;Right: Presentation of Urban design project, source: https://beogradske.rs/blok-37-pobuna-stanara-zbog-gradnje-poslovne-zgrade/

The key problem was that, while the investor legally held a building permit, the underlying administrative process lacked transparency. In February 2008, the City Construction Land Directorate organized a public bidding where the land was leased to the company "Durst Development" for a period of 99 years, for the construction of a parking/garage, based on MPB 2003 (Fig. 4), and for years nothing has being done.

However, in 2015, based on the new "Law on the Conversion of the Right of Use into the Right of Ownership of Construction Land with a Fee" [14], "Durst Development" became the owner of the land and initiated an urban design project [15] for the new use of the building lot, which was officially approved in December 2015. This urban design project was placed on public presentation in October 2015 for a very short period (9–15th October), but the citizens were not informed about this change in the urban plan[16]. The local authorities issued the planning permit in April 2016, followed by a building permit for a nine-story building (28,000 sqm) in 2017 (Fig. 4).

Consequently, when construction of the new (so-called "Monster“) building began in 2021 the local residents reacted immediately. Aware of the consequences—not only that the project would diminish the quality of life in nearby buildings, but also that it would place even more pressure on other public open spaces (POS)—citizens gathered in large numbers to halt construction on the site (Fig. 5). Based on arguments and analysis of documents and regulations (provided by citizen-experts) they negotiated with key institutions and city representatives, and after several months, a solution was reached. The city provided the investor with an alternative location for their commercial project, and the building plot in Block 37 was returned to municipal ownership, once again becoming public property. Although the parking issue has not yet been resolved (as the planned garage was not built), this intervention successfully prevented future private initiatives from jeopardizing the quality of life in Block 37.



Figure 5. Protests against "Monster building" source: https://blok37.rs/aktivnosti-zajednice/

4.3. Community Action(s) - Formation of Local Civic Organization "Blok37 " and Improving the Quality of Public Open Spaces

This event had two important consequences for future activities regarding POS in Blok 37. First, citizens recognized the importance of being organized in order to channel better communication towards the officials and second, they realized that they have to be informed and pro-active to safeguard and improve their living environment. For this reason citizens' association "Blok 37" was formed as a new actor in initiating and protecting rights of inhabitants in shaping their everyday environment, and as their representative in collaboration with official institutions. The Association "Block 37" is a non-political, non-governmental, and non-profit organization established with the aim of improving living conditions and securing the rights of citizens in Block 37. Several „expert-citizens" form the special group of residents that articulates and communicates community interests, initiates and mannage different activities, coordinates communication with institutions and city officials, and works on informing, education and community building.



Figure 6. Citizens' association "Blok 37" activities: source https://blok37.rs/aktivnosti-zajednice/

In following years citizens' association "Blok 37" organized independently or in partnership with relevant institutions (Bina, University of Belgrade-Faculty of Architecture) several workshops for envisioning the future of POS in Blok 37, and

realized public gatherings for POS maintaining ("Bag in the pocket for my block")(Fig.6). Currently, they are negotiating with city officials and institutions on best solution for parking problem, based on the results of the Blok 37 experts working group analysis.

Besides using social networks as a communication channels, the Association has developed a *website* (https://blok37.rs)as a digital tool for citizen participation. It serves as a platform for informing and educating citizens about issues relevant to the quality of life in the block, as well as about activities in which they can participate to protect and improve their living environment. In addition to general information about the Association, the platform features three main thematic sections. The “Information” section provides information about specific events and activities in the form of blog posts, while also enabling citizen engagement through comments. The “Community Activities” section informs and educates citizens about community initiatives in which the Association “Block 37” participates, and invites citizens to propose new activities that the Association can organize or support. The “Sense of Community” section features reflections on life in the block, written by current or former residents of Block 37 in the form of essays, poems, photo essays, and similar contributions (Fig. 7).

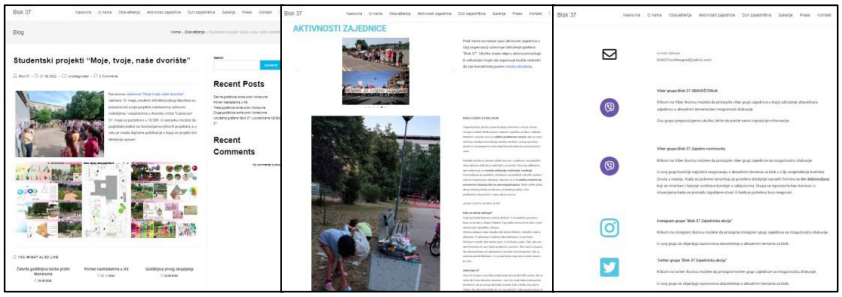


Figure 7. Citizens' association "Blok 37" website: source https://blok37.rs

4.4. Analysis and Discussion

Evolution of citizen engagement in POS development in Block 37 reveals different *modalities,* following the path from pro-active to re-active and back to pro-active involvement. Based on bottom-up citizens *pro-active initial activities* that were successfully linked to local government’s visions to improve the quality of life in New Belgrade’s super blocks, a new multifunctional POS was made. It became an important gathering place where more inhabitants have chosen to spend their free time. In parallel, the result of the project was *raising citizens’ awareness* of the importance of POS, and bringing *confidence* that their needs and opinion matter.

This helped in initiating the *re-active modality* of Blok 37 citizen engagement in which when they persisted in protecting POS quality and their right to live in healthy environment. In their fight against the new “Monster” building, *good organization, expert-citizens engagement, and willingness to negotiate with politicians and institutions* in evidence supported and non-aggressive manner, turned out to be a good and effective strategy and a *factor of success*. Finally, the *pro-active formation of citizens' association "Blok 37"* was a step forward to preventing similar problems from happening in the future, but also established an institutional base for pro-active initiatives considering future POS management and improvement. Their *web-site* is a

source of information on relevant issues, capacity-building platform and place for mobilizing local community toward pro-active and re-active initiatives, thus confirming the necessary use of new technologies as one of the emerging factors for successful engagement of citizens.

Our study reveals that individual, collective, and institutional factors all matter, highlighting the particular importance of personal knowledge, human connections, trust, and a sense of place and belonging. These elements may evolve over time, driven by mutual respect and supported by the positive outcomes of common efforts to protect and enhance the everyday living environment.

5. CONCLUSION

Community engagement and participation is widely promoted as a tool for enhancement and revitalization of public open spaces. Yet different personal, collective and institutional factors influence its effective implementation in practice. Our research on the case of Block 37 reveals that while working on overcoming institutional barriers to public participation in Serbian context, potential for the improvement lays in recognizing individual and collective factors of success. Key among them are: building trust, good community organization, role of expert-citizens, and the use of digital technologies for communication, education and community building.

Therefore, to support effective citizen engagement in reclaiming POS in multifamily housing in Serbia and other post-socialist countries, grassroots initiatives should be supported, and collaboration between public institutions and residents should be enhanced. Besides that, residents shall work on better organization and networking through variety of engagement forms, but also on making their initiatives and results visible by using new media. „Expert-citizens“might have a key role in realizing this, in the context where formal public participation is at its infancy. Besides their role in representing the interest of the community in official terms, they can significantly contribute to education, activation and strengthening of community ties through organization of local events and activities that connect people both with place and among themselves. Potential interventions to be institutionalized in urban policy therefore refer to: a) Mandatory early-stage digital notifications for residents regarding any land-use changes in their immediate neighbourhood; b) Institutional recognition of local civic associations as stakeholders in early-stage planning consultations, and c) Establishment of "Expert-Citizen" advisory boards to co-review urban interventions alongside planners to bridge the gap between top-down development and local needs..

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Research paper

ANALYSIS OF INCLUSIVENESS AND ACCESSIBILITY OF SCHOOLYARDS: A COMPARATIVE STUDY OF THREE SCHOOLS IN THE CITY OF STIP

Vladica Nikolovska[1], Vaska Sandeva[2], Katerina Despot[3]

Abstract

This study analyzes the level of accessibility of schoolyards for people with physical disabilities, with a particular emphasis on the opportunities for independent and safe use of outdoor school space. The study was conducted through the analysis of three case studies of primary schools built during a period when accessibility was not a significant criterion in the design of educational facilities. The methodology is based on an assessment of key elements of accessibility, including access from a public area, entrance ground areas, yard movement, and providing a ground-to-facility connection.

An accessibility index is calculated for each case study, which allows for quantitative evaluation, comparative analysis of examples, and problem identification. The results show that the adaptations and renovations carried out contributed to improving the level of accessibility in all schools analyzed, but at the same time reveal the presence of residual architectural barriers. The most commonly identified deficiencies are inadequate parking spaces and access ramps that do not allow for fully independent use by persons with a physical disability.

The research suggests that despite the progress made, additional interventions are needed to align schoolyards with universal design principles and modern accessibility standards. The findings of the research can serve as a basis for planning future renovations and creating a more inclusive educational environment for all users.

Key words: *inclusive education, accessibility, universal design, primary school, physical disabilities*

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1. INTRODUCTION

Designing and building an environment without architectural barriers allows for equal inclusion of all members of society. Today, the development of an inclusive environment is inextricably linked to the philosophy of universal design. This concept calls for the creation of an accessible built environment, in which everyone can develop their potential equally. School buildings, as the subject of this paper, should be designed or adapted in a way that will allow for easy, safe and independent use by all users—students, teaching staff, parents, and visitors—regardless of their age, size, capacity, or degree of mobility. When the principles of universal design are applied in school environments, architectural solutions do not separate people with disabilities through special adaptations. Instead, they create spaces that are accessible and usable for everyone as an equal part of the community. The schoolyard as a physical space that forms a link between the public space and the school building is one of the key segments in providing inclusive education.

In the global context of schools and their accessibility, which is the focus of this research, data from 2017 show that 88% of countries have laws that guarantee the right of children with disabilities to participate in education. However, only 33% of countries have schools that provide a physically accessible environment for these children. [1]

In North Macedonia, most schools were built in the 1960s and 1980s under different social and political conditions. Today, these buildings are still used for the same purpose, although educational needs and teaching approaches have changed over time. However, at the time these schools were designed and constructed, children with disabilities were mainly educated in special schools under separate legal regulations. As a result, accessibility and inclusion were not key considerations in school design. Based on this context, the research is guided by the following hypothesis: Schools built between the 1960s and 1980s, during a period when awareness of disability and inclusive education was limited, currently have architectural barriers that hinder the implementation of inclusive education.

To evaluate this hypothesis, the study examines the schoolyards of three primary schools in the city of Stip. Through field observations, photographs, and documentation of the schools and their surrounding areas, the level of accessibility will be assessed and compared. The analysis will help determine whether the hypothesis is confirmed or rejected, while the mapping of movement routes will identify existing barriers and accessibility challenges within the schoolyards.

2. THEORETICAL ASPECTS OF ARCHITECTURAL ACCESSIBILITY

The principles, policies and practices in education for persons with disabilities, according to the Salamanca Declaration, are that they "must have access to regular schools that should meet their needs by applying a child-centered pedagogical approach", stressing that "a fundamental principle of an inclusive school is that all children should learn together, whenever possible, regardless of the difficulties and

differences that may exist. Inclusive schools must recognize and respond to the diverse needs of their pupils, addressing their different learning styles and speeds and providing quality education for all, through appropriate curricula, organizational setups, instructional strategies, resource application and through partnerships with local communities." [2]

In an architectural context, inclusivity is terminologically related to universal design. Universal design aims to create spaces that can be used by everyone, regardless of their physical or cognitive abilities. Although the terms "design for all" or "equitable design" had been discussed earlier, the term “universal design” was first introduced by architect Ronald Mace in the 1980s. Mace, who founded the Center for Universal Design in Raleigh, North Carolina, believed that environments designed to meet the needs of people with disabilities could also improve usability for everyone. Based on this idea, he developed the concept of universal design, also known as inclusive or barrier-free design, which aims to create spaces that can be used by all people regardless of their abilities. Ronald Mace defined universal design as the design of products and built environments that should be usable to all people, to the greatest extent possible, without the need for adaptation or specialized design. [3]

Today, the definition of universal design is included in the text of the United Nations Convention on the Rights of Persons with Special Needs. In that text, universal design is defined as the design of products, environments, programs, or services for use by all people to the highest possible extent, without the need for customization or specialized design. [4]

Basic strategies that can improve the accessibility of children with disabilities to the school building include providing sidewalks with designed curb ramps, creating smooth and obstacle-free pathways, and installing protective barriers or curbs in areas with level differences or steep slopes. These features help ensure safe and independent access for children with disabilities while also improving safety and convenience for all users of the school environment. [5]

3. NATIONAL ACCESSIBILITY REGULATIONS AND CRITERIA FOR ANALYSIS

To meet the criteria for architectural accessibility of schoolyards, the analysis is based on the requirements defined in The Law of Construction and Design Standards and Regulations, as well as the provisions of the Regulations on the technical characteristics and dimensions of the route for the movement of persons with body handicap and visually impaired persons [6]. This regulation prescribes technical characteristics for the dimensions of sidewalks and paths for the movement of people with physical disabilities as the target group of this paper.

According to Regulations on the manner of ensuring unimpeded access, movement (horizontal and vertical), residence and work of persons with disabilities to and in buildings with public and business purposes, buildings for residential and commercial purposes, buildings for residential and business purposes [7], schools should provide continuous and barrier-free access for people with reduced mobility from the public area and the schoolyard to the school building. Table 1 defines the criteria in accordance with the previously mentioned applicable legal requirements.

Table 1. Table of defined criteria and sub-criteria for the level of accessibility of the schoolyard

	Criteria	Sub-criteria	Technical Normative	Legal/Regulatory Reference
1	**Public Access** (Street to Courtyard)	Parking for people with disabilities	Min 1 parking place 370 x 500 cm (or 5% of the total) located closest to the entrance	*Articles 38 and 50, the Rules of Procedure ...* [7]
		Sidewalks and ramps of rabbis	Gradient ≤5%, width 180 cm, at a crossing with the track the rim to be replaced by a ramp with a gradient of max 8.33%	*Articles 2 and 3, the Technical Regulations;* [6] *Article 193, Urban Planning Rulebook* [8]
2	**Entrance Ground Areas** (Courtyard Entrance)	Entrance gate width	Net width of entrance gate min 90 cm	*The Rules of Procedure ...* [7]
		Architectural barriers to entry	Absence of thresholds, chains or metal barriers, permissible floor displacement max 0.5 cm	
3	**Yard Movement** (Internal pedestrian paths)	Type and quality of substrate	Sturdy, flat and non-slip surface, free of damage and uneven pads of 0.5 cm	*Articles 2 and 3, the Technical Regulations ...;* [6] *Article 193, Urban Planning Rulebook* [8]
		Longitudinal and transverse slopes	Maximum longitudinal inclination 5% (1:20), maximum transverse inclination 2%	
4	**Link Schoolyard - Facility (**Main Entrance)	Access ramp	Slope 5% - 8.33%, width 120 cm	*Article 10, the Rules of Procedure ...* [7]
		Grips & Protective Edges	Double-sided handlebars at two heights of 60 and 90 cm, edge of the ramp min 5 cm	

Using these criteria and sub-criteria, the accessibility of the schoolyards of three selected primary schools in the city of Stip will be analyzed. Quantitative-qualitative comparative analysis will be conducted by evaluating each criterion and sub-criterion according to the following three levels:

0 – complete absence / non-compliance with legal norms

1 – partial compliance

2 – full compliance

A score of 0 indicates the absence of the analyzed element or its non-compliance with legal requirements, a score of 1 indicates partial compliance, meaning that the element is present but does not fully meet the prescribed accessibility standards (e.g., a ramp without the required width, slope, or handrails), while a score of 2 indicates full compliance with all applicable accessibility regulations and standards. The calculation of the level of accessibility of the schoolyards of the elementary schools analyzed will be performed using the general equation:

$$accessibility\ index = \left(\frac{scored\ points}{maximum\ possible\ points}\right) \times 100$$

In this way, the resulting percentage shows the level of accessibility of the schoolyard and allows the identification of accessibility deficiencies, as well as a comparison of the three analyzed schools. No weighting factors were applied in the calculation of the accessibility index and all criteria contributed equally to the final score. This approach was adopted because each analyzed element represents an essential

component of an accessible schoolyard, and the absence of any criterion may create a barrier to use, ensuring a transparent, simple, and comparable assessment of accessibility.

4. CASE STUDY – THREE PRIMARY SCHOOLS IN THE CITY OF STIP

The town of Stip is located in the eastern part of the Republic of North Macedonia and there are five primary and six secondary schools, one for children with disabilities and one university. This paper covers three primary school case studies to analyze the architectural accessibility of the schoolyard.

The location of the three schools is in the town of Stip (Figure 1), as follows:

1. "Vancho Prke" Primary School, in the center of the city, next to the Otinja River, opposite the town square.
2. "Tosho Arsov" Primary School, in the urban settlement 8th November.
3. "Dimitar Vlahov" Primary School, in the urban settlement Senjak.

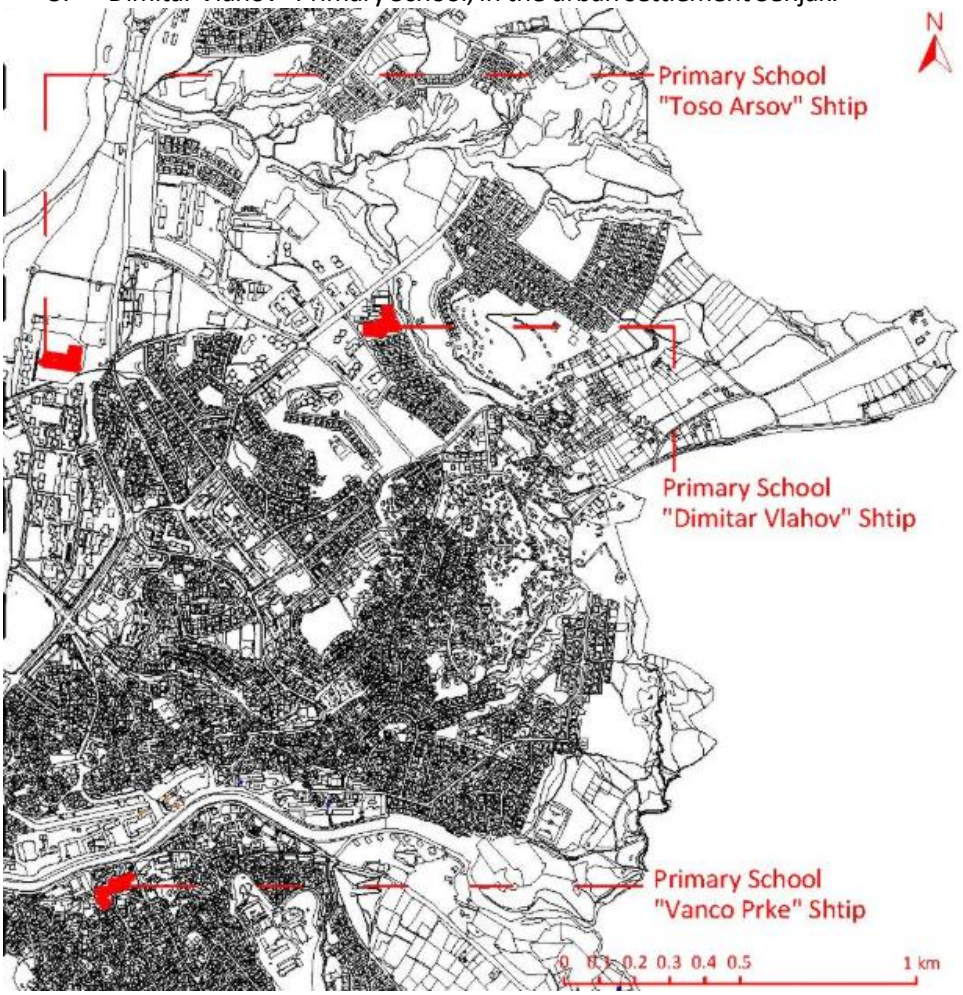


Figure 1. Location of the analyzed primary schools, author

Table 2 provides general data for each of the schools analyzed in this paper.

Table 2. Table with general data for the examples analyzed

Attribute	School Name	Location	Year of construction	Yard area (m^2)
U1	"Vancho Prke"	The center of the city	1962	5141
U2	"Tosho Arsov"	8th November, Stip	1977	12792
U3	"Dimitar Vlahov"	Senjak, Stip	1982	3963

Access to the schoolyard of U1 is provided through four entrances from three access streets. The access streets of this school have a higher frequency of traffic, and the highest frequency is in front of the main entrance to the schoolyard where a protective fence has been installed. There is no parking space within the schoolyard, but the nearest parking area is used in front of the main entrance to the schoolyard. The entrances are open, without entrance gates, and have sufficient width to allow access to the schoolyard. However, only one entrance (the main entrance) enables unobstructed movement through the schoolyard and access to the school facility. The other three entrances contain architectural barriers (stairs) for people with disabilities, which limit movement within the courtyard. The pedestrian paths in the schoolyard are made of interlocking concrete pavers that meet the requirement of a solid, flat, and non-slip surface. An access ramp has been provided to the main entrance of the school, enabling access for people with physical disabilities. However, according to technical standards, fully independent movement is not possible due to deficiencies in the design and construction of the handrail. The ramp was additionally installed as an improvement measure to enhance accessibility conditions within the school for people with physical disabilities. The previous and current conditions are presented in Figure 3.

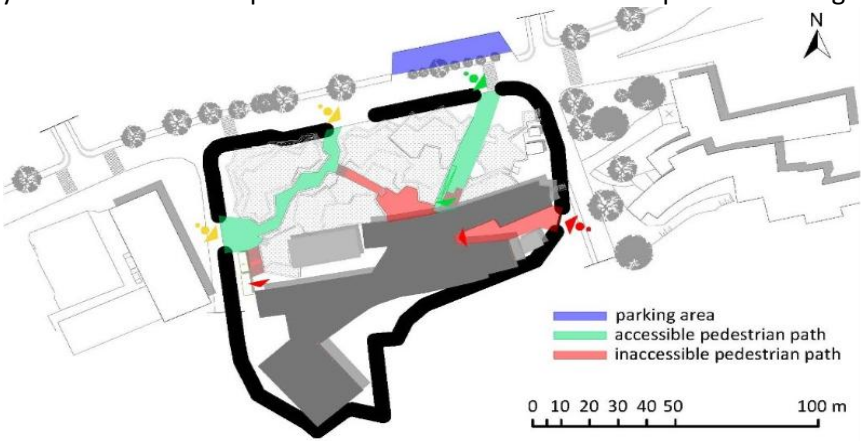


Figure 2. Accessibility of example U1, author



Figure 3. Photos before and after adaptation of example U1

The U2 school has access from an access street in urban settlement 8th November, which does not have a very high frequency of traffic. There is no parking space in the schoolyard, and parking is provided with parking spaces next to the entrance, which are also used by the residents of the surrounding residential buildings. The schoolyard is flat, without displacement, which allows free and unhindered movement for everyone, including those with physical disabilities. The pedestrian paths are made of interlocking concrete pavers, providing a solid, flat and non-slip surface. Entrance to the school facility is on the same level as the courtyard, which gives equal freedom of use to all users. This solution for entry without level differences was made later, because in the basic design from 1977, there was a level difference resolved by stairs (Figure 5).

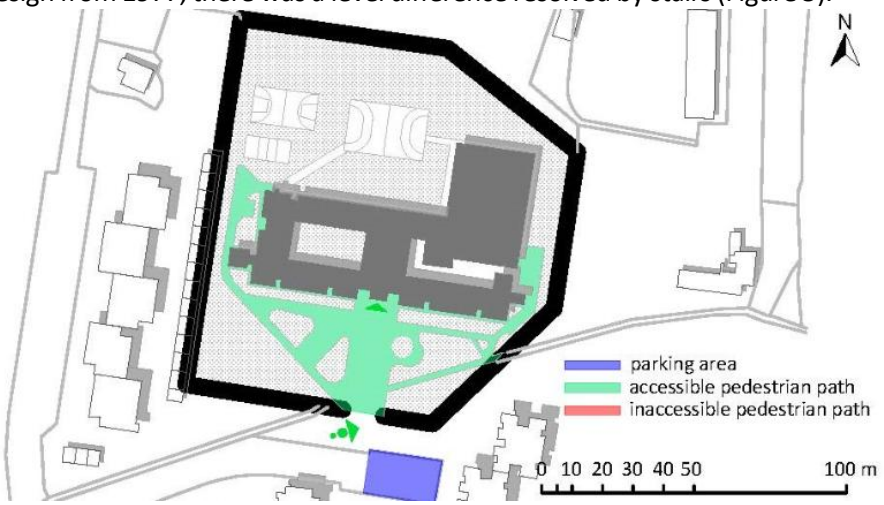


Figure 4. Accessibility of example U2, author

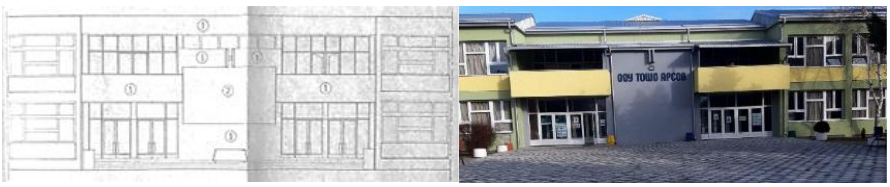


Figure 5. Photos of located adaptations to improve accessibility of example U2

The U3 school has access to the courtyard through three entrances from two access streets. Around the schoolyard, a protective fence is installed. There is no parking space within the schoolyard, but the nearest parking spaces located near the main entrance to the schoolyard are used, which are also used by the residents of the surrounding residential buildings. Entrances are closed with entrance gates that are wide enough to allow access to the schoolyard for people with disabilities. The two main entrances to the building are connected to access ramp, which provide entry to the school and allows free and unimpeded movement for persons with disabilities. The entrance on the north side provides access to the courtyard; however, it does not allow direct access to the school building due to the presence of architectural barriers for people with physical disabilities. Barriers are steps that solve the level differences of the ground, as that entrance is at a significantly lower level than the rest of the yard area.

The pedestrian paths in the schoolyard are made of interlocking concrete pavers that meet the requirement of a solid, flat, and non-slip surface. An access ramp is provided at the main entrance to the school, which allows free and independent movement of people with physical disabilities towards the entrance to the school. The two ramps leading from the main entrance to the courtyard area and the ramp connecting to the school facility were later constructed to increase the accessibility of the school for people with disabilities (Figure 7).

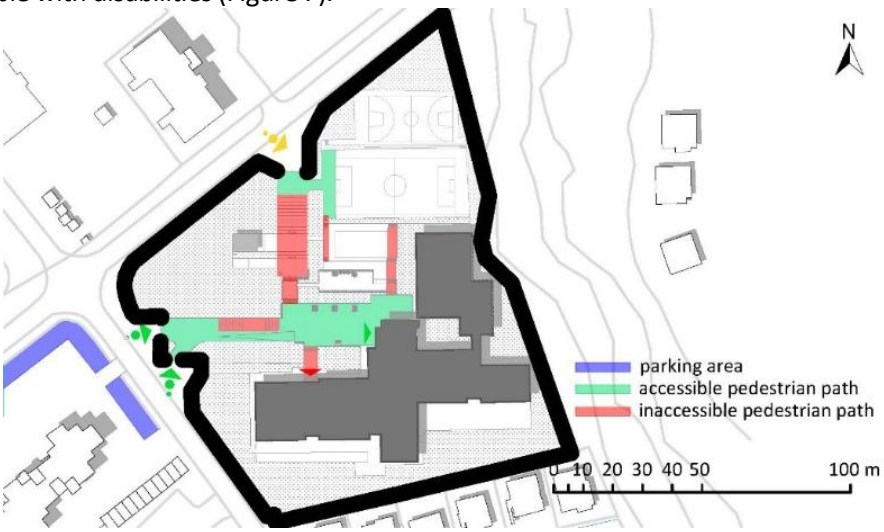


Figure 6. Accessibility of example U3, author



Figure 7. Photos of example U3

5. COMPARATIVE ANALYSIS AND DISCUSSION

The evaluation of the accessibility level of the three analyzed schoolyards was conducted by evaluating the selected criteria and sub-criteria according to the technical norms defined in Table 1. The analysis is based on the current state of the schoolyard with the changes and adaptations undertaken during the period of its operation. Table 3 shows the quantitative evaluation of the criteria according to the degree of fulfillment for the three examples analyzed.

Table 3. Table with general data for the examples analyzed

Criteria		Sub-criteria	U1	U2	U3
1	**Public·Access**·(Street·to·Courtyard)	Parking·for·people·with·disabilities·(according·to·technical·regulations·Table·1)	0	0	0
		Sidewalks·and·ramps·of·workers·(according·to·technical·standard·Table·1)	1	1	1
2	**Entrance·Ground·Areas**·(Courtyard·Entrance)	Width·of·the·entrance·gate·(according·to·the·technical·standard·Table·1)	2	2	2
		Architectural·barriers·to·entry·(according·to·technical·regulations·Table·1)	2	2	2
3	**Yard·Movement**·(Internal·Trails)	Type·and·quality·of·substrate·(according·to·technical·standards·Table·1)	2	2	2
		Longitudinal·and·transverse·slopes·(according·to·technical·standards·Table·1)	1	1	1
4	**Link·Schoolyard·-·Facility**·(Main·Entrance)	Access·ramp·to·the·entrance·(according·to·technical·regulations·Table·1)	1	2	1
		Handles·and·protective·edges·(according·to·technical·regulations·Table·1)	1	2	2
		Total	**10**	**12**	**11**

The calculation of the schoolyard accessibility index of the primary schools analyzed using the defined general equation is:

$$\textbf{U1} - accessibility\ index\ (I_1) = \left(\frac{10}{16}\right) \times 100 = \mathbf{62.5}\%$$

$$\textbf{U2} - accessibility\ index\ (I_2) = \left(\frac{12}{16}\right) \times 100 = \mathbf{75.0}\%$$

$$\textbf{U3} - accessibility\ index\ (I_3) = \left(\frac{11}{16}\right) \times 100 = \mathbf{68.8}\%$$

The analysis showed that the achieved accessibility level in all three examples was a result of various adaptations and interventions implemented in each of the analyzed cases. This leads to the conclusion that facilities built at the end of the 20th century do not fully meet the needs of people with physical disabilities, and that significant improvements in accessibility have been achieved through additional interventions, especially in terms of continuity of movement and the reduction of physical barriers. However, the analysis shows certain shortcomings that still limit the full implementation of universal design principles. The weakest point is the parking spaces for persons with disabilities, in which there is a complete absence from the boundaries of the schoolyard, and according to the Norms and Standards for School Premises, Equipment and Teaching Aids for Primary Schools in the Republic of North Macedonia, they should be present as an integral part of the schoolyard [9]. In addition, examples U1 and U3 show deviations from the standards regarding the technical characteristics of the access ramp, making them unsafe for independent use. Therefore, it can be concluded that the implemented adaptations have contributed to a higher level of accessibility, but additional interventions are still needed to ensure a fully inclusive and independently accessible environment.

6. CONCLUSION

Schools built between 1960 and 1980 were designed during a period when issues related to accessibility and the inclusion of people with disabilities were not sufficiently represented in architectural and urban practice. As a result, many of these buildings still contain architectural barriers that limit or prevent equal use of educational spaces. Although measures have been taken in recent years to improve accessibility through various adaptations and reconstructions, the analysis shows that these interventions are often partial and do not provide complete independence in the use of space.

The study shows that despite legal regulations, adaptations and interventions implemented, the average accessibility index in the schoolyards analyzed is 69%. This confirms that improving physical accessibility should not be limited to meeting minimum technical requirements but should be based on a comprehensive approach that will ensure equal opportunities for all users. In this direction, additional interventions aimed at removing the remaining barriers and improving the quality of the access environment are needed. Such measures will contribute to the creation of a more inclusive, safer and more accessible educational space, which will meet the needs of all students and visitors regardless of their physical abilities.

Although the analyzed schoolyards in Stip represent only one segment of the overall school environment, the results indicate similar challenges to those identified in the international literature discussed above, particularly regarding the partial compliance of certain elements with accessibility standards. This confirms that the need for systematic improvement of accessibility in outdoor educational spaces represents a current issue not only at the local but also at the international level.

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Review paper

SUSTAINABLE URBAN DESIGN OF ISAR HILL (STIP, NORTH MACEDONIA): INTEGRATED APPROACH TO GIS AND LANDSCAPE URBANISM

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Abstract

This paper examines the potential transformation of the urban hill of Isar in Štip as a model of sustainable urban design. Through applied theoretical approaches – including planning in dialogue with nature and Landscape Urbanism – the natural, social and urban layers of the space are analyzed. Furthermore, specific scenarios and principles of intervention are proposed that simultaneously protect the ecology and improve the quality of public space. This paper highlights the importance of integrated urban design as a means of promoting sustainable urban environments.

The study applies GIS-based spatial analysis and NDVI (Normalized Difference Vegetation Index) to assess vegetation density and ecological potential.

Key words: *sustainable urban design, landscape architecture, GIS analysis, NDVI, green infrastructure, urban hills*

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1. INTRODUCTION

Urban environments globally are increasingly facing complex challenges related to accelerated urbanization, climate change, environmental degradation, and declining quality of life [1]. In this context, green infrastructure and landscape architecture-based approaches are emerging as key components of sustainable urban development, providing ecosystem services such as climate regulation, biodiversity conservation, stormwater management, and improving social well-being.

In recent decades, the concept of Landscape Urbanism has redefined the relationship between natural systems and urban form, positioning the landscape as the primary medium through which cities are organized and transformed [2]. This approach emphasizes adaptability, natural processes, and multifunctionality, enabling cities to respond more effectively to environmental and social pressures.

Despite the growing body of research in the field of sustainable urban landscapes, urban hills and elevated terrains – especially in Southeastern Europe – remain significantly under-researched as integrated ecological and social systems. In many post-socialist cities, these spaces are often marginalized, fragmented or insufficiently integrated into urban plans, resulting in missed opportunities for ecological rehabilitation and development of public spaces.

The Isar Hill in Shtip, North Macedonia, is a characteristic example of such an underutilized urban landscape. Although it possesses significant ecological, morphological and cultural values, the space currently faces challenges such as vegetation degradation, erosion processes and lack of structured public accessibility. At the same time, its topographic dominance and spatial position offer strong potential for transformation into a multifunctional urban landscape.

This paper addresses this research gap by proposing an integrative, landscape-based approach for the sustainable transformation of urban hills, using the Isar as a case study. The research combines spatial, ecological and social analysis in order to develop contextually adapted design principles that strike a balance between environmental protection and urban functionality.

The main objective of the paper is to assess the potential of the Isar as a model for sustainable urban design through three key dimensions: (1) ecological rehabilitation, (2) integration of cultural heritage and (3) social activation of public space. In addition, the paper explores how the principles of Landscape Urbanism and nature-based design can be applied to create adaptive, resilient and inclusive urban environments.

2. THEORETICAL FRAMEWORK

2.1 Landscape Architecture and Sustainable Design

Landscape architecture is a discipline that integrates the natural, social and urban context to create functional, aesthetic and sustainable spaces [3]. Sustainable design in landscape architecture is based on principles that minimize negative impacts on nature, optimize the use of natural resources and provide functional and social value to public

space [1]. In the context of the Isar, these principles are crucial for preserving the natural landscape, integrating green corridors and creating public spaces that enable environmental and social well-being.

2.2 Landscape Urbanism

Landscape Urbanism promotes nature as a foundation for urban design and sees it as a structural element that defines the urban fabric [2]. The principles of Landscape Urbanism include:

- Integration of natural processes such as water, topography and vegetation into the urban fabric.
- Dynamic and adaptive systems that allow for flexibility in public space.
- Balancing social needs and ecological function, by creating spaces for recreation, interaction and learning.

Landscape urbanism provides a basis for interventions that not only preserve nature, but use it as a key resource for urban organization.

2.3 Examples of sustainable urban design

International projects show how an integrated approach can transform urban spaces:

- **High Line, New York** – an abandoned railway line that was transformed into a public park with the integration of local vegetation and public paths [4].
- **Superkilen Park, Copenhagen** – a public space that integrates the cultural and social aspects of the local community through multifunctional zones [2].
- **Parque La Mexicana, Mexico City** – an ecologically integrated park that combines recreational, educational and ecological functions [4].

These examples illustrate the application of the principles of Landscape Urbanism and dialogue with nature, with the aim of creating public spaces that are adaptive, sustainable and socially inclusive.

3.METHODOLOGY

This research is based on an integrated methodological approach that combines spatial analysis, ecosystem evaluation and social interpretation of the Isar Hill as an urban-landscape system. The methodology is structured in three main phases: (1) data collection and processing, (2) spatial and ecological analysis and (3) synthesis and development of design principles.

3.1 Data collection and processing

In the first phase, various data sources are used in order to provide a comprehensive analysis of the space:

- Spatial data – topographic maps, orthophotos and satellite data (Google Earth, Copernicus).

- GIS data – digital terrain model (DEM), vegetation and land use layers.
- Statistical data – demographic and urban information (State Statistical Office).
- Field research – visual analysis, photographic documentation and identification of spatial features.

The collected data was processed using GIS tools (QGIS / ArcGIS), in order to create thematic maps and analyze spatial relationships.

3.2 Spatial analysis

The spatial analysis focuses on the morphological and visual characteristics of the Isar Hill. The analysis includes:

- Slope analysis – to identify erosion zones and potential areas for intervention.
- Aspect analysis – to assess solar exposure and microclimatic conditions.
- Viewshed analysis – to identify visual corridors and panoramic points.
- Accessibility analysis – existing and potential pedestrian connections.

The results of this analysis are presented in Figure 1 – GIS spatial analysis of the Isar, which integrates key spatial layers.

3.3 Ecosystem analysis

The ecosystem analysis aims to identify the natural processes and ecological potentials of the site. In this phase, the following are applied:

- NDVI analysis (Normalized Difference Vegetation Index) – to assess the density and health of vegetation.
- Erosion analysis – based on slope and vegetation coverage.
- Hydrological analysis – identification of surface flows and potential water retention zones.
- Biodiversity analysis – assessment of existing and potential green corridors.

The results are visualized through Figure 2 – NDVI map and ecological potentials, which allows a clear interpretation of the state of vegetation.

3.4 Social analysis

Social analysis is based on assessing the use of space by the local population and the level of accessibility. Methods include:

- direct observation of activities.
- mapping of informal paths (desire paths).
- identification of gathering points.
- analysis of the functionality of the space.

This analysis allows for an understanding of the relationship between users and space, which is key to developing sustainable and inclusive design solutions.

3.5 Synthesis and development of design principles

In the final phase, the results of all analyses are integrated into a synthetic model that serves as a basis for the development of design strategies. This phase includes:

- identification of zones with different potential (ecological, social, cultural).
- definition of priorities for intervention.
- development of sustainable design principles (adaptability, reversibility, minimal intervention).

This integrated approach is illustrated in Figure 3 – Isar's Sustainable Transformation Model, which represents a conceptual framework for future interventions.

4. RESULTS

The analysis of Isar Hill showed that the hill represents a complex combination of natural processes, existing infrastructures and opportunities for public space integration. The results are classified into three main aspects: morphology and natural processes, ecosystem potentials and constraints, and design potentials.

4.1 Morphology and natural processes

The topographic structure of the Isar defines the natural drainage, visual corridors and microclimate in the surrounding settlements. The hill provides a natural barrier that influences the distribution of sunlight and winds, which can be used in the positioning of pedestrian paths, recreational zones and stabilisation or protection of high-risk areas. The daily use of the hill by the local population shows natural gathering points and activities, which can be formalized as public spaces without significant interventions [1].

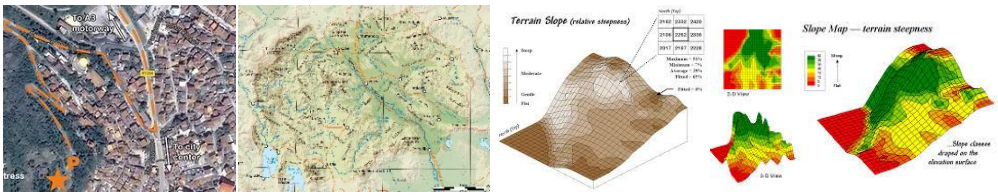


Figure 1. GIS-based spatial analysis of the Isar hill in Shtip, North Macedonia, showing the topography, slope distribution, vegetation patterns, and spatial structure of the terrain. The map integrates multiple spatial layers to identify ecological potentials, areas prone to erosion, and zones suitable for landscape intervention. Source: Author's elaboration using AI-generated GIS visualization.

The GIS-based spatial analysis (Figure 1) reveals the morphological complexity of the Isar Hill, characterized by different slope gradients, fragmented vegetation cover and different visual corridors. Steeper areas are primarily associated with a higher risk of erosion, while moderately sloping zones present favorable conditions for the development of hiking trails and recreational spaces. The spatial structure also highlights the potential for establishing ecological corridors connecting vegetated areas across the hill.

4.2 Ecosystem potentials and constraints

Erosion processes and vegetation fragmentation have been identified as major environmental challenges. However, the Isar has significant potential for establishing green corridors that would connect different parts of the hill and enhance biodiversity. The use of indigenous plant species will allow for soil stabilization and improvement of the local ecology. Watercourses can be used to create natural reservoirs and rainwater management systems, thus reducing the risk of erosion and flooding [3].

Table 1. NDVI classification chart showing the relationship between NDVI values and vegetation density, highlighting ecological quality and levels of degradation

NDVI value	Vegetation category	Interpretation
0.6 – 1.0	Dense vegetation	High biological activity, stable ecosystems, high biodiversity potential
0.3 – 0.6	Medium vegetation	Moderate coverage, potential for improvement through interventions
0.1 – 0.3	Weak vegetation	Fragmented surfaces, increased risk of erosion
< 0.1	No/degraded vegetation	Minimal biological activity, high degradation, priority zones for rehabilitation

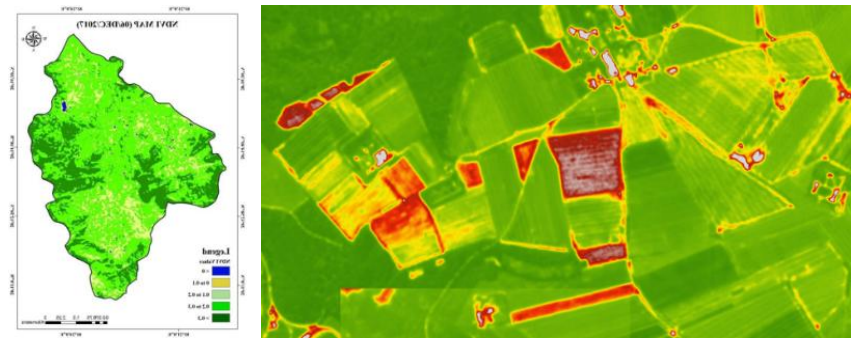


Figure 2. NDVI (Normalized Difference Vegetation Index) analysis of the Isar Hill, indicating the spatial distribution of vegetation density. Areas with higher NDVI values (green) represent dense and healthy vegetation, while lower values (yellow to red) indicate sparse vegetation and potential zones of degradation and erosion risk. Source: Author's elaboration using AI-generated visualization.

The NDVI analysis (Figure 2) provides a quantitative assessment of vegetation density across the Isar ridge. Areas with high NDVI values correspond to zones with dense and relatively stable vegetation, indicating greater ecological resilience and potential for biodiversity conservation. Conversely, areas with low NDVI values reveal fragmented or degraded vegetation cover, often associated with increased erosion risk and reduced ecological functionality. These findings highlight priority zones for ecological restoration and the introduction of native plant species.

NDVI values were classified into four categories representing different vegetation conditions, ranging from degraded areas to dense vegetation cover (Table 1 and Figure 2). This classification allows for a clear interpretation of ecological quality and supports the identification of priority areas for restoration and intervention in the landscape.

4.3 Design potentials

The Isar Hill has the potential to be transformed into an integrated urban landscape system that combines ecological, cultural and recreational functions. Design possibilities include:

- **Recreational trails and corridors –** using the natural topography for pedestrian and bicycle paths, which are integrated with existing green belts.
- **Educational and information points –** creating trails with information boards about the flora, fauna and geological features of the hill, thus encouraging an educational function.
- **Cultural and historical points –** preserving and presenting archaeological sites and historical traces, which are part of the cultural heritage of Shtip.
- **Microclimatic solutions –** integrating tree shades, green covers and water features to improve comfort and protect against extreme temperatures.
- **Socially integrated public spaces –** places for gathering, recreation and activities that increase the sense of community and social interaction [2, 4].

The proposed design intervention is visualized in Figure 3, which illustrates the transformation of the Isar into a terraced, accessible and ecologically integrated landscape. The design incorporates natural materials, adaptive pathways and observation platforms, while preserving the existing topography and enhancing the spatial experience of users.

The integration of these elements creates the potential for the transformation of the Isar from a passive natural hill into a functional, adaptive and sustainable urban-landscape system.



Figure 3. Visualization of the proposed landscape intervention on the Isar Hill, illustrating terraced paths, integrated vegetation, seating areas, and viewing platforms designed according to sustainable and contextually sensitive principles.

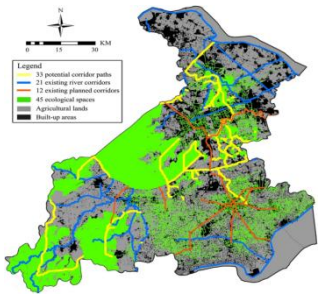


Figure 4. Conceptual model of sustainable transformation of the Isar hill, integrating ecological rehabilitation, social activation and cultural heritage preservation. The model illustrates the spatial relationships between green corridors, public spaces and intervention zones, based on the principles of landscape urbanism and nature-based design. Source: Author's elaboration using AI-generated visualization.

The conceptual model (Figure 4) synthesizes the results of spatial, ecological and social analyses into an integrated framework for sustainable transformation. The model defines key intervention zones, including ecological restoration areas, recreational corridors and cultural nodes. The connections between these zones are structured through a network of green corridors and pedestrian paths, ensuring ecological continuity and social accessibility. This approach reflects the principles of landscape urbanism, where the landscape functions as the primary organizing element of urban space.

5. DISCUSSION

Isar's analysis emphasizes the importance of an integrated approach to the urban and natural landscape. Sustainable urban design is not limited to visual aesthetics, but involves a systematic consideration of the ecological, social and cultural functions of space [1].

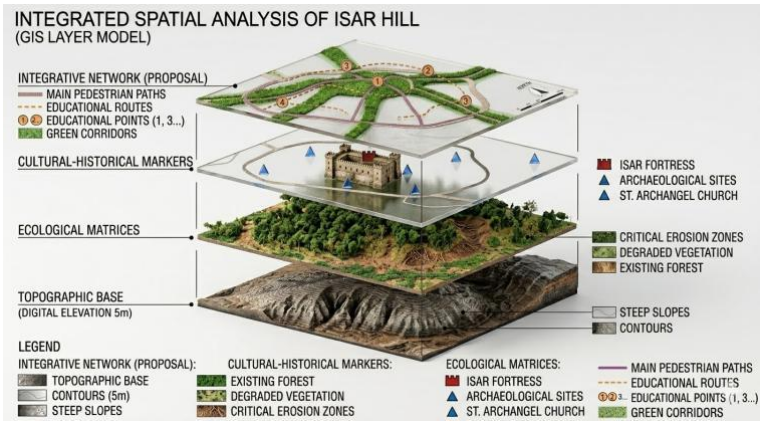


Figure 5. Integrated conceptual model for the sustainable transformation of the Isar Hill based on GIS, illustrating the interaction between the topographic structure, ecological matrices, cultural-historical elements and the proposed pedestrian and green infrastructure networks. Source: Author's elaboration using AI-generated visualization.

The integrated spatial model (Figure 5) illustrates the multi-layered structure of the proposed intervention, combining topographic conditions, ecological matrices and cultural-historical elements into a unified design framework. The model highlights the role of green corridors and pedestrian networks as key structural elements that ensure both ecological continuity and social accessibility.

The interventions in Isar, based on the principles of Landscape Urbanism, allow nature to become a structural element of the urban system, resulting in multifunctional public spaces. The application of green corridors, educational paths and integrated recreational zones increases the quality of the environment, while preserving the natural structure and biodiversity [2].

The discussion also highlights the importance of the adaptability and reversibility of the interventions. The spaces need to be flexible and able to respond to future changes,

such as climate change or increased urban density. This adaptability enables long-term sustainability of the space, reducing the need for radical reconstructions [3].

The application of international examples, such as the High Line in New York and Superkilen Park in Copenhagen, indicates that public spaces that integrate nature and urban life can achieve a high level of social interaction and ecological functionality [4]. Similarly, the Isar has the potential to develop into a public space that not only provides recreation, but also educational, cultural and ecological functions, creating a model of urban-landscape integration that can serve as an example for other urban hills in the country and the region.

A key aspect in the discussion is also the importance of contextuality – any intervention must be adapted to the local natural conditions, the existing infrastructure and the cultural heritage of the Isar. In doing so, planning must respect existing natural corridors, visible lines and ecosystem functions, in order to achieve harmonious and sustainable integration [5]. In conclusion, the discussion confirms that the Isar can be transformed into an integrated public space with significant ecological, social and cultural value, if a systemic and contextual approach is applied that combines the principles of sustainable urban design and Landscape Urbanism.

The results highlight the importance of urban green infrastructure as a key driver of ecosystem services in transitional urban landscapes. The NDVI-based assessment confirms that vegetation density directly influences ecological stability, microclimate regulation, and spatial quality.

6. CONCLUSION

The Isar Hill represents a significant potential for sustainable urban design, as it combines nature, urban fabric and cultural heritage of the city of Shtip. The analysis showed that the space has important natural, ecosystem and morphological characteristics that can be used for the development of integrated public spaces with multifunctional purposes.

The application of the principles of sustainable urban design and Landscape Urbanism enables the creation of public spaces that:

- preserve the natural structure and biodiversity;
- enable adaptive and reversible interventions;
- integrate cultural and historical elements;
- increase social interaction and recreational function;
- provide educational and ecological values.

The results of the analysis and discussion indicate that the Isar can be transformed into a model for urban-landscape integration, which offers functional, ecological and socially valuable spaces. This model can serve as an example for similar urban hills and natural resources in urban environments in Macedonia and beyond.

In the future, further research could focus on specific design solutions, monitoring of environmental effects and analysis of the use of public spaces, in order to confirm the long-term sustainability of interventions. At the same time, the application of a systemic and contextual approach will allow balancing the needs of the community

with the preservation of the natural and cultural values of the Isar [1, 2]. In conclusion, the Isar represents a potential laboratory for sustainable urban design, where nature, urbanism and cultural heritage are integrated to create public spaces with a high quality of life and functional value.

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GREEN BUILDING CONFERENCE
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Research paper

TEMPORAL LANDSCAPE OBSERVATION WITHIN RESEARCH-BY-DESIGN

Svetlana Momčilović[1]

Abstract

Peri-urban landscapes are commonly described as fragmented because productive, ecological, recreational and institutional landscape systems are managed independently despite their close spatial proximity. Conventional landscape analysis primarily interprets fragmentation through spatial structure and land-use patterns, offering limited insight into functional relationships that remain difficult to recognize through spatial analysis alone.

This paper introduces Temporal Landscape Observation (TLO) as a systematic temporal observation method integrated within a Research-by-Design (RbD) framework. Its analytical value derives from systematically comparing repeated observations of the same locations across seasons to trace ecological, management and use-related change. Observations were documented through analytical mapping, georeferenced photography and field notes.

The method was applied in the peri-urban landscape of Altstetten, Zurich, at the foot of Uetliberg, where a historically continuous agricultural landscape has evolved into a mosaic of neighbouring systems with distinct functions and management regimes. Their systematic comparison, however, progressively revised the initial interpretation of these systems as functionally separate by revealing recurring functional relationships between neighbouring systems. Although spatially and institutionally separated, these systems were periodically connected through ecological processes, management practices, and the movement and activities of people and wildlife.

These findings informed adaptive landscape interventions that strengthen existing functional relationships rather than creating entirely new spatial connections. The study's principal contribution is methodological. By introducing systematic temporal comparison as an analytical procedure within Research-by-Design, TLO complements conventional spatial analysis and offers a replicable empirical procedure for informing adaptive planning and design in multifunctional peri-urban landscapes.

Key words: *peri-urban landscapes, Temporal Landscape Observation, Research-by-Design, functional relationships, temporal comparison*

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1. INTRODUCTION

Peri-urban landscapes are typically multifunctional territories in which productive, ecological, recreational and institutional uses coexist in close spatial proximity [1]. Despite this proximity, neighbouring landscape systems are often perceived and managed as separate territories because they fulfil different functions and operate under distinct institutional regimes.

Research on peri-urban landscapes has extensively documented changes in land cover, land use and landscape configuration, while studies of fragmentation frequently employ spatial patterns and landscape metrics [2,3]. These approaches have advanced the understanding of landscape organization but provide a more limited account of how recurring relationships between neighbouring systems become recognizable through seasonal change, management cycles and patterns of use.

Time therefore becomes an analytical dimension through which functional landscape relationships can progressively be recognized [4]. Different landscape systems follow distinct temporal rhythms whose periodic overlap may enable relationships to extend across functional and institutional boundaries. Conventional maps and single site visits document conditions at particular moments but provide limited insight into processes that become apparent only through temporal comparison. Building on existing walking-based, repeat-photography and temporal landscape approaches [6,7], TLO uses systematic comparison of repeated situated observations to identify recurring functional relationships between neighbouring landscape systems within Research-by-Design.

To address this limitation, the paper introduces Temporal Landscape Observation (TLO) as a systematic temporal observation method integrated within a Research-by-Design framework [5]. TLO systematically compares repeated walking observations of the same locations under changing seasonal conditions, supported by analytical mapping, georeferenced photography and field notes. Walking provides situated access to landscape processes, while systematic temporal comparison constitutes the principal analytical procedure through which recurring functional relationships become recognizable.

This research asks:

How can Temporal Landscape Observation reveal functional landscape relationships that remain difficult to recognize through conventional spatial analysis and translate them into adaptive interventions within a Research-by-Design process?

2. METHODOLOGY

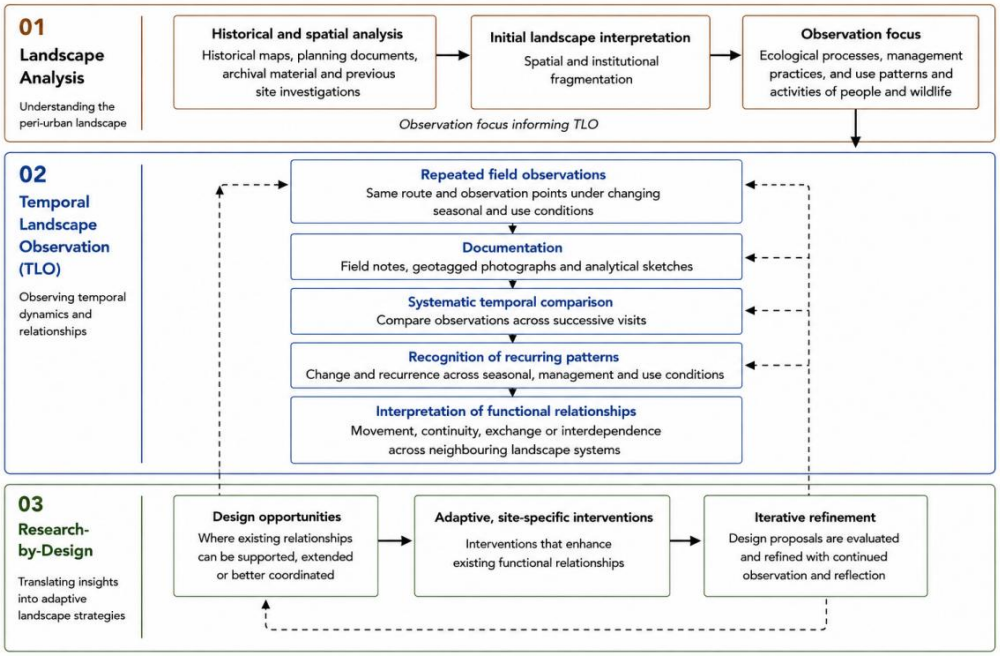


Figure 1. Integrated methodological framework linking Temporal Landscape Observation and Research-by-Design

The methodological process progressed from historical and spatial analysis to repeated field observation and systematic temporal comparison. Recurring patterns were interpreted as functional landscape relationships and translated into design principles and adaptive interventions, while emerging design questions fed back into further observation and refinement (Figure 1).

2.1. Research Design

Research-by-Design uses design to investigate landscape processes, generate knowledge and test spatial interventions [5]. Historical and spatial analysis, repeated field observation and design exploration developed iteratively rather than linearly.

The research was undertaken within the ETH MAS Urban and Territorial Design programme [8] in collaboration with Grün Stadt Zürich. Historical and spatial material provided the initial understanding of the study area, subsequently refined through repeated observations. Collaborative analyses provided contextual knowledge, while the primary empirical evidence derives from repeated field observations and their systematic comparison by the author.

2.2 Study Area



Figure 2. Study area and neighbouring landscape in Altstetten, Zürich

The study area is located in Altstetten, Zurich, at the foot of Uetliberg. It comprises the agricultural farms Hof Meyer and Berghof Seiler, Grünhölzli Community Gardens, Eichbühl Cemetery, Buchlern Sports Centre and the adjacent forest edge.

The study area and neighbouring landscape systems are shown in Figure 2.

Although contiguous, these areas fulfil different productive, ecological, recreational and institutional functions and operate under distinct management and temporal regimes. Their proximity and contrasting regimes provided an appropriate setting for examining functional relationships across their boundaries.

2.3 Temporal Landscape Observation

Temporal Landscape Observation developed from repeated walking into a structured process of systematic temporal observation and comparison. Walking provided situated access to landscape processes, while temporal comparison constituted the principal analytical procedure.

Fieldwork comprised ten site visits from February to early June 2025 under different weather conditions, days of the week and times of day. Each visit followed the same predefined route and observation points, enabling comparison under changing seasonal, management and use conditions. The five-month observation period captures conditions from late winter to early summer and therefore does not represent a full annual cycle.

Field notes, georeferenced photographs from repeated viewpoints and analytical sketches documented changes between visits, focusing on ecological processes, vegetation cycles, agricultural and maintenance practices, and the movement and activities of people and wildlife.

After each visit, records were compared to identify temporary, recurring or progressively changing processes and whether they extended across landscape boundaries. Patterns recurring across successive visits or following recognizable seasonal, ecological or management rhythms were interpreted as functional relationships when they showed spatial consistency and indications of movement, continuity, exchange or interdependence across neighbouring systems.

3. RESULTS

3.1 Historical Continuity Beneath Contemporary Fragmentation

Historical analysis showed that the contemporary landscape of Altstetten developed through the transformation of a historically continuous agricultural landscape. Until the mid-twentieth century, agricultural fields remained connected to the forest edge and surrounding open land. Subsequent urban expansion introduced Eichbühl Cemetery, Buchlern Sports Centre and Grünhölzli Community Gardens, while elements of the agricultural structure remained physically present.

The area consequently developed into a multifunctional landscape in which distinct systems coexist within a spatial framework inherited from its agricultural past (Figure 3).

3.2 Different Temporal Regimes of Neighbouring Landscape Systems

Repeated observations showed distinct temporal regimes across neighbouring systems. Agricultural land followed seasonal cultivation cycles; Grünhölzli combined cultivation with community use; Eichbühl Cemetery followed institutional maintenance schedules alongside flowering and wildlife activity; Buchlern Sports Centre varied with organized programmes, weather and weekly use; and the forest edge remained comparatively stable.

These different rhythms meant that relationships between systems were not consistently apparent during individual visits and became recognizable through comparison across successive observations.

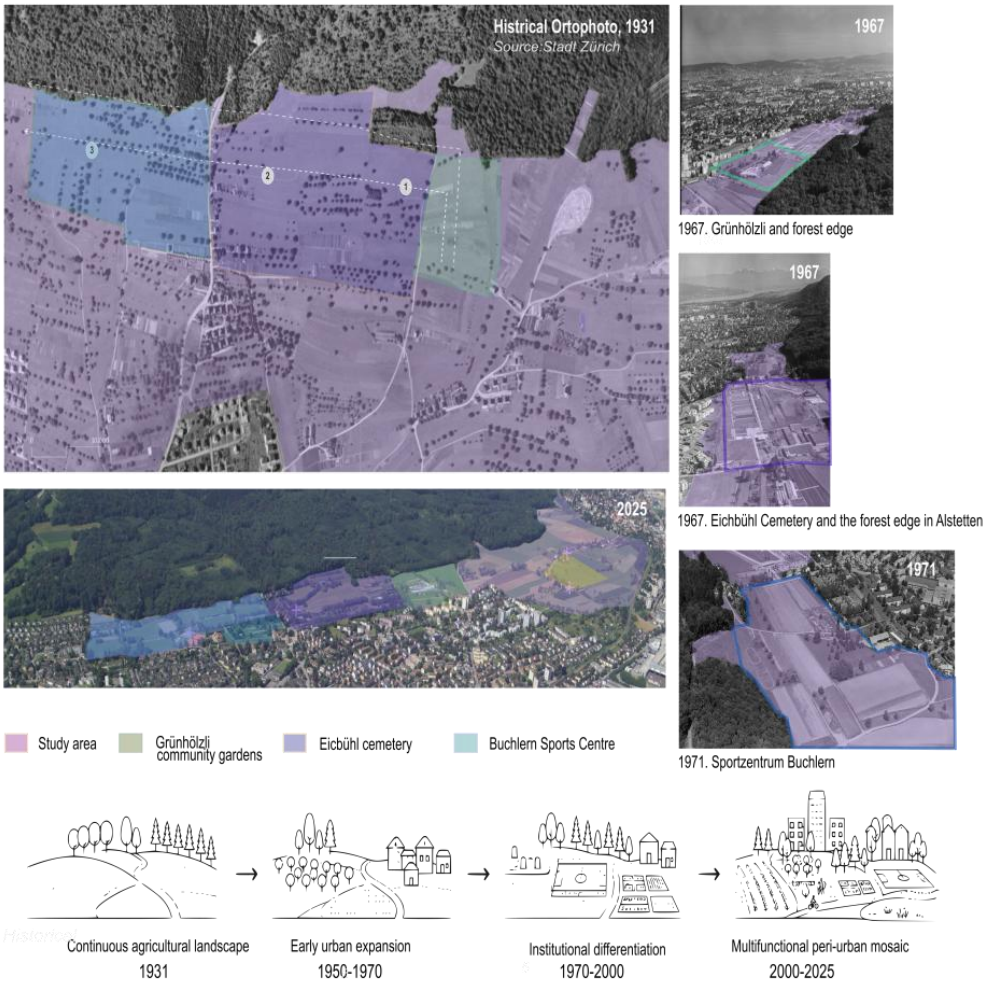


Figure 3. Historical transformation of the study area from agricultural continuity to contemporary fragmentation. Adapted from [8]

3.3 Revealing Functional Relationships Through Repeated Observation

Observations from February to early June were compared to identify recurring processes and relationships across neighbouring systems (Figure 4).

Late Winter: February–March

Initial observations reinforced an interpretation of functional fragmentation: agricultural activity was limited, vegetation largely dormant, and outdoor community and recreational activity scarce. Repeated visits nevertheless recorded continuing greenhouse cultivation and seed production in Grünhölzli, wildlife activity in Eichbühl Cemetery, routine management and stable forest-edge conditions. At this stage, differences between temporal regimes were more apparent than functional relationships.

Spring: April–May

Ecological, productive and social activity intensified across agricultural land, community gardens, cemetery habitats and the forest edge. Phased mowing maintained flowering areas at different moments, while recurring pollinator activity and pedestrian movement across neighbouring systems indicated ecological and social relationships across institutional boundaries.

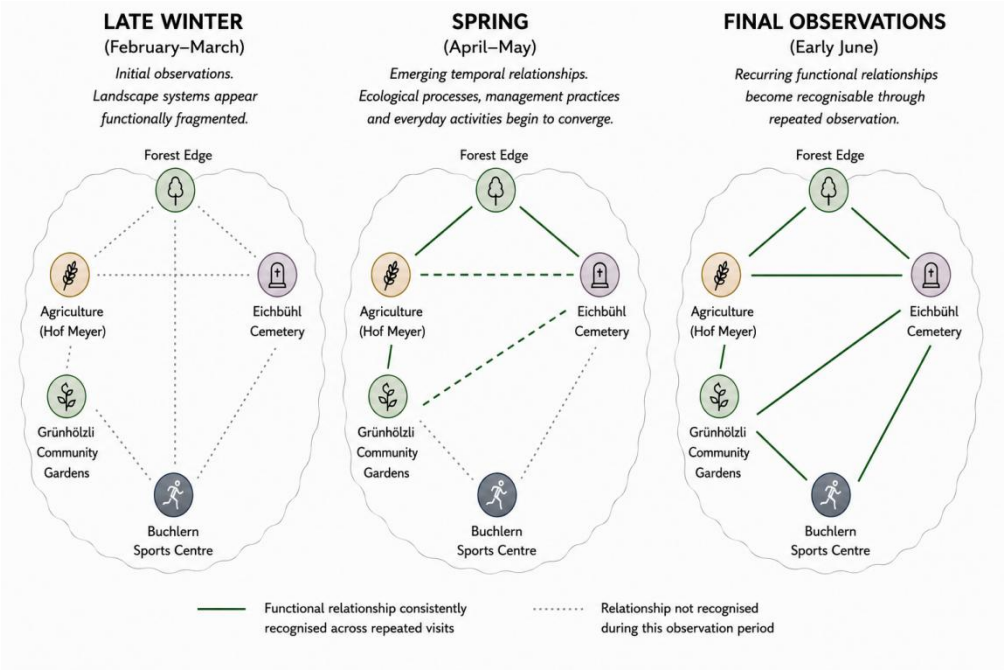


Figure 4. Temporal comparison of recurring functional relationships

Early June

Accumulated comparison made these relationships consistently recognizable. Pollinator activity continued across flowering habitats, phased mowing maintained differentiated vegetation conditions, and everyday circulation crossed institutional boundaries. Their recurrence indicated that spatial and institutional fragmentation coexisted with ecological and social relationships revealed through temporal comparison.

3.4 Translating Revealed Relationships into Research-by-Design

TLO findings were translated into design principles by considering when and under which conditions recurring relationships became active, rather than only where neighbouring landscape systems were located.

Recurring pollinator activity across flowering habitats indicated a temporal relationship between pollinator activity and the seasonal availability of flowering resources,

informing coordinated flowering periods and mowing regimes and the proposal for pollinator corridors.

Repeated productive activity across agricultural land and Grünhölzli Community Gardens indicated a recurring productive overlap, informing cultivated pockets at selected interfaces. Repeated everyday movement across shared edges demonstrated recurring social use between neighbouring systems and informed the agroecological path as a space for shared activities and participation. Comparatively stable forest-edge conditions, together with recurring ecological activity at adjacent habitats, informed the principle of strengthening habitat continuity through forest-edge extension (Figure 5).

The resulting interventions strengthened recurring ecological, productive and social relationships rather than attempting comprehensive spatial restructuring (Table 1).

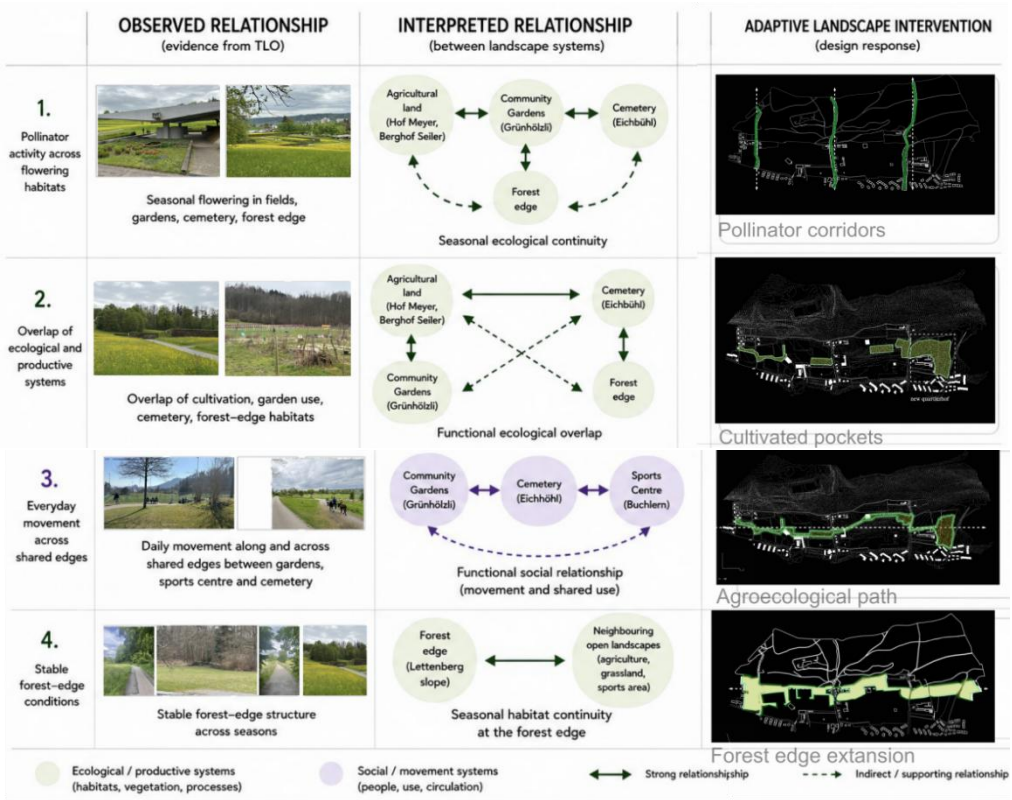


Figure 5. Translating functional relationships into adaptive landscape interventions. Design diagrams adapted from work by S. Momcilovic and C. Terricabras Jove [8]

Table 1. Recurring functional relationships and their design implications

Observed process	Temporal evidence	Landscape systems involved	Design implication
Pollinator activity	Repeated spring observations across flowering habitats	Agricultural land – Grünhölzli Community Gardens – Eichbühl Cemetery – Forest edge	Pollinator corridors
Forest-edge stability and adjacent ecological activity	Comparatively stable forest-edge conditions across visits with recurring ecological activity in adjacent habitats	Eichbühl Cemetery – Forest edge	Forest-edge extension
Productive activities	Seasonal overlap of agricultural cultivation and community gardening	Agricultural land – Grünhölzli Community Gardens	Cultivated pockets
Everyday movement	Repeated use of shared edges and routes across neighbouring systems	Community Gardens – Cemetery – Sports Centre	Agroecological path

4. DISCUSSION

4.1 Interpreting Functional Landscape Relationships Through Time

The findings from Altstetten suggest that fragmentation in multifunctional peri-urban landscapes cannot be understood solely as a spatial condition. Although neighbouring systems remain spatially and institutionally distinct, systematic temporal comparison revealed recurring ecological, productive and social relationships across their boundaries.

These findings complement approaches focused on land-use change, landscape configuration and spatial metrics [2,3], and extend discussions of peri-urban multifunctionality [1] by showing that functional relationships may become legible only through changing seasonal, management and use conditions. In this sense, TLO adds a temporal interpretive layer to spatial analysis and supports the understanding of time as an active dimension of landscape interpretation [4].

4.2 Methodological Implications and Limitations

TLO's methodological contribution lies in systematic comparison rather than repeated site visits alone. Building on walking-based and repeated temporal

observation approaches [6,7], it distinguishes isolated observations from recurring or progressively changing processes and supports interpretation of functional relationships between neighbouring systems.

The study covers a single peri-urban case over five months, from late winter to early summer, and therefore captures only part of the annual dynamics. It does not quantify ecological performance or long-term stability. Future research could test TLO across other contexts and longer observation periods, combined with quantitative ecological monitoring.

5. CONCLUSION

The Altstetten case demonstrates how spatial and institutional fragmentation can coexist with recurring ecological, productive and social relationships that become progressively legible through systematic temporal comparison. TLO therefore provides an empirical basis for distinguishing recurring functional relationships from isolated events and translating them into design decisions.

Within Research-by-Design, these findings informed adaptive interventions that strengthened existing relationships rather than attempting comprehensive spatial restructuring. The study thus positions time as an analytical dimension for recognizing functional landscape relationships and informing adaptive landscape planning and design.

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Research paper

NATURE-BASED SOLUTIONS AS A TOOL FOR THE REVITALIZATION OF ARCHITECTURAL HERITAGE BUILDINGS

Natalija Ilić[1], Ana Momčilović Petronijević[2], Anđela Stevčić[3]

Abstract

Industrialization and subsequent deindustrialization processes have left numerous cities with abandoned industrial buildings and brownfield sites, creating environmental, spatial, and functional challenges. In this context, Nature-Based Solutions (NbS) have emerged as an important approach for integrating natural systems into urban regeneration and architectural revitalization processes. The aim of this paper is to examine the potential of NbS principles in the revitalization of architectural heritage buildings, with a particular focus on industrial heritage, and to identify possible directions for their application in the local context.

The research is based on a combination of theoretical analysis, case study methodology, and comparative analysis. The theoretical framework examines the concepts of urban revitalization, adaptive reuse, and Nature-Based Solutions, emphasizing their role in sustainable urban development. Two international examples of good practice - CaixaForum Madrid and La Fábrica in Barcelona - are analyzed in order to identify different models of NbS implementation in the transformation of industrial heritage. Based on the findings, the paper explores the possibilities for applying similar principles to the former "Đuka Dinić" leather factory complex in Niš, Serbia.

The results indicate that NbS can significantly contribute to the revitalization of industrial buildings through interventions such as green roofs, vertical greenery systems, passive microclimatic strategies, and the enhancement of open and public spaces. The analyzed examples demonstrate that there is no single approach to revitalization through Nature-Based Solutions; instead, successful approaches range from targeted architectural interventions to comprehensive and long-term spatial transformations. The study concludes that NbS represent an effective tool for improving the ecological, functional, and spatial performance of existing buildings while supporting the sustainable regeneration of post-industrial urban areas.

Key words: *Nature-Based Solutions (NbS); Industrial heritage; Revitalization; Adaptive reuse; Sustainable urban development*

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1. INTRODUCTION

Deindustrialisation processes have given rise to a substantial number of abandoned industrial facilities and brownfield sites which, following the loss of their original function, become spatially, functionally, and socially marginalised within the urban fabric. These spaces pose a significant challenge to contemporary urban development due to physical degradation, underutilised land, compromised ecological conditions, and a deterioration of public space quality. Simultaneously, post-industrial cities are confronted with the urban heat island effect, declining biodiversity, a deficit of green areas, and heightened exposure to climate extremes, circumstances that underscore the need for novel approaches to urban revitalisation. Within this context, the concept of Nature-based Solutions (NbS) emerges as a contemporary response to complex urban and ecological challenges. In contrast to conventional technical approaches, NbS entails the integration of natural processes into spatial planning and transformation, with the aim of enhancing ecological performance, urban resilience, and quality of life. Its significance is particularly pronounced in the revitalisation of industrial heritage, where nature assumes an active role as an agent of spatial transformation.

The subject of this paper is an examination of the possibilities for revitalising architectural structures through the application of NbS principles, with a focus on industrial heritage. The objective is to assess the potential of this concept for improving the ecological, functional, and spatial characteristics of existing buildings, as well as to establish guidelines for its implementation within a local context. The methodological approach encompasses theoretical analysis, case studies, and comparative analysis. The paper initially addresses the fundamental concepts, definitions, and principles underlying NbS, along with its relationship to processes of revitalisation and adaptive reuse. This is followed by an analysis of best-practice examples, CaixaForum Madrid and La Fábrica in Barcelona, with the aim of identifying distinct models of NbS implementation in the revitalisation of industrial heritage. Drawing on the conclusions derived from this analysis, the final section of the paper considers the applicability of these models to the former leather factory "Đuka Dinić" in Niš, through an assessment of the site's existing conditions and the potential for implementing NbS principles at the level of the existing structures and their immediate surroundings.

2. THEORETICAL FRAMEWORK

Cities with a pronounced industrial heritage face complex developmental challenges arising from the consequences of deindustrialisation, including abandoned and degraded spaces, contaminated land, and socio-economic problems such as unemployment and social segregation [1]. These conditions, compounded by a lack of green areas, the urban heat island effect, and increased vulnerability to climate change, directly affect quality of life and highlight the need for new approaches to urban development. In this regard, regeneration and revitalisation constitute related yet distinct concepts: regeneration encompasses a broader, integrated process of urban change, whereas revitalisation refers to the reactivation of existing spaces. Urban regeneration is defined as a coordinated

process of improving economic, social, and physical conditions [2], while revitalisation represents its operational component directed at the transformation of existing structures through an interdisciplinary and long-term sustainable approach. It is of particular significance in the context of brownfield sites and industrial heritage, where innovative models such as adaptive reuse are employed to extend the lifecycle of buildings and enable new functional interpretations [3, 4].

In the post-industrial period, nature transitions from a marginalised resource to an active agent of urban development. Within this framework, Nature-based Solutions (NbS) has emerged as the broadest and most encompassing ecologically oriented concept. Its development gained momentum from the UNFCCC process in 2009 and was subsequently formalised through IUCN and EU programmes, including Horizon 2020 [5, 6]. NbS are defined as actions based on the protection, sustainable management, and restoration of ecosystems, which simultaneously address societal challenges and contribute to biodiversity and quality of life [6, 7], supporting the objectives of the circular economy, emissions reduction, and climate resilience, with particular focus on urban regeneration, brownfield revitalisation, and the prevention of urban sprawl. In the context of architectural revitalisation, NbS enable the integration of natural systems across multiple scales through interventions such as green roofs and facades, bio-retention systems, permeable surfaces, and urban gardens, contributing to microclimate improvement, mitigation of the urban heat island effect, energy efficiency, and biodiversity [8]. The preservation of existing structures and application of circular principles further reinforce the sustainability of the revitalisation process. Contemporary revitalisation models are grounded in integrated planning, spatial multifunctionality, community participation, and sustainable solutions, with NbS emerging as a key mediator between natural systems and the built environment. The implementation process is iterative, encompassing phases from problem identification through planning and realisation to monitoring and evaluation, with continuous stakeholder engagement and adaptability to specific contextual conditions [6, 9].

3. ANALYSIS OF BEST PRACTICE EXAMPLES

The selection of best-practice examples was based on three criteria: (1) the industrial heritage character of the buildings, (2) the integration of Nature-Based Solutions (NbS) within the revitalisation process, and (3) the availability of reliable documentation regarding pre- and post-intervention conditions. CaixaForum Madrid and La Fábrica in Barcelona were selected as representative examples due to their transformation of industrial structures of comparable typology through distinct revitalisation approaches. Additionally, both projects are located within a similar Mediterranean climatic and urban context, enabling a more consistent comparison of design strategies and NbS implementation while minimizing the influence of external environmental factors.

3.1. CaixaForum, Herzog & de Meuron, Madrid

The transformation of the former Central Eléctrica de Mediodía power station into the CaixaForum Madrid cultural centre, designed by Herzog & de Meuron, represents a

notable example of industrial heritage revitalisation through adaptive reuse and the integration of Nature-Based Solutions (NbS). Located near the Museo del Prado and Parque del Retiro, the project forms part of the broader regeneration of the Recoletos-Prado corridor. Prior to intervention, the abandoned power station and surrounding structures limited the site's urban potential (Fig. 1a). The revitalisation involved the removal of adjacent buildings and the opening of the site towards Paseo del Prado, improving its spatial integration with the surrounding urban fabric [10].

The project retained the original brick façade while introducing a new metallic envelope and a completely redesigned interior. The removal of the base podium elevated the building above ground level, creating a covered public space that serves as both an entrance area and a gathering place. The building now functions as a cultural centre comprising exhibition spaces, an auditorium, workshops, and public amenities [11,12]. The most prominent NbS intervention is Patrick Blanc's vertical green wall, consisting of approximately 15,000 plants from 250 species. Together with the newly created public space and the adaptive reuse of the existing structure, this intervention contributes to microclimate regulation, urban heat island mitigation, improved air quality, and the overall ecological and spatial transformation of the site (Fig. 1b).



a) *b)*

Figure 1. a) Pre-intervention state of the analysed site, b) Post-intervention condition, Source: https://www.herzogdemeuron.com/projects/201-caixaforum-madrid

Overall, the project demonstrates how adaptive reuse, combined with vegetation-based interventions and public space creation, can simultaneously enhance environmental performance, cultural value, and urban integration, illustrating the potential of NbS to support the sustainable transformation of industrial heritage.

3.2. The Factory (La Fábrica), Ricardo Bofill, Barcelona

The transformation of the La Fábrica industrial complex in Barcelona, initiated by Ricardo Bofill in 1973, represents an early and influential example of industrial heritage revitalisation through adaptive reuse and the long-term integration of NbS. Originally an abandoned cement factory occupying approximately 31,000 m², the complex consisted of silos, chimneys, and underground structures scheduled for demolition (Fig. 2a). Through selective demolition and the reinterpretation of existing industrial elements, the site was transformed into a multifunctional architectural complex [13,14].

The revitalisation process retained and adapted key structural components, converting former industrial volumes into offices, studios, archives, workshops, exhibition spaces, and residential units. Rather than following a fixed programme, the complex evolved gradually in response to changing functional requirements [15].

The most prominent NbS intervention is the extensive integration of vegetation through gardens, rooftop plantings, and vegetated façades, creating a "living architecture" that contributes to microclimate regulation, natural shading, and improved air quality (Fig. 2b) [13,16]. The preservation of the existing concrete structure further supports resource efficiency by reducing material consumption and embodied carbon, while courtyards and large openings strengthen the relationship between indoor and outdoor spaces.



a) *b)*

Figure 2. a) Pre-intervention state of the analysed site, b) Post-intervention condition, Source: a) Bofill, 2025, b) https://www.xuanyinliu.com/

Overall, La Fábrica demonstrates how the adaptive reuse of industrial heritage, combined with vegetation-based interventions and flexible spatial organisation, can create a resilient and evolving environment that integrates ecological, functional, and cultural values.

3.3. Comparative Analysis of the Cases

The comparative analysis was conducted using four criteria: revitalisation approach, type and intensity of NbS integration, functional transformation, and contribution to environmental and spatial quality. The aim was to identify different models of industrial heritage revitalisation and assess the transferability of selected NbS principles to the local context of the former "Đuka Dinić" leather factory in Niš.

A comparative analysis of CaixaForum Madrid and La Fábrica in Barcelona reveals two distinct approaches to the revitalisation of industrial heritage through the application of Nature-Based Solutions. Although both projects are based on adaptive reuse, they differ in their revitalisation strategy, integration of natural elements, and relationship with the surrounding urban context.

The most significant difference lies in the revitalisation approach. CaixaForum represents a clearly defined intervention that preserves the original brick façade while extensively transforming the interior and creating a new public space beneath the elevated structure. In contrast, La Fábrica evolved through a long-term process of selective demolition and gradual adaptation, resulting in a flexible architectural system shaped by continuous transformation. These examples illustrate two complementary models of

revitalisation: a planned and predetermined approach and an adaptive, process-oriented approach.

Differences are also evident in the integration of NbS principles. In CaixaForum, NbS are primarily represented through the vertical green wall, which functions as a targeted intervention with measurable microclimatic benefits. In La Fábrica, vegetation is embedded throughout the complex as an integral component of the architectural and spatial structure, contributing to microclimate regulation, natural shading, and environmental quality. This distinction highlights the potential of NbS to function either as a specific technical measure or as a comprehensive design strategy.

The projects also differ in their degree of publicness and functional organisation. CaixaForum operates as a publicly accessible cultural centre that actively contributes to urban life, whereas La Fábrica is characterised by a more introverted spatial concept focused on creative work, residence, and artistic production. While CaixaForum accommodates clearly defined functions, La Fábrica remains a flexible and evolving environment capable of adapting to changing user needs.

Despite these differences, both projects demonstrate the value of preserving existing structures, reducing resource consumption, and integrating natural systems into the revitalisation process. Table 1 summarises the key similarities and differences between the analysed examples. The findings indicate that successful NbS-based revitalisation can be achieved through different design approaches, providing valuable insights for the future transformation of the former "Đuka Dinić" industrial complex.

Table 1. NbS application comparison across analysed cases, Source: Authors

Analysis criterion	CaixaForum Madrid	La Fábrica, Barselona
Building type (pre-revitalisation)	Industrial building - power station	Industrial complex - cement factory
Revitalisation approach	Radical, design-controlled intervention	Gradual, evolutionary and experimental process
Treatment of existing structure	External brick envelope retained, interior transformed	Selective demolition and reinterpretation of existing structures
Type of intervention	Single, clearly defined architectural intervention	Prolonged multi-phase transformation process
NbS application model	Partial application (single dominant element)	Systemic application (vegetation integrated throughout)
Type and method of vegetation integration	Vertical green system ("living wall")	Vegetation on facades, rooftops, interior, and landscape
Role of vegetation	Reduction of urban heat island, air quality improvement	Natural shading, thermal stabilisation, integral microclimate regulation
Relationship to public space	Extroverted	Introverted
Functional programme	Clearly defined cultural centre	Hybrid – work, residential, artistic
Spatial flexibility	Limited	High
Sustainability aspect – materials	Preservation of brick facade	Preservation of concrete structure
Ecological approach	Targeted	Holistic
Visual identity	Contrast of industrial architecture and "living wall"	Symbiosis of brutalism and vegetation

4. ASSESSMENT OF REVITALIZATION OPPORTUNITIES FOR THE FORMER “ĐUKA DINIĆ” LEATHER FACTORY IN NIŠ THROUGH THE APPLICATION OF NATURE-BASED SOLUTIONS

The selection of the former "Đuka Dinić" leather factory is grounded in the fact that the site possesses characteristics conducive to the application of the various revitalisation models identified through the analysed best-practice examples. The preserved industrial structures represent a potential for the implementation of NbS principles at the level of individual architectural elements, whilst the position of the complex along the Nišava River also points to the possibilities for a broader transformation of the wider industrial area. Nevertheless, the focus of this paper remains directed towards the revitalisation of the existing buildings. Accordingly, the following section presents an analysis of the current condition of the site, identifies its principal challenges and developmental potentials, and subsequently examines the possibilities for applying NbS principles at the level of the existing structures and their immediate surroundings, with the aim of enhancing the ecological, microclimatic, and spatial qualities of the area.

The complex of the former "Đuka Dinić" leather factory is situated on the bank of the Nišava River, approximately 700 metres downstream from the city centre of Niš, within the municipal district of Crveni Krst. Covering an area of approximately 4 hectares, it constitutes a significant segment of the city's former industrial zone and possesses considerable potential for revitalisation and adaptive reuse (Fig. 3a). Within the complex, two preserved industrial heritage buildings can be distinguished, each with a floor area of approximately 3,700 m² and a height of ground floor plus one upper floor plus attic (G+1+A), constructed using a massive structural system with brick facades (Fig. 3b). In addition, a subsequently appended single-storey hall of approximately 4,300 m² features a skeletal structural system and a flat roof. Once regarded as one of the most advanced industrial facilities in the Balkans, the complex is today degraded and functionally inactive. The principal challenges of the site are reflected in the deterioration of the structures, inadequate land use, neglected open areas, and the absence of planned maintenance. A further concern is the insufficient valorisation of the industrial heritage, as a result of which both the buildings and the open spaces continue to deteriorate. At the same time, the site possesses significant developmental potential, owing to its preserved structures, extensive areas of unoccupied land, and its immediate position along the Nišava River.



a) *b)*

Figure 3. a) Site plan, b) Perspective view of the preserved buildings, Source: a) GeoSrbija; b) Authors' documentation

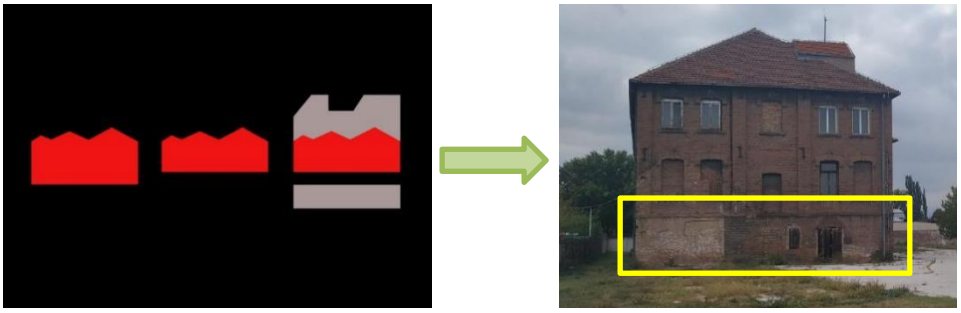
The possibilities for revitalisation may be considered through the integration of natural elements and passive ecological strategies alongside the preservation of the industrial identity of the existing structures. Particular potential is attributed to the single-storey hall with a flat roof, which is well suited to the implementation of green roofs. Such an intervention would contribute to improvements in energy efficiency, mitigation of the urban heat island effect, and enhancement of microclimatic conditions, whilst also affording the possibility of creating additional spaces for occupant use. The preserved brick structures provide a suitable foundation for the application of vertical green systems, following the precedent established by CaixaForum Madrid. The integration of green walls could contribute to microclimatic regulation, air quality improvement, and the aesthetic articulation of the spatial environment (Fig. 4).



a) b) c)

Figure 4. a) Vertical green wall at CaixaForum Madrid, b), c) Potential application of green walls on buildings within the former "Đuka Dinić" complex, Source: a) https://www.herzogdemeuron.com/projects/201-caixaforum-madrid/, b,c) Authors' documentation

Furthermore, the activation of the ground floor zones through the creation of covered public spaces would enhance accessibility, social interaction, and connectivity with the surrounding context (Fig 5).



a) b)

Figure 5. a) Elevated ground-floor concept at CaixaForum Madrid, b) Potential application at the former "Đuka Dinić" complex, Source: a) https://www.herzogdemeuron.com/projects/201-caixaforum-madrid/, b) Authors' documentation

At the level of open surfaces, NbS principles may be applied through the arrangement of green areas, permeable paving, bio-retention elements, and stormwater management systems. A particular developmental potential derives from the direct relationship with the Nišava River. The landscaping of the riparian zone through a linear park or green corridor

would facilitate the integration of the site with existing pedestrian routes, the creation of new public spaces, and the improvement of microclimatic conditions. On the basis of the identified characteristics and potentials, it may be concluded that the revitalisation of the complex through the application of NbS principles represents a viable means of enhancing the physical and functional structure of the buildings, improving the quality of the urban environment, and preserving the industrial identity of the site.

5. CONCLUDING CONSIDERATIONS

On the basis of the theoretical research conducted, the examination of the NbS concept, and the analysis of best-practice examples, it may be concluded that the revitalisation of architectural structures today extends beyond the scope of their physical renewal and presupposes an integrated approach that simultaneously addresses the ecological, spatial, functional, and social dimensions of spatial transformation. Within this process, the concept of Nature-based Solutions (NbS) proves to be a significant instrument of contemporary revitalisation, as it enables the articulation of natural systems and architectural structures in the service of improving environmental quality and urban resilience.

The analysis of CaixaForum Madrid and La Fábrica in Barcelona identified distinct models of NbS application in the revitalisation of industrial heritage. Whereas in the CaixaForum project natural elements are integrated through targeted interventions at the level of individual architectural components, La Fábrica represents a comprehensive and evolutionary process of transformation in which nature becomes a constitutive part of the spatial organisation and identity of the complex. Despite their differences, both examples affirm the importance of preserving existing structures, integrating vegetation, and applying passive ecological strategies.

The investigation of the possibilities for applying these principles to the former "Đuka Dinić" leather factory demonstrated that the local context possesses considerable potential for the implementation of the NbS concept. At the same time, the feasibility of its application is contingent upon the structural characteristics of the buildings, their degree of preservation, available financial capacities, property and legal conditions, and the existence of an appropriate planning and institutional framework. Furthermore, certain interventions require continuous maintenance and technical oversight, which necessitates that their implementation be adapted to the specific conditions of the given site. It may be concluded that the revitalisation of industrial buildings through the implementation of NbS principles represents a significant direction of sustainable development, particularly in cities with a pronounced post-industrial heritage.

Through the integration of natural elements into processes of spatial transformation, it becomes possible to enhance ecological performance, improve the quality of the urban environment, and reactivate neglected sites. In this manner, the potential of the NbS concept for improving the ecological, functional, and spatial characteristics of existing structures has been confirmed, thereby fulfilling the principal objective of the research and demonstrating the possibilities for its application in the revitalisation of industrial heritage within a local context.

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Research paper

ENCLOSURE OF PRIVATE OPEN AREAS OF GROUND-FLOOR APARTMENTS IN MULTI-FAMILY RESIDENTIAL BUILDINGS

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Abstract

Although many people prefer houses with a private yard for peace and greenery, the government's sustainable development policies promote compact cities with higher population density. In order to bridge the gap between user preferences and environmental goals, hybrid housing models are being developed that combine the advantages of private open space and dense urban environments. Private yards in ground-floor apartments give residents the feeling of living in a family house, serve as a green buffer zone that increases privacy and can significantly increase the value of the property. This paper applies a multi-layered methodological approach to the analysis of spatial characteristics and methods of enclosing private open areas on the ground floor of multi-family residential buildings. The focus is on contemporary, representative foreign examples that offer innovative spatial and programmatic solutions within the framework of common urban practice. The research analyzes the spatial, functional and visual relationships between the private gardens of the ground-floor apartments and their environment through the criteria of private-public relations, seclusion, security, microclimatic conditions. Certain demarcating patterns have been recognized, and their systematization can serve as a guideline for architectural design. The enclosing modalities observed in the analyzed examples are denivelation of the private open area level in relation to the surrounding terrain, fencing, application of greenery and various architectural elements. The analysis shows that the identified demarcating categories are most often combined in order to achieve a satisfactory level of openness/closure, privacy, protection and environmental comfort. The research also concludes that certain modalities, which are widely applied in European practice, may not be suitable for environments where the need for privacy is an integral part of the housing culture.

Key words: *Private Open Area, Ground-floor Apartment, Multi-family Housing, Enclosure*

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1. INTRODUCTION

A primary advantage of single-family houses over apartments is the private yard, which offers peace, quiet, and green space in suburban environments [1]. This non-compensatory housing feature is highly preferred by residents [2], making the private garden a critical criterion for evaluating residential quality and environment [3, 4]. Contrary to the wishes of the users for a green, peaceful settlement and a house with a garden, sustainable urban agendas frequently promote the compact city concept. By encouraging higher population density, mixed land use, and reduced car reliance, this urban model serves as a primary strategy to mitigate the environmental degradation caused by urbanization [5]. To bridge the gap between government policies and consumer housing preferences, hybrid residential concepts are emerging. These high-density models integrate the optimal features of both single-family and multi-family housing, effectively fulfilling the demand for private open spaces [3, 4].

As the direct connection of the unit to the ground is lost with the increase in the height of the building, it is quite clear that only apartments on the ground floor can have an associated open area in the form of different variations of yards. Allocating a piece of land directly in front of the window of a ground-floor apartment has multiple benefits. First, a residential unit in a multi-story residential building gets its own green oasis and extra space for outdoor activities, which are characteristics of a family house. Furthermore, the private open area distances the windows of the rooms on the ground floor from the public paths, thus acting as a kind of buffer zone and ensuring privateness. Finally, the application of this concept raises the value of the real estate and the ground floor, from an undesirable floor, becomes an attractive alternative to a family house.

Research on private gardens in multi-family housing remains scarce, with existing literature predominantly focusing on the general physical and psychological well-being benefits of domestic green spaces. Specifically, scholars note that gardens foster socio-ecological relationships [6], that their size dictates health outcomes [7], and that they serve as a critical space for conceptualizing 'home' in modern society [8]. Research also shows that units with an attached garden are particularly attractive to households with children [2]. On the other hand, although ground-floor apartments allow for private yards, research also indicates they suffer from reduced security, increased noise, and compromised visual privacy [9]. Furthermore, residents face persistent challenges, including limited shielding and excessive social interaction due to proximity to building entrances and shared spaces [10].

Western European residential buildings integrated ground-floor private yards over a century ago to counter industrial overcrowding and unsanitary conditions [11]. However, this concept only gained widespread European adoption late last century, evolving into a contemporary standard for modern residential design [12]. Although ground-floor apartments in Serbia historically faced low demand and lower prices, modern residential complexes have reversed this trend [13], driving interest in scarce ground-floor units with private yards. However, while these gardens enhance residential quality, lack of urban oversight often leads to aggressive enclosures—a

result of cultural, historical, and institutional factors that diverge from Western European practices.

This paper explores different designs for demarcating private open spaces of ground-floor apartments of multi-family residential buildings from public areas. The paper analyzes examples of contemporary trends in developed countries.

2. RESEARCH METHODS

In order to analyze the spatial performance and the way of enclosing the private outdoor areas of ground-floor apartments in multi-family residential buildings, a multi-level methodological approach was applied that combines theoretical analysis, a case study and morphological classification.

This paper analyzes contemporary design solutions, realized in environments where the implementation of a wide range of private open spaces on the ground floor represents an established urban planning and design practice. The selection of foreign examples is guided by the criterion of representativeness, with a focus on innovative spatial and programmatic solutions. The backbone of the research is the evaluation of the spatial and visual relationships between private open areas of the apartments on the ground floor and their immediate surroundings. During the evaluation, the criteria of visual and physical access, level of privacy, microclimatic conditions and security were applied.

The empirical data for this study consists of original photographic documentation collected during extensive fieldwork and study trips conducted between 2022 and 2026. The spatial focus of the field research encompasses Copenhagen (Denmark), Amsterdam (the Netherlands), Vienna (Austria), and Stockholm (Sweden). The systematic photographic recording targeted the methods of boundary demarcation and enclosure of private open spaces attached to ground-floor apartments in multi-story residential buildings. The research corpus includes over 50 analyzed case sites, built over the past two decades. Through a comparative analysis of this photographic database, recurring design patterns were identified. After a detailed analysis of spatial relations, the inductive method of classification was applied. The detected modalities of physical and visual separation of private gardens from semi-public and public spaces (for example denivelation, use of vegetation, transparent and non-transparent fences, architectural elements) were systematized. Based on these parameters, a typological classification of physical and visual barriers was formed, which can serve as a guideline for future architectural design. The chosen photographs are employed throughout the paper to elucidate the proposed typology and are not intended as individual subjects of analysis.

Although there is an evident difference in the level of publicness between the street, footpaths and the shared courtyard of a residential block [12], the research suggests that the way and degree of separation and enclosing of private open spaces of ground-floor apartments from public and semi-public spaces do not depend exclusively on this parameter. Therefore, the focus on these three key spatial interfaces did not serve as a basis for the subject typology, but it was carried out on the basis of spatial, functional and aesthetic characteristics.

3. RESULTS

The analysis of the selected examples shows several basic categories of enclosing the private open areas of the ground-floor apartments from the environment, namely denivelation, fencing, use of greenery and use of various architectural elements. The analyzed examples usually contain characteristics of several categories.

3.1. Denivelation

Planning the floor level of the ground-floor apartment above the level of the surrounding terrain is a common approach in the design of residential buildings. In addition to protection against moisture and atmospheric precipitation, this measure is also applied to achieve greater privacy of the residential unit. The latter also applies to the associated open areas of the apartment. However, a small denivelation (for example, less than half a meter), has a symbolic significance rather than ensuring privacy and security. If this measure is combined with other modalities and such elevated terrace is also enclosed with carefully selected greenery (Fig. 1a) or a non-transparent fence (Fig. 1b), then it is completely physically and visually protected. If the height of the barrier formed in this manner exceeds 1.5 meters relative to the public circulation area, it can be classified as a real security barrier, as in that case the open area and its amenities move out of the view of passers-by. When access to the unit is planned through the associated open area, there is an entrance gate within the fence itself, and several steps connect the public space with the private terrace.



Figure 1. Elevated open area level: a) Combined with greenery (Copenhagen, 2016), b) Combined with non-transparent fence and greenery (Copenhagen, 2017), c) Combined with a plant bed at the same level as public space (Copenhagen, 2016), d) Combined with bushy and shrubby greenery at the same level as public space (Copenhagen, 2008) (Source: Stoiljković)

The planning of the greenery in front of the raised private open space moves it away from the public space, which additionally contributes to achieving seclusion. The green area can be at the same level as the public area (Fig. 1c), in the form of a slope or a hill. How much privacy and protection will be achieved depends on the size of the green area and the type of greenery. Low vegetation (especially if the area under the greenery is wide) has more of a role in distancing passers-by from the terrace than creating a barrier to achieve privacy. The use of bushy and shrubby greenery forms an impenetrable barrier between public and private space (Fig. 1d), so a potential passerby cannot approach such a private terrace, and greater privacy is achieved. In addition, the presence of greenery makes the open area more pleasant to stay in.

3.2. Fencing

Placing a fence (or a railing) around the private open area of the ground-floor apartment aims to physically separate the associated open space from semi-public and public facilities in the immediate environment and depending on the height and design of the fence itself, visual protection. The use of a standard height railing (about 1 m) aims to provide safety and demarcate private and public space, rather than achieving intimacy and access control. Such open areas are still visible from adjacent public spaces, but it is clearly indicated where the public zone ends and where the private one begins (Fig. 2a). On the other hand, if the priority is to achieve increased privateness and security, which is most often the case when a private open area borders a busy street, a non-transparent high fence is installed, which makes it sheltered and peaceful (Fig. 2b).



Figure 2. Fencing of private open area: a) Standard height railing (Copenhagen, 2010), b) High non-transparent fence (Vienna, 2015), c) Partially enclosed terrace (Stockholm, 2007), d) Green area in front of the fenced terrace (Copenhagen, 2006) (Source: Stoiljković)

However, tall, solid boundaries around private ground-floor open spaces fundamentally reshape the streetscape, converting vibrant social spheres into mere transitional corridors. Streets with inactive, blank facades impose profound psychological, sociological, and aesthetic repercussions on the pedestrian experience—eroding the perception of safety, generating a monotonous and visually exhausting street front, and undermining social interaction.

If the intention is to experience the public space (most often a common courtyard) as a continuation of the private terrace, and to promote the "overflow" of outdoor activities from private to public open space, then it is only partially enclosed (Fig. 2c). In order to achieve a more pleasant environment, but also greater shielding, the installation of a fence can be combined with the introduction of greenery. Planning the green area in front of the terrace can further physically separate it from the public area (Fig. 2d), while the use of shrubby greenery or a hedge can additionally contribute to intimacy, but also to the improvement of microclimatic conditions.

3.3. Greenery

The use of greenery for the purpose of enclosing the associated open areas of ground-floor apartments has multiple significance. First, it is directly and indirectly beneficial for residents, because in addition to providing a physical framework for rest and recreation, it is responsible for improving aesthetics and regulating the microclimate.



Figure 3. Enclosing with greenery: a) Physical demarcation (Copenhagen, 2019), b) Combined with fence for security protection (Copenhagen, 2020), c) Dense vegetation for complete privacy (Vienna, 2015), d) Enclosing the terrace with a hedge (Copenhagen, 2018) (Source: Stoiljković)

Depending on the size of the plant bed, type of greenery, its size and quality, this kind of barrier can serve purely as a physical demarcation (Figure 3a), or as complete privacy

protection, with all possible modalities between these two cases. The width of the flowerbed, as well as the type and quality of plants, will affect the degree of privacy of the terrace. The narrow plant bed and low vegetation and bushes serve more as a boundary that separates what is private and what is public zone. To achieve greater privacy and protection from physical intrusion, in addition to the use of denser and higher greenery, this measure is often combined with the installation of a fence facing neighboring terraces or public circulation routes (Fig. 3b). With the increase in the width of the green belt in front of the private terrace, it moves away from public areas, and greater seclusion is achieved. The integration of dense vegetation not only creates a shaded, comfortable microclimate but also transforms the outdoor space into a fully screened, private domain. (Fig. 3c). The use of hedges is also a common approach in the enclosure of private terraces. They combine the characteristics of both fences and greenery and are therefore multi-purpose. They serve to demarcate private from public areas, and depending on their height and quality, they can also serve as a visual and intrusion-preventing barrier (Fig. 3d).

3.4. Various architectural elements

Placing planters with greenery around the ground-floor terrace also provides multiple benefits. Planters as architectural elements serve to demarcate public and private spaces, while at the same time the greenery grown in them provides visual protection and contributes to the creation of a pleasant environment. Smaller planters only have the role of physical demarcation between private and public areas, while perimeter defense and shielding cannot be achieved (Fig. 4a). If the goal is to achieve a more serious physical and visual barrier, larger planters are used, strategically placed so that the greenery in them protects the privateness of the terrace and apartment rooms (Fig. 4b). This measure is often combined with elevating the level of the terrace, which further contributes to the creation of a quiet and safe private outdoor space.



Figure 4. Enclosing with various elements: a) Small planters for physical demarcation (Copenhagen, 2017), b) Larger planters for greater privacy (Stockholm, 2018), c) Demarcation by different floor treatments (Amsterdam, 2010), d) Demarcation towards a neighbor (Copenhagen, 2016) (Source: Stoiljković)

Also the use of other architectural elements, such as gabions, awnings, movable screens, etc. can serve to separate the private open area from the public ones. Depending on their design, size and transparency, the physical separation is more or less pronounced, while privacy and protection are generally more difficult to achieve by applying these measures.

Within this category, examples should also be mentioned where there is no form of physical barrier between the private space of the terrace and the public surrounding space, but rather the terraces are demarcated from the surrounding only by a difference in floor treatment, which marks what is private and what is public area (Fig. 4c). In this way, the boundary between private and public space is blurred, the private open space is more tightly connected to the public space, and more intensive use of public space is encouraged and emboldened. This design approach has significant functional and spatial benefits, as the area available to users for outdoor activities is significantly increased. On the other hand, this architectural principle is not suitable for environments where the need for privacy is an integral part of the housing culture or where the safety of the residents would be endangered in this way. It is interesting in some examples of this type that despite the very discrete and vague demarcation of the belonging open space to the public space, the demarcation towards the neighbors is clearly expressed (Fig. 4d).

4. DISCUSSION

An analysis of selected case studies reveals that ground-floor private open spaces are typically enclosed through a combination of four primary methods: denivelation, fencing, landscaping, and use of various architectural elements.

Elevating the level of the associated open area in relation to the surrounding terrain is an effective method for demarcating private and public space, increasing privateness and safeguarding. In combination with a fence, green areas in front of an open space or dense vegetation, a pleasant environment can be created, completely visually and physically hidden from the public space. Placing a fence around the private open space on the ground floor primarily serves to physically demarcate zones, while the level of visual protection and access control directly depends on its height, transparency and eventual combination with greenery. Standard and partial fences clearly define the boundaries of the property without completely isolating it from the environment, which is suitable for the spatial interface between private terraces and shared yards, while high, non-transparent fences provide maximum shielding towards busy public spaces such as the street. The use of greenery for the purpose of enclosing private terraces on the ground floor is a multifunctional solution that, in addition to physical demarcation and visual protection, actively improves the aesthetics and microclimate of private open spaces. This measure is often combined with others, successfully balancing the need for intimacy, physical distance and improvement of microclimate conditions in the private outdoor space. The use of planters with greenery and other architectural elements provides multiple aesthetic and spatial advantages, but their effectiveness in achieving safeguarding and privacy directly depends on dimensions,

design and strategic positioning. The complete absence of physical barriers, where the demarcation of private and public space is done solely by different floor treatments, blurs the boundaries and creates a fluid, expanded space for outdoor activities, but directly sacrifices the privacy and protection of the occupants. This design is not applicable in environments with a housing culture that requires a high level of privacy, nor in environments where such a solution could threaten the safety of the occupants.

The difference in the perception and treatment of ground-floor open spaces between Serbia and Western European countries (such as Denmark and the Netherlands) is clearly manifested through contrasting spatial and socio-cultural patterns. While privacy in Serbia is primarily defined as complete physical isolation from the public sphere and freedom from visual intrusion, in Western Europe it is achieved through social integration and a visual dialogue with the surroundings. Consequently, the main motive for enclosure in the domestic context is the need for security—namely, defense against burglaries and noise—whereas Western European models treat fences through the lenses of aesthetics, landscape design, and microclimatic comfort. This approach directly shapes the attitude toward passersby: in Serbia, a pedestrian on the sidewalk is often perceived as a potential threat, whereas in Denmark or the Netherlands, they are viewed as an integral part of the local community. Finally, these differences are deeply reinforced by legal frameworks—weak institutional control and the toleration of unauthorized modifications in Serbia enable aesthetic anarchy along street fronts, in sharp contrast to rigorous Western European regulations that strictly dictate the permitted height, materialization, and transparency of fences.

5. CONCLUSIONS

While sustainable compact city models demand high-density multi-family housing, user preferences heavily favor individual homes with private yards. To accommodate urban population growth, contemporary architecture must balance high density with private green spaces. Multi-story residential buildings with different types of private ground-floor open areas provide an effective model to reconcile these conflicting demands.

This research analyzes the modalities of enclosure of ground-level open spaces in multi-family residential buildings, relying on primary empirical data collected through several years of study tours. Based on the rigorous analysis and evaluation of these representative examples, a comprehensive typological classification of visual and physical barriers was established. The identified and systematized typologies of private space enclosures can serve as a robust analytical basis for formulating precise design guidelines in architectural practice.

The primary limitation of this work lies in the contextual specificity of the developed framework, which may not be directly transferable to the Republic of Serbia due to distinct institutional and socio-cultural factors. Consequently, future research is required to adapt these guidelines, ensuring their feasibility and relevance within the domestic planning and legislative landscape.

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Research paper

BUILDING TRANSFORMATION AS A RESPONSE TO SUSTAINABILITY CHALLENGES AND EMERGING HOUSING MODELS

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Abstract

Contemporary social, environmental, and economic challenges are reshaping housing practices by promoting more efficient and responsible use of natural resources. Within this framework, the adaptive reuse of existing buildings has emerged as a key strategy for sustainable development, enabling the transformation of obsolete or underutilized structures into new architectural functions while minimizing resource consumption and environmental impact. Such transformations are closely linked to contemporary lifestyles, which are increasingly influenced by changing family structures and evolving patterns of work, generating a growing demand for more flexible, adaptable, and resilient living environments.

This paper examines the transformation of existing buildings with diverse original functions into residential spaces while preserving their essential architectural form, thereby offering a sustainable response to contemporary housing needs and emerging residential models. The research focuses on the adaptive reuse of public and non-residential buildings for housing purposes, exploring the spatial, functional, environmental, and social dimensions of these transformations. The primary objective of the study is to analyze and systematize architectural approaches to adaptive reuse through three selected case studies that exemplify successful strategies for addressing contemporary sustainability challenges. By identifying key design principles and transformation mechanisms, the research contributes to a broader understanding of how existing building stock can be converted into sustainable, flexible, and context-sensitive housing models capable of responding to the changing demands of contemporary society.

Key words: *adaptive reuse, building transformation, existing building stock, contemporary housing, sustainable architecture.*

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1. INTRODUCTION

Contemporary architectural aesthetics are increasingly shaped by the principles of sustainable development, which serve as a fundamental framework for achieving a balanced relationship between humans and the natural environment. One of the most complex challenges facing contemporary society is environmental pollution and the excessive consumption of energy resources within the construction sector [1]. A significant proportion of the existing building stock fails to meet contemporary environmental protection requirements, exhibiting low energy efficiency and high maintenance costs. These challenges can be addressed through the application of sustainable design principles, as well as the integration of advanced materials and technologies aimed at energy generation, conservation, and efficiency improvement [2]. However, a significant challenge facing contemporary architectural and construction practice is the existence of a deteriorated building stock that has lost its original function or no longer serves any meaningful purpose. In this context, an important question arises: should such buildings be demolished, or should they be assigned new functions through adaptive reuse strategies? Current practice demonstrates that demolition is not always the most rational or sustainable solution. On the contrary, the preservation and enhancement of existing structures through carefully planned interventions often result in more effective and environmentally responsible outcomes. Furthermore, a key principle of sustainable architecture lies in designing and transforming buildings in a manner that enables them to accommodate future changes and evolving user requirements, thereby extending their lifespan and increasing their long-term functional value [3].

From the perspective of sustainability, building transformation, or adaptive reuse, represents one of the key approaches to sustainable architecture, as it enables the extension of a building's life cycle through its adaptation to new needs and conditions of use [4]. Adaptive reuse constitutes a specialized form of building refurbishment that presents complex challenges for designers. The conversion of a building to a new functional use introduces additional regulatory requirements and may require amendments to planning regulations or formal approval for a change of use. Despite these challenges, the substantial economic, environmental, and social benefits associated with adaptive reuse make it an increasingly attractive strategy for investors and policymakers [5]. Building transformations can be implemented at different scales and in various forms. They encompass interventions ranging from the preservation of a building's external appearance while reorganizing its internal spatial layout, to the restoration and reconstruction of historic buildings, as well as changes of use, extensions, and additions to existing structures [6]. The scope of interventions may range from minor modifications to comprehensive spatial and functional transformations, depending on the characteristics of the building and the objectives of the adaptive reuse project. Adaptive reuse is particularly significant in contexts with historical, architectural, or cultural value. By revitalizing existing buildings, it helps preserve the identity of place and the continuity of local culture while preventing the deterioration or loss of valuable built heritage [7].

In this way, adaptive reuse creates a connection between the past and the evolving needs of contemporary communities by enabling existing buildings to accommodate new functions while preserving their authenticity. Owing to their distinctive character and historical significance, such spaces often offer a unique experiential and cultural value, making them particularly attractive to users.

2. RESEARCH METHODOLOGY

This study investigates the adaptive reuse of the existing building stock as a strategy for creating new forms of housing. In this context, building transformation is examined as a sustainable approach that simultaneously enables the preservation of existing structures and their adaptation to contemporary residential functions. The research adopts a multi-method approach that integrates theoretical analysis with empirical investigation. The methodological framework is based on a comparative case study analysis supported by typological and spatial-functional analyses. These methods enable a systematic examination of the architectural characteristics of existing buildings, the processes of their transformation, and the housing typologies resulting from adaptive reuse.

Comparative analysis serves as the principal analytical framework of the study. Three case studies were selected according to predefined criteria: (1) the diversity of the buildings' original functions, (2) the successful conversion of the buildings into residential use, (3) the architectural and spatial complexity of the transformation process, (4) the availability of relevant project documentation and reliable information regarding the completed projects, and (5) geographical diversity. The application of these criteria ensured the selection of representative examples illustrating different adaptive reuse strategies while providing a sufficiently broad basis for comparative analysis across diverse cultural and urban contexts. The comparative evaluation is conducted using a unified analytical framework in which each case is assessed according to the same parameters: the original function and architectural characteristics of the building, the extent of spatial and functional interventions, the relationship between preserved and newly introduced architectural elements, the resulting housing typology, and the contribution of the transformation to environmental, functional, and cultural sustainability. Applying identical evaluation criteria to all case studies ensures methodological consistency and facilitates the identification of common design principles as well as context-specific solutions.

Based on these selection criteria, three representative case studies were chosen for detailed analysis. The first case study examines Grange Hall, a former nineteenth-century school building in London. The second focuses on Rassvet Loft, an adaptive reuse project involving the conversion of the former Rassvet furniture factory in central Moscow into residential units. The third case study analyzes House Altinho, a historic house in Lisbon that was transformed into a contemporary residential building while preserving its architectural identity.

Considered collectively, these case studies represent three distinct building typologies—educational, industrial, and warehouse buildings—illustrating different

approaches to adaptive reuse across diverse cultural contexts. Their comparative analysis provides a foundation for identifying transferable design principles and supports broader conclusions regarding the role of adaptive reuse in promoting sustainable housing development while preserving the architectural and cultural values of the existing building stock.

3. ANALYSIS OF CASE STUDIES ON THE ADAPTIVE REUSE OF BUILDINGS FOR RESIDENTIAL FUNCTIONS

The selected case studies illustrate three distinct approaches to the adaptive reuse of existing buildings for residential purposes. Although the projects differ in their original functions, architectural characteristics, and geographical contexts, they share a common objective: preserving the existing building structure while adapting it to contemporary residential needs. The comparative analysis focuses on identifying the transformation strategies, spatial interventions, and design approaches that enable the integration of new residential functions while maintaining the architectural identity and contextual values of existing buildings.

The analyzed examples demonstrate that adaptive reuse requires context-specific solutions tailored to the architectural, historical, and functional characteristics of each building. Through the preservation of existing structures and the introduction of carefully considered interventions, adaptive reuse contributes to sustainable development by extending the functional life of buildings and enhancing the adaptability of the built environment.

3.1. GRANGE HALL | Nissen Richards Studio London | United Kingdom

Grange Hall (Figures 1–4) is a historic school building constructed in 1837, originally designed for educational purposes. Following the cessation of its educational function in the 1960s, the building was temporarily used as a storage facility before being converted into a multi-family residential building. Owing to its outstanding Georgian architectural features and historical significance, preserving its architectural identity was the primary objective of the transformation project. The adaptive reuse strategy adopted a conservation-led approach that retained the original building form, structural system, material palette, and significant façade elements while introducing contemporary residential functions [8]. Rather than creating a strong contrast between the historic fabric and new additions, the design achieved a balanced integration of heritage values and contemporary architectural expression [9]. The principal spatial intervention involved the reorganization of the interior while preserving the existing building envelope. The structure was divided into nine independent residential units through vertical zoning across two storeys and a converted attic. Bedrooms were located on the lower floors, while the living areas occupied the attic level, maximizing the potential of the existing roof space. Original window openings on the principal façade were preserved, whereas new openings on the side elevations improved natural daylight without altering the building's historic character.



Figure 1. First floor plan



Figure 2. Second floor plan



Figure 3. Front façade of the building



Figure 4. View of the building

Figures 1-4, Source https://www.archdaily.com/930782/grange-hall-house-nissen-richards-studio

3.2. Rassvet Loft Studio Renovation | DNK ag | Moscow, Russia

Rassvet Loft Studio (Figures 5–8) is an adaptive reuse project located in central Moscow on the site of the former Muir & Mirrielees furniture factory, later converted into the Rassvet machine manufacturing plant during the Soviet period. The transformation sought to preserve the site's industrial heritage while integrating it into the contemporary residential fabric of the city. The adaptive reuse strategy retained the existing structural framework and respected the historical identity and *genius loci* of the site. Instead of replacing the industrial complex with new construction, the project reinterpreted its architectural character for residential use. The design of the new additions was informed by the surrounding historic context, including the former factory, the Neo-Gothic cathedral, and the Shchukin Estate, ensuring continuity between the historic environment and the new residential development [10]. The principal intervention transformed the former industrial building into contemporary housing while preserving its prefabricated reinforced-concrete structure. New residential volumes were inserted within the existing envelope, with each structural bay accommodating a single residential unit. The original six-metre floor height enabled the creation of duplex apartments with mezzanine levels, while the attic and basement were converted into additional residential space and parking facilities. Ground-floor apartments were complemented by private courtyards, creating a clear transition between public and private space. A second intervention rehabilitated an ancillary building originally intended for demolition, converting it into a series of low-rise townhouses with internal courtyards, attic floors, and covered parking. The consistent use of handcrafted red clinker brick visually unified the development, strengthened its

relationship with the surrounding historic buildings, and transformed former service areas into high-quality public spaces.

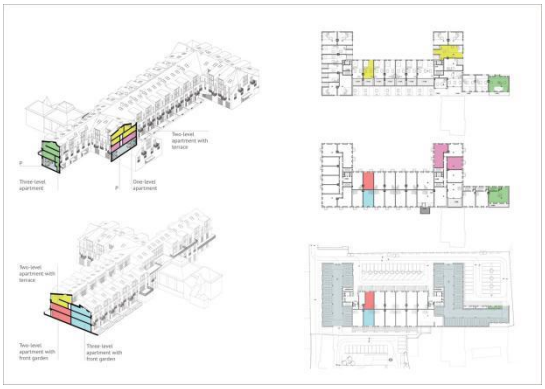


Figure 5. Axonometric view, section, and floor plans of the building.



Figure 6. Detail of the façade

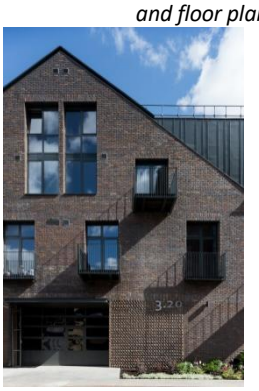


Figure 7. Detail of the façade



Figure 8. Industrial building transformed into multifamily building

Figures 5-8, Source: https://www.archdaily.com/904661/rassvet-loft-renovation-dnk-ag

3.3. House Altinho | António Costa Lima Arquitectos | Lisbon, Portugal

House Altinho (Figures 9–12) represents an example of the adaptive reuse and typological transformation of a former industrial warehouse into a contemporary single-family residence. Located on the banks of the Tagus River in Lisbon's Junqueira district, the project preserves the site's industrial heritage while adapting it to contemporary residential requirements. The adaptive reuse strategy is based on a conservation-oriented approach that retains the existing perimeter walls of the former warehouse as the defining element of the new architectural composition. By preserving the original urban morphology and reinterpreting the warehouse typology, the project establishes a dialogue between the historic industrial structure and contemporary residential architecture. The intervention combines the adaptation of the existing building with a volumetric extension that formally reinterprets the original warehouse while remaining within the permitted building envelope [12]. The principal spatial intervention organizes the residential programme within the preserved perimeter walls, complemented by internal courtyards and terraces that enhance spatial quality and natural lighting. The functional layout adopts an inverted vertical zoning strategy, placing the private (night) zone on the first floor and the public (day) zone on the

uppermost level in order to maximize southern orientation and views towards the surrounding urban landscape and the MAAT Museum [13]. The architectural treatment reinforces the relationship between continuity and innovation. Brick, selected to match the colour of the original masonry, ensures visual continuity with the historic structure, while its contemporary application through perforated brickwork clearly distinguishes the new intervention from the preserved building fabric.



Figure 9. Floor plans

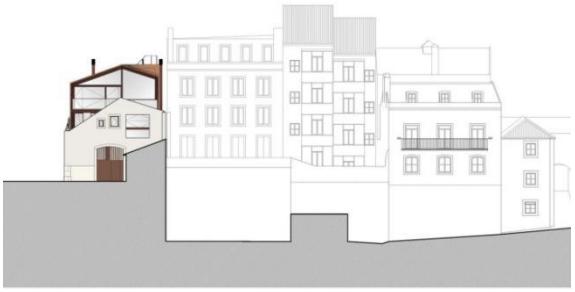


Figure 10. Façade drawing



Figure 11. Front façade



Figure 12. Back façade

Figures 9-12, Source: https://www.archdaily.com/962922/house-altinho-antonio-costa-lima-arquitectos/60bbf47bd898a00164926f16-house-altinho-antonio-costa-lima-arquitectos-photo

4. DISCUSSION

The contemporary concept of sustainability in architecture increasingly emphasizes the preservation and enhancement of the existing building stock, recognizing adaptive reuse as an effective alternative to new construction. By preserving existing structures, adaptive reuse reduces resource consumption, construction waste, and carbon emissions while extending the service life of buildings. Consequently, it represents an integrated approach that addresses environmental, economic, social, and cultural aspects of sustainability while responding to contemporary housing needs.

The comparative analysis demonstrates that, despite differences in their original functions, architectural characteristics, and geographical contexts, all three case studies share a common objective: preserving the existing building structure while adapting it to contemporary residential requirements. In each project, significant structural and spatial elements were retained, while new interventions introduced residential

functions without compromising the architectural identity of the buildings. These findings confirm the flexibility of adaptive reuse as a strategy applicable to diverse building typologies.

At the same time, the analyzed projects reveal different transformation approaches. Grange Hall demonstrates a conservation-led strategy focused on preserving the historical character and spatial organization of a former educational building. Rassvet Loft illustrates a more intensive transformation, where an industrial structure was reinterpreted through the introduction of contemporary residential typologies while maintaining its structural framework and industrial identity. House Altinho represents a context-sensitive approach that combines the preservation of an industrial heritage structure with contemporary architectural interventions and innovative spatial organization. These differences indicate that successful adaptive reuse depends on strategies tailored to the specific architectural, functional, and historical characteristics of each building rather than on a universal design model.

The findings support the research objective by demonstrating that adaptive reuse can facilitate the development of new housing forms within the existing building stock. The analyzed examples show that successful transformation depends on achieving a balance between heritage preservation and contemporary spatial requirements. Therefore, adaptive reuse should be understood not only as a conservation practice but also as a comprehensive design methodology that promotes architectural continuity, functional flexibility, and sustainable housing development.

5. CONCLUSION

Contemporary architectural practice increasingly recognizes adaptive reuse as an important strategy for transforming the existing building stock and developing new forms of housing. Adaptive reuse does not imply the replication of historical forms, but rather the creation of context-sensitive design solutions that establish continuity between inherited architectural values and future needs. Rather, it requires design interventions that respond to contemporary needs while respecting the architectural values and historical significance of the existing building. More broadly, processes such as adaptive reuse, rehabilitation, renovation, conversion, extension, and expansion establish continuity between inherited architectural values and future societal needs. From a sustainability perspective, this approach offers multiple benefits. It reduces the generation of construction and demolition waste, minimizes the consumption of new building materials through the reuse and recycling of existing structural and building components, and consequently contributes to a substantial reduction in environmental impacts. In the context of contemporary housing, adaptive reuse requires an innovative and carefully considered design approach, as emerging housing models are becoming increasingly flexible, dynamic, and responsive to the changing needs of modern society. Rather than prescribing a single housing typology or a fixed spatial model, each adaptive reuse project generates a context-specific architectural solution shaped by the characteristics of the existing building and the evolving functional requirements of its users.

The findings of this research suggest that adaptive reuse represents a viable alternative to new residential construction by encouraging innovative design approaches and supporting the development of new housing models. The reuse of existing buildings extends their service life, reduces pollution and construction waste associated with demolition, and decreases the demand for new construction materials. Consequently, adaptive reuse has the potential to make a substantial contribution to the environmental, economic, and social sustainability of the built environment.

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Research paper

WORKPLACE QUALITY IN INDUSTRIAL ARCHITECTURE: PRODUCTION VS. ADMINISTRATIVE WORKSPACES

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Abstract

Sustainable industrial architecture is increasingly expected to provide not only environmental performance but also healthy and equitable working environments for all employee groups. This study investigates workplace quality in contemporary industrial buildings, with particular emphasis on the relationship between Indoor Environmental Quality (IEQ), spatial organization, and workplace equality. The research applies a qualitative multiple-case study approach to eight contemporary industrial complexes, using an assessment framework structured around four analytical domains: spatial and functional quality, environmental comfort, architectural quality, and well-being and social sustainability.

The comparative analysis reveals different degrees of spatial integration between production and administrative workspaces. While segregated organizational concepts maintain functional separation and unequal workplace conditions, more integrated solutions provide stronger visual and physical connections, comparable environmental quality, and greater accessibility to shared employee amenities. These findings demonstrate that workplace quality depends not only on environmental parameters such as daylight and ventilation but also on the overall architectural organization of industrial facilities.

The principal contribution of the study is the proposed conceptual framework that classifies contemporary industrial buildings according to the degree of spatial integration and workplace equality. The findings highlight workplace quality as an important component of social sustainability and provide an additional perspective for evaluating and designing more equitable industrial workplaces.

Key words: *Workplace quality, Indoor Environmental Quality (IEQ), Industrial architecture, Workplace equality, Social sustainability*

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1. INTRODUCTION

Although sustainable industrial architecture has increasingly embraced green design principles, indoor environmental quality (IEQ) is often not provided equally to all categories of workers [1,2]. Administrative spaces typically receive greater attention in terms of daylight, thermal comfort, acoustics, and visual quality than production areas. This historical division reflects the socio-spatial dichotomy between "white-collar" (administrative) and "blue-collar" (production) workers, where spatial hierarchy traditionally mirrored corporate status [3].

While extensive research addresses overall energy efficiency in industrial facilities, a clear research gap remains regarding the equitable distribution of IEQ parameters and their direct impact on employee health and well-being across different functional zones [1,4]. Contemporary industrial design must integrate social sustainability and spatial equity across the entire workforce rather than restricting high-quality environments to management sectors [5,6].

The subject of this research is the spatial and environmental quality of administrative and production workspaces within contemporary industrial complexes. The main objective of the paper is to evaluate the degree of spatial equity and desegregation achieved across different user groups through modern architectural design. To ensure a systematic assessment, the evaluation is structured around four key domains: spatial and functional quality, environmental comfort, architectural quality, and social sustainability related to health and well-being.

2.THEORETICAL BACKGROUND

The contemporary theoretical discourse on industrial architecture increasingly moves away from purely utilitarian and functionalist paradigms, shifting its core focus onto the quality of the working environment and its impact on the psychophysical health and social well-being of all employees [1,3].

2.1. Indoor Environmental Quality (IEQ)

Indoor Environmental Quality (IEQ) encompasses a multidisciplinary set of parameters: thermal comfort, acoustic comfort, indoor air quality, and visual comfort (both natural and artificial lighting) [2]. In traditional industrial facilities, high IEQ standards were predominantly reserved for administrative areas, while production halls were treated as strictly technical zones with secondary levels of lighting and microclimatic control [4]. Contemporary architectural design theory emphasizes that IEQ directly influences circadian rhythms, productivity, and stress reduction across the entire workforce [1]. Modern approaches demand an equitable distribution of daylight and fresh air through shed roofs, skylights, and smart HVAC systems, thereby democratizing IEQ parameters across the entire facility [2].

2.2. International Space Assessment Standards: LEED and WELL

Contemporary certification systems for green and human-centric architecture provide both a quantitative and qualitative framework for analyzing the spatial treatment of workers:

LEED (Leadership in Energy and Environmental Design): Although primarily focused on energy efficiency and material sustainability, the LEED system evaluates daylighting, quality views, and the use of non-toxic, low-emitting materials through its Indoor Environmental Quality category [7]. In modern industrial facilities, these criteria are increasingly applied to production halls rather than being restricted to administrative wings.

WELL Building Standard: Unlike LEED, WELL focuses primarily on human health and well-being within the built environment. Through concepts such as Air, Light, Comfort, Mind, and Community, WELL advocates for spaces that promote healthy lifestyles, reduce fatigue, and provide equal access to restorative and recreational areas. Applying WELL principles within the industrial sector directly redefines the status of the production worker, transforming the factory into a healthy workplace [2,8].

2.3. Social Sustainability and Spatial Equity

Social sustainability in architecture entails creating spaces that foster equality, social cohesion, and inclusiveness [5]. In an industrial context, this directly links to the concept of Spatial Equity-a principle stating that all employees, regardless of their position in the corporate hierarchy ("blue-collar" or "white-collar"), should enjoy an equal quality of workspace, access to daylight, and shared socialization zones [2,5].

Biophilic design and the integration of communal amenities (cafeterias, entrance atriums, green terraces) function as spatial mediators of social sustainability [9]. These spaces dismantle traditional spatial segregation and enable the creation of a unified corporate identity based on mutual respect among all workers.

3. METHODOLOGY

This research applies a qualitative multiple-case study approach to examine workplace quality in contemporary industrial buildings, with particular emphasis on differences between production and administrative workspaces. The study adopts a comparative assessment framework addressing spatial, environmental, architectural, and social dimensions of workplace quality. The methodological approach is based on the assumption that sustainable industrial architecture should provide equitable workplace conditions for all categories of users, regardless of their role within the production process.

The research sample consists of eight contemporary industrial complexes selected through purposive sampling from an initial pool of approximately 20 industrial projects. The initial selection focused on projects completed within the last 15 years in order to ensure their relevance to contemporary industrial architecture. From this initial pool, eight case studies were selected based on the following criteria: the integration of

production and administrative functions within the same architectural complex; the availability of sufficient architectural documentation to enable the analysis of both workspace types; and diversity in industrial sectors and geographical contexts. Based on these criteria, the final sample included: Buda Recypark (Belgium), Amplio Automation (Hungary), Ampliación de Instalaciones (Spain), SmartMill (Canada), Greyder Shoe Factory (Türkiye), Arya Sanat Factory (Iran), Steelform (Portugal), and Ferneto SA (Portugal).

The criteria for the comparative analysis were defined based on the theoretical framework and a preliminary analysis of spatial relationships and workplace conditions in contemporary industrial architecture. Rather than being adopted from a single existing assessment method, the criteria were synthesized from the key aspects identified through this analysis and further supported by relevant literature on Indoor Environmental Quality (IEQ), workplace design, employee well-being, and social sustainability [1–3, 5, 7, 8]. This process resulted in four complementary analytical domains that reflect the spatial, environmental, architectural, and social dimensions of workplace quality:

- **Spatial and Functional Quality**, including the organization and relationship between production and administrative areas, spatial accessibility, and visual connectivity;
- **Environmental Comfort**, encompassing the availability of natural daylight, ventilation strategies, and conditions affecting thermal and visual comfort;
- **Architectural Quality**, examining material treatment, architectural expression, and the overall spatial identity of different working environments;
- **Well-being and Social Sustainability**, evaluating the availability and quality of shared facilities, such as canteens, break areas, locker rooms, sanitary spaces, and other amenities supporting employee well-being.

The research was conducted in three phases. First, publicly available architectural documentation, including project descriptions, drawings, and photographs, was collected and systematized. Second, each case study was evaluated according to the predefined assessment framework. Finally, the results were comparatively analyzed to identify recurring spatial patterns and differences in the treatment of production and administrative workspaces and their contribution to workplace quality and equality.

4. RESULTS

4.1. Spatial and Functional Quality

The comparative analysis identified different approaches to the spatial organization of production and administrative workspaces across the analyzed industrial complexes (Table 1). Representative spatial configurations identified across the analyzed case studies are illustrated in Figure 1. Three case studies (Greyder Shoe Factory, Ampliación de Instalaciones and Steelform) maintain a clear physical separation between the two functional zones, whereas the remaining projects adopt more integrated layouts through attached administrative blocks or unified building compositions. Administrative

areas positioned above or overlooking production spaces were identified in Amplio Automation and Arya Sanat Project, enabling direct visual contact with manufacturing activities. Visual connectivity is established in most projects through glazed bridges, transparent partitions, atria or internal circulation spaces. Circulation connections between production and administrative areas are present in all analyzed case studies, although their degree of sharing and accessibility varies. The highest level of spatial integration is observed in Buda Recypark and Ferneto SA, where production and administration function within a unified architectural composition.

Table 1. Spatial and Functional Characteristics of the Analyzed Case Studies

Case study	Spatial organization	Spatial relationship	Shared circulation
1. Buda Recypark (Brussels, Belgium) 2024	Rectangular production hall with attached administrative annex	Administration connected to the hall through a glazed bridge	Shared entrance with bridge connection between functions
2. Amplio Automation (Székesfehérvár, Hungary) 2018	Rectangular hall with integrated service and office annex	Administration positioned within the same building volume	Shared internal circulation through the service zone
3. Ampliación de Instalaciones (Crevillente, Spain) 2020	Production developed through successive hall extensions with separate administrative block	Functional connection between production and administration	Circulation partially overlaps with cafeteria and service areas
4. SmartMill (Lévis, Canada) 2022	Rectangular hall with compact administrative annex	Offices directly connected to production through entrance zone	Shared entrance hall connecting both sectors
5. Greyder Shoe Factory (Çorum, Turkey) 2015	Large-span production hall with multi-level administrative block	Administration physically separated but internally connected	Vertical circulation links administration and production
6. Arya Sanat Project (Tehran, Iran) 2025	Rectangular hall with administrative mezzanines	Vertically separated administration and worker facilities; visual supervision of production from upper levels	Controlled vertical connection between administration and production
7. Steelform (São Roque, Portugal)2020	Non-orthogonal production hall with attached administrative wing	Direct corridor connection between both sectors	Shared internal corridor
8. Ferneto SA (Vagos, Portugal) 2022	Large industrial hall with integrated administrative block	Unified spatial organization with direct functional links	Shared circulation and multiple access points

4.2. Environmental Comfort

The assessment of Indoor Environmental Quality focused on daylighting and ventilation strategies in production and administrative workspaces (Table 2). Natural daylight represents the primary lighting strategy in all analyzed projects. Production spaces predominantly rely on zenithal daylight through skylights, saw-tooth roofs or roof openings, whereas administrative workspaces generally combine façade glazing with natural daylight. Natural ventilation is incorporated in several projects either as

the primary or a complementary environmental strategy, while mechanical systems are applied where required by production processes. Buda Recypark demonstrates a uniformly daylit production environment through roof lighting, whereas Ferneto SA provides a higher level of visual comfort within the administrative sector through extensive façade glazing. Comparable environmental conditions for both workplace categories are observed in projects such as SmartMill and Arya Sanat Project.

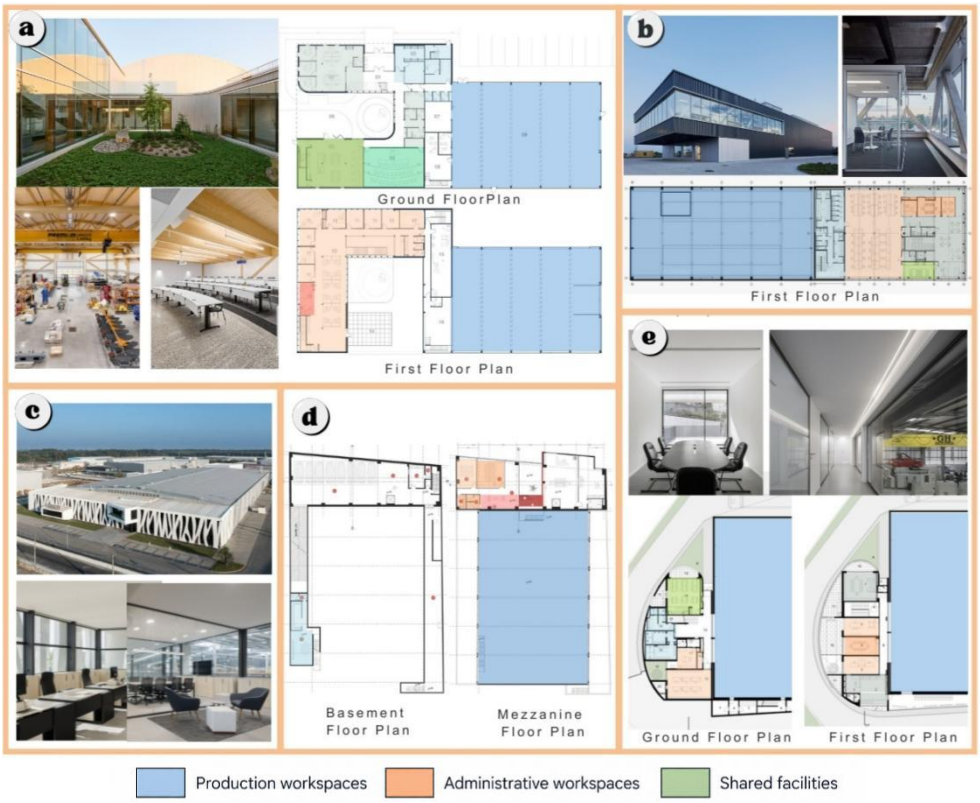


Figure 1. Representative case studies illustrating spatial relationships between production and administrative workspaces: (a) SmartMill; (b) Amplio Automation Headquarters; (c) Ferneto SA; (d) Arya Sanat Factory; (e) Steelform Factory

Table 2. IEQ Characteristics of Production and Administrative Workspaces

Case study	Production workspace (daylighting, ventilation)	Administrative workspace (daylighting, ventilation)
1. Buda Recypark	Roof daylighting; natural and mechanical ventilation	Curtain-wall façade; mixed ventilation with natural air circulation
2. Amplio Automation	Controlled artificial and natural lighting; mechanical ventilation	Full-height curtain-wall glazing; automated ventilation and lighting systems
3. Ampliación	Saw-tooth roof and façade openings; predominantly mechanical ventilation	Extensive curtain-wall glazing; abundant natural daylight
4. SmartMill	Continuous roof skylights providing uniform daylight; natural ventilation	Daylighting through courtyard and façade openings; naturally ventilated spaces
5. Greyder Shoe Factory	Large façade openings with mechanical ventilation	Extensive glazing providing high daylight availability; mechanical ventilation

6. Arya Sanat Project	Skylights supporting uniform daylight distribution; natural ventilation	Mezzanine offices illuminated from the central atrium; natural ventilation
7. Steelform	Roof lighting supporting industrial workspace; natural ventilation	Large facade openings providing daylight; natural ventilation
8. Ferneto SA	Roof skylights ensuring uniform daylight; mechanical ventilation	Large glazed façades ensuring high daylight quality; mechanical ventilation

4.3. Architectural Quality

The architectural treatment of production and administrative workspaces differs primarily in terms of materiality and spatial identity (Table 3). Production areas are generally characterized by exposed structural systems and functional industrial finishes, while administrative workspaces incorporate a broader range of materials, transparent facades and contemporary interior design. Projects such as SmartMill and Buda Recypark demonstrate a coherent architectural language across both functional zones, whereas Ferneto SA and Amplio Automation place greater emphasis on the architectural identity of administrative spaces.

4.4. Well-being and Social Sustainability

Employee-oriented amenities are incorporated in all analyzed industrial complexes, although their organization and accessibility vary according to the overall spatial concept (Table 3). Shared facilities include cafeterias, informal meeting areas, courtyards, outdoor terraces and common circulation spaces. Outdoor gathering areas accessible to both production and administrative employees are particularly evident in Buda Recypark, SmartMill and Ferneto SA, while the remaining projects predominantly rely on indoor shared spaces to support everyday interaction between different user groups.

Table 3 . Architectural and Well-being Characteristics of Production and Administrative Workspaces

Case study	Production workspace (materiality, spatial identity)	Administrative workspace *(materiality, spatial identity)*	Shared amenities (break areas, canteen, outdoor spaces)
1. Buda Recypark	Exposed steel structure, concrete finishes, industrial aesthetic	Glazed office spaces with contemporary interior finishes	Central courtyard and shared outdoor space
2. Amplio Automation	Exposed structural elements, neutral industrial finishes	Open-plan offices with contemporary materials	Shared cafeteria and informal meeting areas
3. Ampliación)	Industrial concrete finishes, functional production environment	Bright office interiors with glazed façades	Employee dining and outdoor break areas
4. SmartMill	Timber structure expressed within production space	Timber finishes creating a warm office environment	Internal courtyard and outdoor relaxation areas
5. Greyder Shoe Factory	Functional industrial finishes with exposed structure	Representative office interiors with higher material quality	Cafeteria and employee recreation spaces
6. Arya Sanat Project	Exposed brick and steel, strong industrial character	Minimal contemporary office interiors overlooking production	Central gathering space and employee facilities

7. Steelform	Steel structure and industrial finishes	Contemporary office interiors with extensive glazing	Shared cafeteria and employee common areas
8. Ferneto SA	Functional industrial environment with exposed production systems	Bright administrative interiors emphasizing transparency	Shared social spaces, education center and cafeteria

5. DISCUSSION

The findings confirm that contemporary industrial architecture increasingly interprets sustainability through workplace quality rather than exclusively through environmental performance [1,2]. While WELL and LEED emphasize Indoor Environmental Quality (IEQ) as a key component of sustainable buildings, the analysis demonstrates that spatial organization and the distribution of environmental quality between employee groups are equally relevant [2,7]. Sustainability therefore extends beyond technical performance to include relationships between production and administrative workspaces, access to shared amenities, and workplace equality.

Environmental comfort reveals differences in how workplace quality is provided across employee groups. Although natural daylight is widely incorporated across the analyzed projects, production halls predominantly rely on zenithal lighting through skylights, saw-tooth roofs, and roof openings, while administrative spaces more frequently benefit from façade glazing and stronger visual connections to the exterior. Ventilation strategies combine natural and mechanical systems according to production requirements. These findings suggest that the presence of daylight and ventilation strategies alone does not ensure equivalent environmental conditions; their spatial distribution between production and administrative workspaces is equally relevant.

Architectural quality reinforces this distinction. Production spaces generally retain exposed structures and functional industrial finishes, whereas administrative areas receive more refined material treatment, transparency, and stronger spatial identity. However, this contrast is not universal: projects such as SmartMill and Buda Recypark demonstrate a more coherent architectural language across production and administrative areas. Materiality and architectural expression can therefore either reinforce the distinction between employee groups or contribute to a more unified workplace identity.

Production halls and supporting facilities, including changing rooms, sanitary facilities, cafeterias, and break areas, are essential components of the industrial workplace. Their organization influences environmental comfort, informal interaction, workplace identity, and employees' sense of belonging [3]. Shared cafeterias, terraces, courtyards, galleries, and outdoor break areas can reduce spatial separation and support interaction between production and administrative employees. In this context, it is not sufficient to ask whether an industrial building provides high-quality indoor environmental conditions; it is also necessary to examine to whom these conditions are provided. This shifts the focus from IEQ performance toward the equitable distribution of workplace quality among employee groups.

Figure 2 synthesizes these findings through three coexisting organizational models rather than a chronological evolution of industrial architecture. The **Segregated model**, represented by Greyder Shoe Factory and Arya Sanat Project, is characterized by a pronounced functional and social separation between production and administrative employees. In Arya Sanat, although visual supervision and controlled vertical connections link administration with the production hall, worker facilities are spatially separated from administrative areas, with distinct kitchens and common spaces. This organization maintains a hierarchical distinction between employee groups despite functional connectivity between the two sectors.

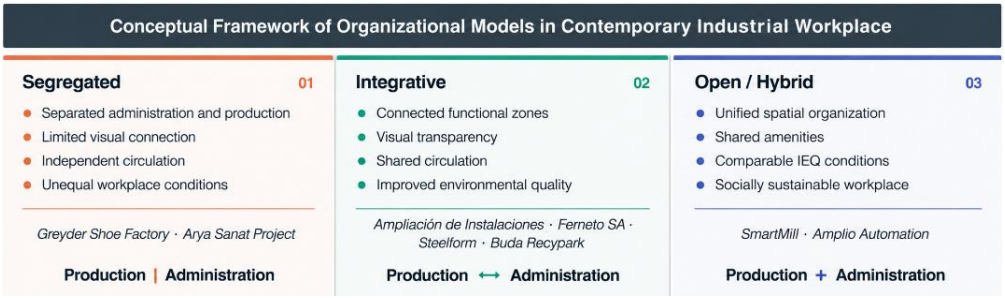


Figure 2. Conceptual framework for classifying contemporary industrial architecture according to the degree of spatial integration and workplace equality

The **Integrative model**, identified in Ampliación de Instalaciones, Ferneto SA, Steelform, and Buda Recypark, establishes stronger relationships through shared circulation, transparent interfaces, and direct connections between production and administrative workspaces. Although both functional zones remain distinguishable, the architectural concept reduces spatial segregation while providing more balanced environmental conditions and greater accessibility to common employee facilities.

The **Open (Hybrid) model**, represented by SmartMill and Amplio Automation, demonstrates the highest degree of workplace integration. Production and administration are conceived as complementary components of a unified architectural system characterized by shared amenities, continuous spatial and visual relationships, and more comparable workplace conditions. Rather than emphasizing organizational hierarchy, these projects prioritize workplace equality and employee well-being as integral components of sustainable industrial architecture.

The proposed framework therefore extends beyond conventional architectural classification by introducing **workplace equality** as an additional criterion. By integrating spatial relationships, IEQ, architectural quality, and employee well-being, it provides a conceptual basis for evaluating industrial buildings from the perspective of social sustainability. Sustainable industrial architecture should consequently be evaluated not only through environmental and technological performance, but also through its capacity to provide equitable, healthy, and socially inclusive workplaces. This interpretation is consistent with previous research emphasizing the role of workplace design in supporting employee well-being and productivity [3].

6. CONCLUSIONS

This study demonstrated that the quality of industrial workplaces should be evaluated not only through environmental performance, but also through the spatial relationship between production and administrative workspaces. By applying a comparative assessment framework to eight contemporary industrial case studies, the research identified different levels of workplace integration and proposed a conceptual framework for classifying industrial buildings according to spatial integration and workplace equality.

The findings indicate that workplace quality emerges from the combined influence of spatial organization, environmental comfort, architectural quality, and employee well-being. The proposed framework highlights that sustainable industrial architecture extends beyond technological efficiency by integrating these dimensions into a unified design approach. In this context, workplace equality emerges as an important architectural criterion that complements conventional environmental indicators and broadens the understanding of sustainability within industrial buildings.

Ultimately, contemporary industrial architecture increasingly positions employees as central users of the built environment rather than solely participants in the production process. Industrial buildings are therefore no longer conceived only as production facilities, but as workplaces where spatial organization, Indoor Environmental Quality, architectural identity, and social interaction collectively influence employee well-being. This perspective is consistent with previous research emphasizing that well-designed work environments actively support employee well-being and productivity and provides a conceptual basis for future research and the design of more equitable and human-centered industrial environments [3].

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Research paper

LEGAL RECOGNITION AND INSTITUTIONAL INTEGRATION OF LANDSCAPE ARCHITECTS IN NORTH MACEDONIA

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Abstract

The legal recognition and institutional integration of landscape architects are essential for sustainable spatial planning and environmental governance. However, in North Macedonia the profession remains insufficiently recognized within the national legislative and institutional framework. This study examines the legal and institutional position of landscape architects through a comparative analysis of North Macedonia, Serbia, Bulgaria, and Greece.

The research is based on a qualitative comparative analysis of national legislation, professional regulatory systems, and European policy documents. Three analytical dimensions were evaluated: legal recognition, licensing systems, and institutional integration.

The findings indicate that North Macedonia has the lowest level of professional recognition among the selected countries, characterized by the absence of explicit legal recognition, dedicated licensing mechanisms, and mandatory participation of landscape architects in planning processes. In contrast, Bulgaria and Greece demonstrate more developed regulatory frameworks, while Serbia exhibits partial institutional integration.

The study concludes that strengthening legal recognition, establishing licensing systems, and improving institutional integration are necessary steps toward aligning national policies with European standards and enhancing sustainable spatial planning.

Key words: *landscape architecture; legal recognition; institutional integration; spatial planning; professional regulation; Southeast Europe; European policy alignment*

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1. INTRODUCTION

Landscape architecture has become an essential discipline in sustainable spatial planning, integrating ecological, social, and cultural dimensions of the built and natural environment. In response to challenges such as climate change, biodiversity loss, and rapid urbanization, landscape architects contribute to resilient public spaces, environmental protection, and the sustainable management of urban and rural landscapes [1,2,3].

At the European level, the importance of landscape is reflected in policy frameworks such as the European Landscape Convention [4], which promotes the integration of landscape considerations into planning policies and emphasizes multidisciplinary collaboration involving qualified landscape professionals. Directive 2013/55/EU further highlights the importance of clearly defined professional qualifications and recognition within the European Union.

Despite these developments, the legal recognition and institutional integration of landscape architects remain uneven across Southeast Europe. In North Macedonia, the profession lacks explicit legal recognition, dedicated licensing mechanisms, and formal participation in spatial planning processes, limiting its contribution to sustainable development [5].

This study examines the legal and institutional position of landscape architects in North Macedonia through a comparative analysis of Serbia, Bulgaria, and Greece. The objective is to identify differences in legal recognition, licensing systems, and institutional integration, as well as to highlight policy gaps and propose directions for improving the professional status of landscape architects in line with European standards.

Based on these objectives, the following research questions were formulated:

RQ1: To what extent is landscape architecture legally recognized within the national legislative framework of North Macedonia?

RQ2: Does North Macedonia provide a formal licensing and professional regulatory system for landscape architects?

RQ3: How does the institutional integration of landscape architects in North Macedonia compare with selected Southeast European countries (Serbia, Bulgaria, and Greece)?

RQ4: What legal and institutional reforms are necessary to improve the professional recognition and integration of landscape architects in North Macedonia in accordance with European standards?

2. THEORETICAL FRAMEWORK

The theoretical foundation of this study is grounded in the intersection of professional recognition, institutional theory, and landscape-based approaches to spatial planning. Landscape architecture is increasingly understood not only as a design discipline, but as a strategic field that integrates ecological processes, cultural landscapes, and governance structures [6,2]. This expanded understanding

positions landscape architecture as a key mediator between environmental systems and planning institutions.

2.1 Landscape as a Planning Paradigm

Contemporary landscape theory views landscape as a dynamic system shaped by the interaction of natural and socio-cultural processes rather than as a static visual entity [7]. Within this perspective, landscape architecture extends beyond aesthetic design to serve as a strategic framework for spatial planning and sustainable development [6]. Consequently, landscape architects play a key role in addressing contemporary challenges such as climate adaptation, biodiversity conservation, and the creation of resilient public spaces [8].

2.2 Professional Recognition and Legal Legitimacy

Contemporary landscape theory views landscape as a dynamic system shaped by natural and socio-cultural processes rather than as a static visual entity [7]. Accordingly, landscape architecture extends beyond aesthetic design to support strategic spatial planning and sustainable development [6]. It therefore plays a key role in addressing challenges such as climate adaptation, biodiversity conservation, and resilient public space design [8].

2.3 Institutional Integration and Governance Structures

Contemporary landscape theory views landscape as a dynamic system shaped by natural and socio-cultural processes rather than as a static visual entity [7]. Accordingly, landscape architecture extends beyond aesthetic design to support strategic spatial planning and sustainable development [6]. Landscape architecture therefore plays a key role in addressing challenges such as climate adaptation, biodiversity conservation, and resilient public space design [8].

2.4 Conceptual Framework and Analytical Dimensions

Contemporary landscape theory views landscape as a dynamic system shaped by natural and socio-cultural processes rather than as a static visual entity [7]. Accordingly, landscape architecture extends beyond aesthetic design to support strategic spatial planning and sustainable development [6], playing a key role in addressing challenges such as climate adaptation, biodiversity conservation, and resilient public space design [8].

3. METHODOLOGY

3.1 Research Design

The study does not generate primary empirical data but presents an original comparative analysis based on the systematic evaluation of legal documents,

institutional frameworks, and European policy instruments. The originality of the research lies in the comparative assessment of professional recognition across the selected Southeast European countries and in the identification of structural policy gaps affecting the profession of landscape architecture.

3.2 Case Selection

The study focuses on North Macedonia, with comparative cases of Serbia, Bulgaria, and Greece. The selection is based on geographical proximity, regulatory diversity, and comparative relevance within Southeast Europe and transitional planning contexts. This allows comparison of different levels of professional recognition and alignment with European standards.

3.3 Data Sources

The research is based on primary and secondary legal and institutional sources, including national laws on spatial planning, construction, environmental protection, and cultural heritage, as well as institutional frameworks and relevant European policy instruments such as the European Landscape Convention and Directive 2013/55/EU.

In addition to national legislation, the comparative assessment was supported by official documents published by professional chambers, governmental institutions, and the European Foundation for Landscape Architecture (EFLA/IFLA Europe), where available.

3.4 Analytical Approach

A comparative matrix-based analysis is applied using three key dimensions: legal recognition, evaluated through legislative references to landscape architecture; licensing systems, assessed through certification and professional regulation; and institutional integration, analyzed through participation in planning and decision-making structures. Results are presented through a structured comparative evaluation matrix based on predefined analytical criteria, supported by documentary evidence from national legislation and professional regulatory sources.

3.5 Link to Research Questions and Discussion

The analytical framework and comparative assessment were designed to systematically address Research Questions RQ1–RQ4 by evaluating three analytical dimensions: (1) legal recognition, (2) licensing systems, and (3) institutional integration.

4. RESULTS

4.1 Legal Recognition of Landscape Architecture in North Macedonia

The analysis indicates that landscape architecture is not explicitly recognized as a regulated profession within the legislative framework governing spatial development in North Macedonia. Although the Law on Spatial and Urban Planning establishes the national planning system, it does not define landscape architecture as a distinct professional discipline. Articles 1 and 7 regulate the scope of spatial planning and the hierarchy of planning documents without recognizing the multidisciplinary role of landscape architects. Furthermore, Article 23, governing the composition of planning commissions, does not require their participation, while Article 44 limits the preparation of planning documentation to licensed entities without providing a dedicated licensing pathway for landscape architects. A similar situation is observed in the Law on Construction, where design, revision, and supervision are reserved for licensed architects and engineers. These findings confirm **RQ1**, demonstrating that the legal recognition of landscape architecture in North Macedonia remains absent, resulting in limited professional status and institutional participation.

4.2 Licensing Systems and Professional Regulation

The analysis reveals that North Macedonia lacks a formal licensing system for landscape architects. Unlike architecture and civil engineering, the profession has no dedicated certification process, professional registry, or legally defined competencies. Consequently, landscape architects have limited access to regulated practice, particularly in public projects and statutory planning procedures, often working under the responsibility of other professions. In contrast, Bulgaria and Greece have established legal and professional frameworks that formally recognize landscape architects through registration and licensing systems, enabling their participation in planning processes [9,10,11]. These findings address **RQ2**, confirming that the absence of a licensing system contributes significantly to the marginalization of the profession in North Macedonia.

4.3 Institutional Integration in Planning Processes

The analysis reveals that North Macedonia lacks a formal licensing system for landscape architects. Unlike architecture and civil engineering, the profession has no dedicated certification process, professional registry, or legally defined competencies. Consequently, landscape architects have limited access to regulated practice, particularly in public projects and statutory planning procedures. In contrast, Bulgaria and Greece have established legal and professional frameworks that formally recognize landscape architects through registration and licensing systems, enabling their participation in planning processes [9,10,11]. These findings address **RQ2**, confirming that the absence of a licensing system significantly contributes to the profession's marginalization in North Macedonia.

4.4 Comparative Analysis of Southeast European Frameworks

The comparative evaluation reveals significant differences in the legal recognition, licensing systems, and institutional integration of landscape architects across the selected countries (Table 1). North Macedonia exhibits the lowest level of professional recognition, characterized by the absence of explicit legal recognition, licensing mechanisms, and institutional inclusion. Serbia represents an intermediate case, with partial recognition and moderate institutional integration. In contrast, Bulgaria and Greece demonstrate more developed regulatory frameworks, including established licensing systems, clearer legal recognition, and stronger institutional integration, resulting in closer alignment with European policy standards.

Table 1. Comparative overview of the legal recognition and institutional integration of landscape architects in North Macedonia and selected neighboring countries

Criteria	North Macedonia	Serbia	Bulgaria	Greece
Legal recognition	✗ Not explicit	⚠ Partial	✓ Defined	✓ Defined
Licensing system	✗ Not available	⚠ Limited	✓ Established	✓ Established
Inclusion in planning process	✗ Not required	⚠ Moderate	✓ Regular	✓ Strong
Institutional representation	✗ Weak	⚠ Moderate	✓ Developed	✓ Developed
EU alignment	⚠ Partial	⚠ Partial	✓ Strong	✓ Strong

Table 1 presents the comparative evaluation of the legal recognition, licensing systems, and institutional integration of landscape architects across the selected countries. North Macedonia exhibits the lowest level of professional recognition, whereas Bulgaria and Greece demonstrate the highest level of institutional and regulatory development.

Table 2. Documentary evidence supporting the comparative assessment

Country	Legal framework	Professional/Institutional evidence	Main references
North Macedonia	Law on Spatial and Urban Planning (2020); Law on Construction (2013)	No legal recognition or licensing	Republic of North Macedonia (2013, 2020)
Serbia	Planning and Construction Law (2018)	Partial multidisciplinary participation	Republic of Serbia (2018); Sandeva et al. (2012)
Bulgaria	Spatial Development Act (2001)	Professional regulation and participation in planning	Republic of Bulgaria (2001); IFLA Europe (2020)
Greece	Urban Planning and Sustainable Development Law (2016)	Professional recognition and institutional participation	Hellenic Republic (2016); IFLA Europe (2020)

Table 2 presents the documentary evidence supporting the comparative assessment of professional recognition across the selected countries. Based on national legislation and institutional regulatory sources, the analysis shows that Bulgaria and Greece have the most developed legal and institutional frameworks, Serbia demonstrates partial integration, and North Macedonia exhibits significant regulatory gaps.

4.5 Synthesis of Findings and Policy Gap Identification

The synthesis of results reveals a consistent pattern: the marginalization of landscape architects in North Macedonia is primarily driven by institutional omission rather than legislative absence. While relevant legal frameworks exist, they do not explicitly include landscape architecture as a recognized profession.

This results in a structural policy gap between the existing regulatory system and the requirements for effective professional integration. The gap is evident across all three analytical dimensions—legal recognition, licensing systems, and institutional integration — indicating a systemic issue rather than isolated deficiencies.

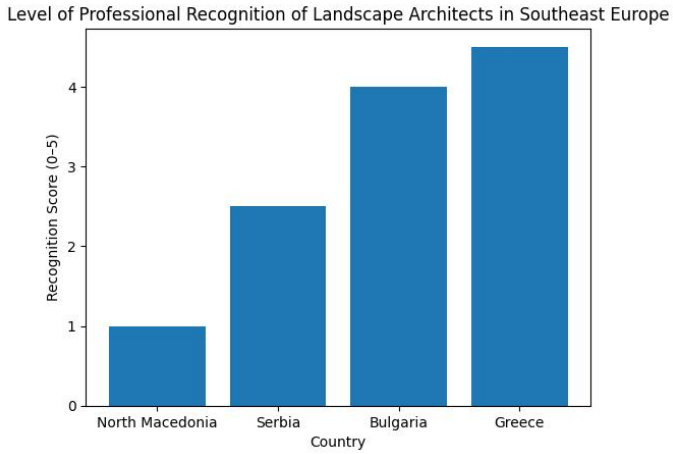


Figure 1. Level of professional recognition of landscape architects in selected Southeast European countries

Figure 1 illustrates the comparative level of professional recognition across the analyzed countries. These findings directly address RQ3 and RQ4, highlighting both regional differences and the need for targeted legal and institutional reforms in North Macedonia.

5. DISCUSSION

The findings of this study provide strong evidence that the professional marginalization of landscape architects in North Macedonia is primarily a consequence of institutional omission within existing legal frameworks, rather than a complete absence of regulation. This distinction is critical, as it shifts the focus from legislative deficiency to issues of professional inclusion and governance design.

The findings support contemporary landscape theory, which defines landscape architecture as a strategic component of sustainable spatial planning rather than merely an aesthetic discipline [6,2]. The absence of explicit legal recognition of landscape architects in North Macedonia reveals a gap between evolving professional roles and existing regulatory frameworks.

According to Antrop [7], effective landscape governance requires integrated planning systems that incorporate ecological and social processes. The exclusion of landscape architects from formal planning structures therefore limits the implementation of integrated and sustainable planning approaches. Similarly, Selman [8] emphasizes the importance of landscape architecture in supporting ecosystem services and sustainable land-use strategies. The weak institutional integration identified in this study indicates that these functions remain insufficiently incorporated into current planning practice in North Macedonia.

5.1 Institutional Omission and Professional Marginalization

The findings indicate that key legal provisions governing planning procedures, licensing, and institutional participation systematically exclude landscape architects from formal professional roles, resulting in structural marginalization despite the existence of the profession in practice.

Unlike systems with no professional regulation, North Macedonia has established legislative frameworks; however, they recognize primarily architects and civil engineers, limiting interdisciplinary collaboration. This supports institutional theory, which emphasizes that effective governance depends on the inclusion of relevant professional expertise. Consequently, the exclusion of landscape architects from planning commissions and licensing systems reduces the diversity of knowledge available for spatial planning and decision-making.

5.2 Comparative Insights and European Alignment

The comparative analysis shows that even partial professional recognition, as observed in Serbia, improves the institutional integration of landscape architects. In contrast, Bulgaria and Greece demonstrate that clear legal recognition, licensing systems, and institutional participation support effective interdisciplinary planning.

These findings are consistent with the European Landscape Convention and Directive 2013/55/EU, both of which emphasize the recognition of qualified professionals and the integration of landscape into planning policies. The current situation in North Macedonia therefore reflects a policy gap that limits both professional practice and the implementation of European spatial planning standards.

5.3 Policy Implications and Pathways for Reform

The identified structural policy gap has important implications for legal and institutional reform. As illustrated in Figure 2, the professional legitimacy of landscape architects depends on three interconnected dimensions: legal

recognition, licensing systems, and institutional integration. Weakness in any of these areas limits their effective participation in spatial planning.

The findings indicate three priorities for reform:

- **Legal recognition** through explicit inclusion of landscape architecture in relevant legislation;
- **Licensing and regulation** by establishing certification systems and clearly defined professional competencies;
- **Institutional integration** through the mandatory involvement of landscape architects in planning processes, commissions, and public projects.

Together, these measures would strengthen interdisciplinary planning and improve alignment with contemporary European standards.



Figure 2. Legal Integration Model for Landscape Architects: conceptual framework illustrating the relationship between legal recognition, licensing systems, and institutional integration

5.4 Contribution to Knowledge and Future Research

This study contributes to the literature by providing a comparative legal and institutional analysis of the professional position of landscape architects in Southeast Europe. By conceptualizing professional marginalization as a consequence of institutional omission, it offers a new perspective on the relationship between legal frameworks and professional practice.

Future research should complement this legal and institutional analysis with empirical studies, including interviews with landscape architects, professional organizations, planning authorities, and policymakers. Such evidence would provide deeper insight into the practical implementation of legal frameworks and support the development of evidence-based policy recommendations.

This study examined the legal and institutional position of landscape architects in North Macedonia through a comparative analysis of selected Southeast

European regulatory frameworks. The findings reveal that the profession remains insufficiently recognized due to the absence of explicit legal recognition, dedicated licensing systems, and effective institutional integration within spatial planning.

The analysis demonstrates that this marginalization results primarily from institutional omission rather than the absence of legislation, limiting the participation of landscape architects in planning and decision-making processes. Comparative evidence from Serbia, Bulgaria, and Greece shows that stronger legal recognition and institutional integration contribute to more effective interdisciplinary planning and closer alignment with European standards.

The study identifies three priorities for reform: (1) formal legal recognition of landscape architecture, (2) the establishment of licensing and accreditation systems, and (3) the institutional inclusion of landscape architects in planning and governance processes. Implementing these measures would strengthen sustainable and interdisciplinary spatial planning.

Finally, this research contributes to the literature by providing a comparative framework for evaluating the legal and institutional status of landscape architects in Southeast Europe. Future research should complement this analysis with empirical evidence from professional practice and institutional stakeholders to support evidence-based policy development.

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Research paper

STATICITY OR FLEXIBILITY OF THE GENERAL SPATIAL DEVELOPMENT PLAN: EXAMPLES FROM BULGARIA

Diana Ivanova[1]

Abstract

The present study is based on spatial planning theory and practice in Bulgaria and, in particular, on the large-scale preparation of general spatial development plans of municipalities (GSDPMs) over the last 10-15 years.

Drawing on practical design experience, this paper examines the staticity of the GSDPM during its implementation, as well as the possibilities for creating prerequisites for its flexible functioning already during the process of its preparation.

The paper applies a qualitative methodology combining normative analysis, typological analysis of recurring implementation problems, and a procedural assessment of the proposed spatial planning solutions.

Through examples of possible solutions to archetypal cases, the paper demonstrates how the potential of the rules and regulations for the implementation (RRI) of the GSDPM and of prospective spatial development regimes can be used to ensure a certain dynamism of the GSDPM during the period of its long-term application.

Key words: *general spatial development plan, staticity and dynamism, spatial development regimes, rules and regulations*

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1. INTRODUCTION

This paper aims to present some identified problems in the process of preparing and subsequently implementing general spatial development plans of municipalities in Bulgaria [1] and, through specific examples, to suggest some possible solutions to these cases.

The research background is defined by the tension between the statutory stability of the GSDPM as a long-term strategic planning instrument and the need to accommodate changing socio-economic, environmental, infrastructural and investment conditions during its period of application. In this context, flexibility is understood not as a departure from the legal framework, but as the capacity of the plan to provide pre-defined, legally regulated options for subsequent detailed planning and implementation.

The ideas presented in this paper are grounded in previous studies [2,3,4,5], practical experience in the preparation of general spatial development plans of municipalities in Bulgaria [1], and the relevant statutory and regulatory framework for spatial planning [6,7].

The following research questions derive from the research aim thus formulated:

- Is it possible to mitigate the staticity of the general spatial development plan so that it remains relevant and dynamic, considering its nature as a long-term document of strategic planning and programming and as the main management instrument of local government in the field of spatial planning?
- What are the common cases in which difficulties may arise in the implementation of the plan because it has not provided possible solutions for situations that are highly likely to occur?
- How can appropriate spatial development conditions be created already during the preparation of the plans, so that potential future conflicts are avoided?

The present study applies a qualitative methodology based on methods of analysis and synthesis, organised in the following research steps:

- normative analysis of the relevant statutory and regulatory framework, including the Spatial Development Act [6], Ordinance No. 8 [7] and the RRI of GSDPMs;
- typological analysis of recurring potentially problematic situations in the implementation of GSDPMs;
- synthesis of possible spatial planning approaches and mechanisms that can be incorporated already during the preparation of the GSDPM;
- procedural assessment of the proposed solutions according to whether they reduce the need for future amendments to the GSDPM, whether they transfer the decision to a subsequent DSDP or SDSDP level, and what implementation procedures remain necessary.

The presented examples were selected according to the following criteria: repeated occurrence in municipal spatial planning practice; direct relation to the implementation of GSDPMs; dependence on the wording of the RRI; relevance to the balance between legal certainty and flexibility; and availability of sufficient professional evidence from the author’s planning practice. They are not treated as a statistical sample, but as illustrative and analytically comparable practice-based cases.

For terminological consistency, the abbreviation GSDPM is used throughout the paper for the general spatial development plan of a municipality. The broader abbreviation GSDP is retained only where the statutory category of general spatial development plans is discussed in general.

2. GENERAL SPATIAL DEVELOPMENT PLAN OF A MUNICIPALITY

Strategic spatial planning [5] should be understood not only as the creation of a static spatial development plan with a fixed end state, but also as a framework for guiding future decisions, coordinating stakeholders, and ensuring applicability under changing conditions. This perspective supports the need to examine how a binding municipal planning and strategic document, such as the GSDPM, can combine stability, legal certainty, and flexibility in implementation.

The paper does not aim to examine in detail the system of documents for planning spatial development in Bulgaria. The specific features of spatial development plans are mentioned only very briefly, insofar as this is necessary to clarify the context of the present study.

According to the Spatial Development Act (SDA) [6], spatial development plans are:

- general spatial development plans (GSDPs), often broadly translated as “master plans”;
- detailed spatial development plans (DSDPs).

The GSDP is a long-term document of strategic planning and programming which, in the hierarchy of spatial planning, stands immediately above the detailed spatial development plans and sets their framework. General spatial development plans have no direct investment application. Framework implementation programmes and detailed spatial development plans are developed in order to implement their provisions. The provisions of the GSDP are mandatory when subsequent DSDPs are prepared. Detailed spatial development plans are documents of operational planning with direct investment application and are a necessary planning basis for issuing visas for survey and design, and for the preparation, approval procedure and implementation of specific investment projects.

For the purposes of this paper, the important statutory features [6, 7] are that the GSDPM defines the overall territorial structure, the predominant designations of territorial parts, the general spatial development regimes, the main infrastructure networks and the areas subject to special protection, restrictions or public functions. In practical terms, it distinguishes territories with general designation, spatial development zones and land plots with independent spatial development regimes. This is sufficient to outline the operational problem addressed here: once these regimes are fixed in the plan, their later adjustment usually requires specific procedures, unless controlled flexibility has already been built into the RRI.

Over time, practice has shown certain problems in the process of implementing the GSDPM, such as:

- insufficient use of the potential of additional specialised spatial development regimes and of the function of the rules and regulations for the implementation of the plan;
- lack of a regulation on how amendments to the GSDPM should be reflected in the original plan;
- how to keep the GSDPM up to date and how it can be flexible and dynamic, insofar as this does not contradict its character and essence.

Given the long-term character of the GSDPM (15-20 years), the setting of "rigid" spatial development regimes during its preparation leads to a certain staticity of the plan, to difficulties for municipalities in its implementation through the imposition of new obligations and additional procedures, for example when its amendment is necessary, and, accordingly, indirectly to limiting investment interest due to the procedures required over time to achieve planning provision and design readiness.

This does not mean that the respective plan has been poorly prepared or that it is non-functional. Even if it has been developed:

- in accordance with the legal and regulatory framework;
- on the basis of demographic, socio-economic and functional-spatial development forecasts;
- and in compliance with environmental conditions and requirements and the factor of immovable cultural heritage;

it could not foresee in detail and in the long term all emerging needs for specific sites and/or their exact future location, nor could it lay them down in the plan with the corresponding spatial development regime.

3. CHARACTERISTIC SITUATIONS AND POSSIBLE SPATIAL PLANNING SOLUTIONS: EXAMPLES FROM PRACTICE

Possible solutions and measures for a more flexible general spatial development plan and for a more harmonious, smoother and efficient implementation can be set already during the process of its preparation, including, but not limited to:

- providing for additional general spatial development regimes;
- providing for additional specialised spatial development regimes;
- providing, in the RRI, for exceptions and deviations from the general spatial development regimes.

3.1. Example 1 – regarding land plots with an independent spatial development regime and linear sites and facilities of the communication-transport and engineering-technical infrastructure networks [1,8,9].

Problem: Linear infrastructure sites and facilities, as well as land plots with an independent spatial development regime, may need to be located in territories where the principal regime prohibits a change of designation. If every such case requires an amendment to the GSDPM, implementation becomes procedurally slow and may block public infrastructure or sites of public significance.

Proposed solution: The RRI of the GSDPM may explicitly allow, by exception, a change of designation for such sites on the basis of a DSDP or parcel plan, without requiring an amendment to the GSDPM, while the necessary environmental and cultural heritage coordination procedures remain applicable at the appropriate subsequent level.

Procedural effect: The strategic plan – GSDPM – is not amended for each individual infrastructure case; the detailed decision is transferred to the operational planning level, which can reduce procedural time and administrative burden while preserving statutory control.

Brief explanatory notes: For these sites, the RRI of the GSDPM allows, by exception, a change of designation of land properties when they fall within territories with the general spatial development regime "prohibition of change of designation". In these cases, the change of designation is allowed on the basis of a detailed spatial development plan (DSDP), without requiring an amendment to the GSDPM. Linear sites and facilities of the communication-transport and engineering-technical infrastructure networks are designed and implemented in accordance with the provisions of the GSDPM and on the basis of a detailed spatial development plan (parcel plan) and investment projects.

The assessment of the necessity and type of environmental procedures is carried out at the DSDP level and subsequently at the level of investment intention and investment design. The same applies to coordination with the National Institute for Immovable Cultural Heritage/Ministry of Culture (NIICH/MC), where applicable.

3.2. Example 2 – regarding the reflection in the GSDPM of a design route of a future road and the spatial development regimes of its adjoining territories [8].

Problem: At the GSDPM stage, the exact route of a future road may not yet be defined by precise geodetic coordinates, while the adjoining territories may already need a spatial planning framework for future compatible functions.

Proposed solution: The GSDPM may indicate the route conceptually and may attach a conditional general spatial development regime to a strip along the future route, to be activated and spatially specified once the investment project defines the exact alignment and parameters of the road.

Procedural effect: The plan provides a predictable future planning framework without freezing the exact spatial position of the road before the necessary transport-communication design is available.

Brief explanatory notes: Where there is a design provision for a new road, for example a ring road around a town, its route is reflected conceptually in the GSDPM, considering the character and essence of the plan and the absence of a specific, at least conceptual, transport-communication solution that can be laid down in the GSDPM with exact geodetic coordinates. If the aim is to develop the territories adjoining the future road with certain related functions, a conditional (territorially bound to certain conditions) general spatial development regime "permissible change of designation" may be provided, for example in a mixed multifunctional spatial development zone, for

the properties falling entirely or partially within the 100-metre strip on both sides of the design route of the road. The territory with "permissible change of designation" around the road is indicated conditionally on the drawing, whereby, without the need for an amendment to the GSDPM, the spatial development regime should be applied around the exact route and parameters of the road according to the investment project after its preparation and approval, as well as upon its future implementation.

It can be said that the spatial development regime is "attached" to the route of the road, and its specific spatial positioning is established and the regime is activated when the actual route of the road itself is specified and laid down.

3.3. Example 3 – regarding the development of the non-urbanised contact territories adjoining the construction boundaries of settlements [1,8,9].

Problem: Contact territories adjoining settlement boundaries and cadastral "contact zones" often generate implementation conflicts because the boundary between urbanised and non-urbanised territories may not correspond to future development needs or cadastral reality.

Proposed solution: The GSDPM may predefine a conditional low-rise residential spatial development regime for a limited strip around settlement boundaries and may regulate how properties in cadastral contact zones are to be treated on the basis of their permanent designation in the cadastral map and cadastral registers.

Procedural effect: The approach provides a controlled reserve for future settlement development and, in typical cases, may save more than one year of procedural time by avoiding the need for a GSDPM amendment before a DSDP is prepared.

Brief explanatory notes: A general spatial development regime "permissible change of designation" is provided in a low-rise residential spatial development zone for the properties falling entirely or partially within the 150-metre strip around the existing construction boundary of the settlements. Where investment interest and intentions have been declared, the change of designation is permitted on the basis of a DSDP, without requiring an amendment to the GSDPM. For each individual case, the relevant coordination procedures are determined and carried out, considering the presence of protected territories for the protection of cultural heritage. These prescriptions are reflected in the RRI of the plan and in the annexes to them.

In this way, the possibility for longer-term future development is regulated and the investment interest of property owners is protected, including beyond the properties designated by the GSDPM for the expansion of settlements and determined on the basis of the studies, analyses and forecasts at the time of preparation of the plan. This does not constitute an arbitrary freedom leading to "fragmented and anarchic development", but rather a logical and lawful way to provide the necessary spatial planning conditions, considering that these land areas for possible future residential development are contact areas adjoining the existing urbanised territories, whose nature presupposes that they are already provided with regulation plans, implemented public improvement measures and constructed communication-transport and engineering-technical infrastructure.

Another case in which provisions in the GSDPM are required for the purpose of its harmonious implementation concerns potentially conflicting territories, the so-called "contact zones" within the meaning of the Cadastre and Property Register Act (CPRA), where there is overlapping or divergence ("white spots") of the property boundaries in the boundary zones between the urbanised territories of settlements and the agricultural or other non-urbanised territories adjoining them. For territories with an approved cadastral map and cadastral registers (CMCR) and falling within "contact zones" within the meaning of the CPRA, the RRI of the GSDPM may provide that they are to be developed with a DSDP in accordance with the permanent designation of the respective property established by the CMCR, without requiring an amendment to the GSDPM.

By providing for these possibilities in the RRI of the GSDPM, both its flexibility is increased and, in the most general case, more than one year of procedural time is saved because no grounds arise for amending the plan, while at the same time the legal and regulatory framework is not violated.

Unfortunately, such approaches and spatial development solutions are still not always recognised in practice by some institutions and administrations, including key ones such as the Ministry of Regional Development and Public Works (MRDPW), the Ministry of Agriculture and Food (MAF), the Ministry of Environment and Water (MOEW), etc., although the approved GSDPM, together with the rules and regulations for its implementation, should function as a local law for the respective municipality, embedded in, and not contradicting but supplementing and specifying, the general legal and regulatory spatial planning framework of the country.

An interesting example of a specific non-standard approach is the definition of an additional general spatial development regime in the GSDPM [1,9,10,11].

The idea is that this additional general spatial development regime would come into effect in the future, provided that a specific set of conditions is met.

A set of conditions is a combination of circumstances, requirements or prerequisites that are simultaneously necessary for the occurrence, realization or understanding of a given event, process or concept. In this case, this means the combination of different factors and prerequisites - environmental, socio-economic, functional-spatial, natural, ecological, etc.

3.4. Example 4 – defining in the GSDPM an additional general spatial development regime that regulates a prospective spatial development zone for alternative agricultural activities [10,11].

Problem: The future emergence of compact territories suitable for alternative agricultural activities depends on a combination of environmental, socio-economic, infrastructural and investment conditions that cannot always be spatially fixed in advance during the preparation of the GSDPM.

Proposed solution: The GSDPM may define an additional general spatial development regime that enters into effect only when the specified set of conditions is present and when the territory is subsequently structured through an SDSDP under Article 111 of the SDA.

Procedural effect: The plan provides a long-term prospective framework for alternative agricultural development without requiring an immediate detailed spatial planning of agricultural lands and their development for alternative agricultural activities, supported by planning, infrastructure, and procedural arrangements.

Brief explanatory notes: For the territories with the principal general spatial development regimes “permissible change of designation” and “prohibition of change of designation”, it is possible to form separate structural parts of the territory (compact territorially distinguishable zones) that are to be designated and developed as “territories mainly for alternative agriculture with the application of ecological and high-tech contemporary methods of agricultural production”.

For the application of this possibility to the principal general spatial development regimes “permissible change of designation” and “prohibition of change of designation”, the GSDPM determines an additional general spatial development regime.

The additional general spatial development regime regulates a prospective spatial development zone for alternative agricultural activities “AAA”, within which, during the implementation of the GSDPM and subsequent detailed spatial planning, the potential of the regime may be realised.

The zone is intended for organic agriculture, drip irrigation and the cultivation of perennial crops, vegetable production, fruit production, herbs, mushrooms, beekeeping, essential oil crops, tobacco production and others.

The regime may be applied to compact territorial structures of at least 20 ha, distinguishable by natural or infrastructural delimiters. Its implementation requires the preparation of a specialised detailed spatial development plan (SDSDP) under Article 111 of the SDA [6], together with a motivated proposal and terms of reference pursuant to Article 125 of the SDA [6]. The SDSDP specifies the territorial structure, the regulated land plots (RLPs), access, irrigation and other public infrastructure requirements. During the restructuring of the territory, up to 15% of the area of the land property (LP) may be provided for public infrastructure works.

For the zone as a whole, the indicators remain very low - maximum building density 2%, maximum FAR (floor area ratio – Bulgarian spatial planning indicator Kint) 0.03, minimum landscaped area 90%, and maximum building height 6 m, with a ridge elevation not exceeding 8.5 m. For individual properties within the zone, a change of designation for non-agricultural purposes may be allowed through a separate DSDP or as part of the SDSDP, provided that the new function is compatible with the zone; in such cases the indicators may not exceed building density 20%, FAR 0.4, landscaped area 55%, and building height 7 m, with a ridge elevation not exceeding 10 m. The additional regime enters into effect only when real investment interest, secured financing, the necessary infrastructure arrangements, a Municipal Council decision and the relevant procedures are in place. For territories under the principal regimes “permissible change of designation” and “prohibition of change of designation”, the prescriptions of the additional regime apply only to those parts falling within its scope of application, as regulated in the RRI of the GSDPM and the annexes thereto.

The present paper by no means exhausts all possible cases, but the examples presented suggest possible approaches and algorithms that can also be applied in other,

generally similar cases, thereby increasing the operational efficiency of local administrations (as bodies implementing the GSDPM), as well as the flexibility of the plan, so that it is consistent with its nature as a long-term strategic and planning document and management instrument.

4. DISCUSSION

The examples indicate that flexibility in a GSDPM can be achieved through three main mechanisms: rule-based exceptions, conditional spatial development regimes, and regimes whose effect is activated by a later set of conditions and a subsequent detailed or specialised plan. In all four cases, flexibility is not achieved by weakening the statutory plan, but by making its rules more explicit and operational.

The procedural assessment shows that the proposed mechanisms may reduce the need for repeated amendments to the GSDPM and may transfer the detailed decision-making to the DSDP or SDSDP level. This is particularly important because a GSDPM amendment usually requires a separate procedure and may delay investment or public infrastructure initiatives. At the same time, the mechanisms do not eliminate environmental assessment, cultural heritage coordination, cadastral checks, Municipal Council decisions or other legally required procedures.

The main limitation of the proposed approach is that its effectiveness depends on the precise wording of the RRI and on the willingness of competent administrations to recognise and apply such mechanisms consistently. Therefore, the proposed solutions should be understood as planning instruments for increasing procedural flexibility within the law, not as automatic permissions for development.

5. CONCLUSION

Through a holistic approach and relying exclusively on urban planning theory and practice in connection with the legal and regulatory framework on spatial development in Bulgaria, this paper offers an answer to the defined research questions.

The types of spatial development plans and the specific features of general spatial development plans are briefly mentioned.

A brief overview is provided of the essence of the general spatial development plan of a municipality within the meaning of the legal and regulatory framework in Bulgaria, its manner of functioning and its interrelations with detailed spatial development plans.

Hypothetical potential difficulties in the implementation of the GSDPM have been identified, which are highly likely to arise during the period of operation of the GSDPM.

Through real examples from practice, the author’s view is demonstrated as to how, already during the preparation of the GSDPM, spatial development conditions may be set that ensure the possibility of resolving the cases that arise without this necessitating an amendment to the GSDPM.

The author hopes that the ideas thus presented will contribute to a deeper understanding of the processes of preparation, procedural approval and implementation of general spatial development plans, and that their use in practice will

increase the flexibility and efficiency of these documents of strategic planning and programming for a more harmonious and conflict-free functional-spatial and socio-economic sustainable development of the territory and society.

The key contribution of the paper is the formulation of a practice-based methodological approach for introducing controlled flexibility into a statutory long-term municipal plan through rules, conditional regimes and subsequent detailed planning instruments. The proposed approach may support municipalities by reducing unnecessary amendments to the GSDPM and by improving the operational link between strategic and detailed spatial planning.

At the same time, the applicability of the proposed mechanisms is limited by the specific legal, environmental, cadastral and administrative context of each municipality. Further research could develop a more systematic empirical comparison of approved GSDPMs and their amendments, including measurable indicators such as number of avoided amendments, duration of procedures, administrative costs and implementation outcomes.

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TOPIC 02

GREEN BUILDINGS & ENERGY EFFICIENCY

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

SUSTAINABLE BUILDING ENVELOPE RENOVATION: INTEGRATION OF APV FACADE AND TIMBER ENERGY SYSTEMS (TES)

Srđan Radanović[1], Darija Gajić[2], Milovan Kotur[3]

Abstract

Improving the energy performance of buildings effectively reduces consumption and heating costs while elevating indoor comfort. This paper is a part of comprehensive research which examines energy poverty among residential building users—a prevalent issue in Bosnia and Herzegovina and neighboring countries. Furthermore, it analyzes various alternative solutions for upgrading the building envelope to demonstrate their feasibility. This paper investigates the role of energy efficiency in residential buildings and evaluates the potential of adaptive photovoltaic (APV) façade systems in deep energy renovation. Focusing on a multi-family residential building in Banja Luka, this study combines theoretical findings on energy performance with an advanced renovation scenario based on the Timber Energy System (TES) envelope and Solskin adaptive photovoltaic technology. A detailed analysis of this prefabricated alternative solution demonstrates that upgrading the building envelope substantially reduces heating demand, while the integrated active photovoltaic elements enable on-site electricity generation. Energy calculation results indicate that this systemic approach maintains specific energy need for heating at a low level of 21.93 kWh/m²a, elevating the building to energy class B in the study area. Furthermore, CO_2 emissions are drastically reduced from 216.75 tCO_2 to 74.85 tCO_2. Ultimately, the research confirms that comprehensive energy renovation not only enhances building performance but directly drives decarbonization, improves the residents' quality of life, and demonstrates how building envelopes can evolve from passive protective elements into active, energy-producing systems that mitigate energy poverty and support climate goals.

Key words: *energy efficiency, energy renovation, adaptive photovoltaic façade, TES envelope*

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1. INTRODUCTION

Buildings are among the largest energy consumers in Europe. A considerable share of the housing stock in Bosnia and Herzegovina was constructed before modern energy-efficiency standards. Consequently, renovation of existing buildings is one of the most effective measures for reducing energy consumption, emissions and energy poverty.

Energy efficiency in buildings implies the rational use of energy while maintaining or improving the quality of indoor spaces and living conditions. In the context of residential buildings, it refers to reducing the energy required for heating, cooling, domestic hot water preparation, and other needs, without compromising the thermal comfort of the occupants.

According to European Union definitions, buildings represent one of the largest energy consumers, accounting for approximately 40% of total final energy consumption and roughly 36% of CO_2 emissions. Consequently, improving the energy efficiency of buildings is recognized as a key measure for achieving climate and energy targets, a priority further underscored by current legislative frameworks such as the updated Energy Performance of Buildings Directive [1].

The energy performance of a residential building depends heavily on the characteristics of its envelope—specifically, the thermal properties of both opaque and transparent structural elements. Insufficient thermal insulation, the presence of thermal bridges, and inadequate fenestration lead to increased transmission losses and a higher energy demand for heating [2]. Multi-family residential buildings constructed prior to the introduction of current regulations are particularly vulnerable, as energy efficiency was not a primary design criterion at the time of their construction [3].

Beyond the technical aspect, energy efficiency carries significant social and economic dimensions. By improving the energy characteristics of buildings, it is possible to reduce energy consumption and heating costs, while simultaneously enhancing indoor comfort conditions. On the other hand, the inability to secure adequate domestic energy services is a defining feature of energy poverty. In this regard, energy efficiency serves as a crucial tool for elevating the quality of housing, especially among socially vulnerable groups [4].

In architectural practice, energy efficiency is achieved through an integrated approach that encompasses envelope design and renovation, the optimization of structural details, the control of thermal bridges, and the application of appropriate materials. Indeed, well-executed envelope details exert a decisive influence on the actual energy performance of a building, often more so than the nominal values of the thermal insulation itself.

Considering the aforementioned, it can be concluded that energy efficiency in residential buildings is not merely a technical parameter, but a complex issue unifying the architectural, energy, and social aspects of housing. This conceptualization of energy efficiency serves as the baseline for analyzing and defining energy renovation measures within this research. The paper was prepared from the master's thesis within the program "Energy Efficiency in Buildings" at the University of Banja Luka, using research tools developed within the European project ENPOWER.

2. THEORETICAL BACKGROUND

The housing stock in Bosnia and Herzegovina (B&H) is characterized by a large number of multi-family residential buildings constructed between the post-World War II period and the late 1980s. This stock is defined by a lack of or insufficient envelope thermal insulation, substandard fenestration, unaddressed thermal bridges, and the low energy efficiency of indoor building systems [5].

According to European Commission data [6] and relevant studies on building energy renovation, retrofitting can lead to substantial energy consumption reductions. Depending on the type and scope of the intervention, these savings frequently range from 30% to 50%. Such measures directly impact the mitigation of energy poverty and enhance residential comfort.

Energy renovation encompasses a series of interventions that can be categorized into:

- Technical interventions on the building envelope – improving the thermal insulation of walls, roofs, and floors, replacing fenestration, and renovating facades and windows.
- Building services solutions – optimizing heating and cooling systems, installing energy-efficient boilers or heat pumps, and implementing controlled ventilation.
- Application of renewable energy sources (RES) – solar panels, passive heating systems, and integrated photovoltaic facades.

Energy renovation in the Western Balkans often faces strict socio-economic constraints due to residents' limited financial capacity, underscoring the critical need for external subsidies, credit lines, or collective management initiatives [7]. Best practice examples in Bosnia and Herzegovina, such as projects led by the United Nations Development Programme (UNDP) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), demonstrate that successful retrofits must pair technical upgrades with user education and active community involvement [7]. In alignment with the European Energy Efficiency Directive [8], such integrated frameworks are essential to guarantee sustainable outcomes, improve housing quality, and address regional socioeconomic challenges [9]. Ultimately, mitigating the high energy losses characteristic of uninsulated, legacy structures [4] not only minimizes the broader environmental footprint and atmospheric emissions but also directly enhances the occupants' quality of life by reducing household financial burdens [9].

The most prevalent issues resulting from low energy efficiency include transmission heat losses through the surface components of the envelope (facade walls, roofs, windows, doors, and floors), as well as linear heat losses caused by thermal bridges across the building envelope. The consequences of these deficiencies directly impair residential comfort, leading to uncomfortable indoor temperatures, moisture condensation, and mold growth. Vulnerable groups, such as low-income households, are particularly affected; the high financial burden of heating or cooling energy triggers energy poverty, restricts access to basic housing conditions, and consequently undermines occupant health and well-being [10].

From an environmental perspective, energy-inefficient buildings increase the consumption of fossil fuels, thereby amplifying greenhouse gas emissions and degrading air quality in urban areas [11].

The impact of energy efficiency on the quality of life is not merely a technical issue, but a profound social phenomenon. Properly insulated and energy-optimized spaces guarantee stable and predictable energy consumption for occupants, which alleviates economic pressure and fosters conditions for better health and psycho-social comfort.

3. METHODOLOGY

The methodology of this study is based on a comprehensive case study analysis of a multi-family residential building located in Banja Luka.

In the primary phase of the research, a detailed energy audit was conducted alongside a thorough, on-site physical and technical assessment of the building's existing condition. This diagnostic stage involved collecting geometric and structural data, evaluating the thermal properties and U-values of both opaque and transparent structural components of the envelope, identifying critical construction deficiencies (such as extensive thermal bridging and air leakage), and calculating baseline energy performance indicators under current operational states. The thermal and heating energy demand calculations were performed in strict compliance with the valid methodology prescribed by the official national Rulebook on the Methodology for Calculating the Energy Performance of Buildings [12]. For data processing, complex algebraic numerical simulations, and monthly energy balance analysis, a custom-developed, rigorously verified calculation model implemented within the Excel software package was utilized.

The existing building is characterized by an envelope compliant with the regulations that were in force until 2016, representing a typical construction style for the 1996–2016 period. The specific energy need for heating is maintained at a high level of $Q_{H,nd}$ = 116.82 kWh/m²a, positioning the building into energy class E [12]. The estimated specific primary energy is E_{prim}= 429.96 kWh/m²a.

Following the quantitative establishment of the baseline operational profile, three distinct and progressive renovation scenarios were systematically developed and simulated to determine the most effective and feasible retrofitting pathway:

- **Scenario 1 (Standard Upgrade):** Focused primarily on conventional passive insulation techniques, including the application of contact thermal insulation (ETICS) on facade walls and standard building service upgrades such as upgrading the central heating substations.
- **Scenario 2 (TES Upgrade):** Investigated the application of a prefabricated, industrialized Timber Energy System (TES) envelope, optimizing the construction process through off-site manufacturing and rapid dry-assembly installation.
- **Scenario 3 (Alternative Solution – TES with APV Facade):** Represented the most advanced scenario, investigating the comprehensive integration of the industrialized TES timber framework with an innovative, dynamic, and adaptive photovoltaic (APV) facade technology (Solskin system).

While the first two scenarios primarily targeted the reduction of transmission losses via static thermal resistance, this paper specifically focuses on the third, Alternative Solution. This advanced scenario introduces a paradigm shift by utilizing real-time solar tracking and automated panel angle optimization to achieve simultaneous heating demand reduction and on-site electricity generation.

By employing comparative and sequential approach, the study evaluates how the building envelope can transition from a passive protective barrier into an active, energy-producing multi-functional system.

The selected and presented alternative holds the greatest significance from the perspectives of sustainable development, energy independence, and long-term system stability.

4. SUSTAINABLE BUILDING ENVELOPE

Alternative Solution represents an advanced concept for the energy renovation of the existing building, based on an industrialized approach to facade envelope renovation and the integration of active energy systems. The solution combines the prefabricated Timber Energy System (TES) facade with Solskin active photovoltaic facade elements, thereby enabling the transformation of the building envelope from a passive protective element into a multifunctional energy system (Figure 1).

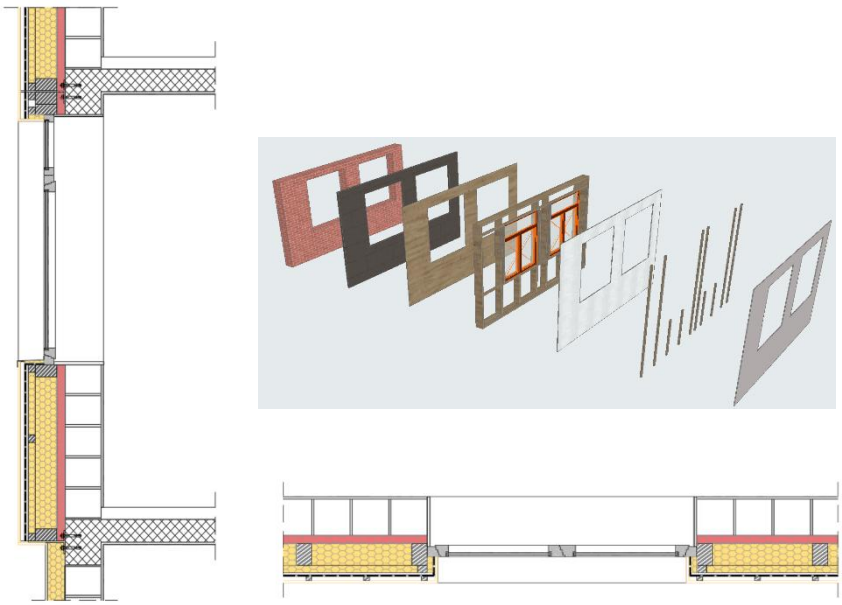


Figure 1. Prefabricate modul and renovation existing envelope with TES facade system

The primary objective of this alternative solution is the simultaneous improvement of the envelope's thermal characteristics, the reduction of heating energy demand, and on-site electricity generation, complemented by the integration of a dynamic shading function. Due to the highest intensity of solar radiation, the south facade stands out as the most favorable orientation for the integration of photovoltaic systems.

The "Solskin adaptive solar façade system" is an adaptive facade system that combines electricity generation, shading control, and daylight management in real time. Unlike conventional shading systems (such as fixed louvers, blinds, and passive photovoltaic panels), this system dynamically tracks the path of the sun and optimizes the panel angle. Consequently, it simultaneously maximizes electricity generation, minimizes overheating risks, and enhances natural daylighting conditions (Figure 2).

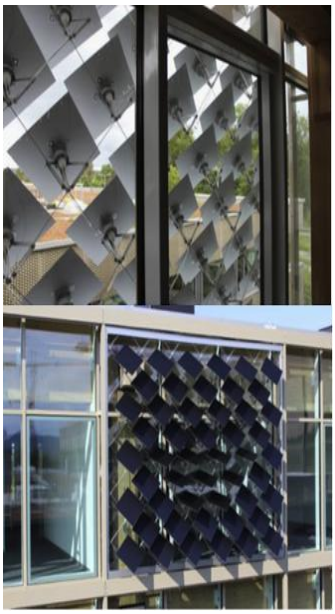


Figure 2. APV façade system prototype according to [13]

5. RESULTS AND DISCUSSION

Research indicates that adaptive systems can achieve up to 56% in energy savings compared to buildings without shading, and approximately 25% compared to buildings equipped with conventional fixed shading systems [13]. Vertical surfaces achieve better utilization of solar radiation during the winter season when energy consumption peaks. According to research conducted for a case study in Zurich, the average annual energy generation via photovoltaic systems amounts to 83.2 kWh/m² [13]. Given that the solar radiation intensity in the territory of Banja Luka is approximately 10–15% higher, the specific annual yield of photovoltaic systems in this area is roughly 1100–1300 kWh/kWp, which translates to an expected area-specific energy generation of about 90–130 kWh/m² per year Figure 3.



Figure 3. Integration of Adaptive PT Systems and Timber Energy Systems (TES) according to authors

By integrating the photovoltaic facade system across a total active surface area of 430 m², the total energy generation presented in Table 1 is achieved.

Table 1. Electricity generation of the photovoltaic systems, source: authors

Parameter	Value
PV surface area	430 m²
Specific generation	90–130 kWh/m²a
Total annual generation	38,700–55,900 kWh/a
Estimated self-consumption	60%
Energy consumed within the building	≈ 23,000–33,000 kWh/a
Surplus energy	≈ 15,000–22,000 kWh/a

Based on 2026 prices, the average cost of the Solskin system, including installation, is approximately 1,125 CHF/m² (≈ 1,179 €/m²). For the analyzed facade surface area of 430 m², the total investment in the photovoltaic systems amounts to approximately 506,994 €. The annual energy benefits encompass savings and revenues totaling approximately 3,100–4,100 €. Although economic analysis is challenging due to market turbulence, the analysis also demonstrates the share of specific works required to execute the aforementioned building envelope improvement, Table 2 presents a summary overview of the characteristic works for Alternative Solution.

Table 2. Summary overview of characteristic works – Alternative Solution, source: authors

Work Category	Value EUR (€)	Share (%)
Preparatory works	15,364.55	1.13%
Dismantling and cleaning	39,300.12	2.89%
Insulation works	51,717.09	1.06%
Sheet metal works	1,825.34	0.13%
Facade works	153,136.26	11.25%
TES elements	273,188.56	20.06%
Locksmith works and fenestration	326,156.20	23.95%
Electrical heating appliances (Norwegian radiators)	23,315.26	1.71%
Photovoltaic systems "SOLSKIN"	506,994.58	37.23%

Work Category	Value EUR (€)	Share (%)
Miscellaneous works	7,657.75	0.56%
Total (excluding VAT)	1,398,667.49	100%
VAT 17%	237,773.47	-
Total (including VAT)	1,636,440.96	-

Based on current energy prices in Bosnia and Herzegovina estimated payback period for Scenario 3 (Alternative solution) is 41 years, while for Scenario 1 it is 25 years, and for Scenario 2 is 34 years. Rising energy prices would reduce the payback period of the investment.

Based on the thermal calculations performed, the energy balances of the building were obtained and are summarized in Table 3.

Table 3. Energy calculation results for Alternative Solution, source: authors

Parameter	Value
Transmission heat losses	2,835.80 W/K
Ventilation heat losses	2,804.49 W/K
Total heat losses	437,844.27 kWh/a
Solar heat gains	241,007.06 kWh/season
Internal heat gains from occupants	27,094.58 kWh/a
Internal heat gains from electrical appliances	103,099.61 kWh/a
Total heat gains	371,201.24 kWh/a
Specific energy need for heating - $Q_{H,nd}$	21.93 kWh/m²a
Specific primary energy – E_{prim}	123.35 kWh/m²a
CO_2 emissions – PV systems included	74.85 tCO_2

Alternative Solution represents the highest level of integration between energy and architectural systems. The specific energy need for heating is maintained at a low level of $Q_{H,nd}$ = 21.93 kWh/m²a, positioning the building into energy class B [12]. The estimated specific primary energy is E_{prim}= 123.35 kWh/m²a.

The key advantage of this solution lies in the introduction of an active energy component through the Solskin system, which enables the facade to actively generate electricity and dynamically control solar heat gains. Compared to passive alternatives, this concept introduces the highest technological complexity but offers long-term energy self-sufficiency. Additionally, a significant reduction in CO_2 emissions is observed. In the previous passive models, emissions amounted to 216.75 tCO_2, whereas in this solution, they are reduced to 74.85 tCO_2. This decline is a direct result of the localized decarbonization of electricity consumption, achieved via the photovoltaic system integrated into the building envelope.

6. CONCLUSION

The deep energy renovation of a residential building in Banja Luka demonstrates that upgrading an envelope typical of the 1996–2016 construction period by implementing a sustainable envelope solution based on the Timber Energy System (TES) can reduce the specific energy need for heating from 116.82 kWh/m²a (Class E) to 21.93 kWh/m²a (Class B). By implementing this industrialized framework integrated with the active 'Solskin' APV facade, the building envelope transitions from a passive barrier into an active, energy-producing system. This highly integrated architectural and energy concept generates between 38,700 and 55,900 kWh of electricity annually, enabling a significant reduction in specific primary energy from 429.96 kWh/m²a to 123.35 kWh/m²a through this advanced solar integration. Consequently, this on-site decarbonization reduces overall CO_2 emissions from 216.75 tCO_2 to 74.85 tCO_2. Although this Alternative Solution introduces substantial investment costs and higher technological complexity compared to standard passive insulation techniques, it establishes a new paradigm for long-term energy self-sufficiency, sustainable urban development, and grid stability. Future energy market volatility and scaling up production could impact the long-term cost-effectiveness of the Solskin facade.

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DISCLAIMER

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, European Research Executive Agency (REA). The European Union, the granting authority, can be held responsible for them.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

RETROFITTING EXISTING MASONRY BUILDINGS TO PASSIVE HOUSE STANDARDS: CHALLENGES AND TECHNICAL SOLUTIONS

Jelena Savić[1], Aleksandra Cilić[2], Danijela Milanović[3], Danijela Đurić Mijović[4]

Abstract

The renovation of the existing building stock is essential for reducing energy consumption and improving indoor environmental quality. Retrofitting existing masonry buildings to high energy-performance standards is particularly challenging because energy-efficiency measures must be adapted to the characteristics of the existing building fabric, moisture behaviour, architectural constraints, and technical feasibility. This paper presents a structured analytical review of the main technical challenges and retrofit measures associated with the application of Passive House principles to existing masonry buildings. Relevant scientific and professional literature was comparatively analyzed and organized according to the principal retrofit measures and their reported effects on building performance. The analysis considers improvements to the thermal envelope, thermal bridge reduction, airtightness, high-performance windows and doors, controlled ventilation with heat recovery, solar control, moisture management, and efficient domestic hot water systems. A criterion-based qualitative framework is used to synthesize the relative contribution of these measures to energy efficiency, thermal comfort, indoor air quality, moisture protection, and building durability. The results indicate that the effectiveness of individual measures depends strongly on their interaction with other retrofit interventions and on the characteristics of the existing building. Continuous insulation, thermal bridge reduction, airtightness, high-performance openings, and mechanical ventilation with heat recovery form the core of an integrated high-performance retrofit strategy, while moisture management represents a cross-cutting requirement. The study provides a structured synthesis of the main technical relationships, performance contributions, and implementation constraints reported in the literature. It concludes that substantial improvements can be achieved through an integrated, building-specific approach, whereas the feasibility of attaining the full Passive House standard should be assessed individually for each existing masonry building.

Key words: *Passive House; EnerPHit; existing masonry buildings; energy retrofit; thermal comfort; airtightness; moisture protection; building durability*

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1. INTRODUCTION

The improvement of the existing building stock represents one of the main challenges in reducing operational energy consumption and improving the overall performance of the built environment. A considerable proportion of existing residential buildings was constructed before the introduction of contemporary energy-efficiency requirements and is characterized by insufficient thermal insulation, uncontrolled air leakage, thermal discontinuities, and inadequate building services. In addition to high energy demand, the ageing of materials and prolonged environmental exposure may affect the functional performance and durability of building components.

Existing masonry buildings present particular challenges for deep energy renovation. Their geometry, wall composition, structural characteristics, and state of preservation often limit the direct application of solutions developed for new buildings. In addition, the improvement of thermal performance may interact with structural requirements, architectural restrictions, and the heat and moisture behaviour of the existing envelope. The integrated consideration of seismic safety and energy retrofit has, for example, been identified as an important aspect in the renovation of existing masonry buildings [1].

The application of Passive House principles offers a comprehensive approach to reducing building energy demand through a highly efficient thermal envelope, minimization of thermal bridges, improved airtightness, high-performance windows and doors, and controlled mechanical ventilation with heat recovery. For existing buildings, these principles can also be applied through the EnerPHit renovation concept, which recognizes the specific technical constraints associated with retrofitting existing structures [6,7]. Previous studies have investigated passive retrofit scenarios and energy-efficiency strategies for existing and heritage buildings under different climatic and technical conditions [2–5].

However, individual retrofit measures cannot be evaluated independently. The improvement of insulation without adequate treatment of thermal bridges may leave areas of increased heat loss and condensation risk. Similarly, increased airtightness requires an appropriate ventilation strategy, while modifications to the thermal envelope can alter the moisture behaviour and drying potential of existing masonry walls. The effectiveness of windows, solar gains, and daylighting also depends on orientation, shading, and the characteristics of the overall envelope.

The objective of this study is therefore to provide a structured comparative synthesis of the principal technical measures associated with the application of Passive House principles to existing masonry buildings. The paper reviews their primary functions, reported performance effects, interactions, and principal implementation constraints. A criterion-based qualitative assessment is further applied to compare their relative contribution to energy efficiency, thermal comfort, indoor air quality, moisture protection, and building durability. The contribution of the study lies in organizing these interconnected measures within a common analytical framework that supports the preliminary evaluation of integrated retrofit strategies for existing masonry buildings.

2. MATERIALS AND METHODOLOGY

2.1 Analytical approach and source selection

The study was conducted as a structured analytical literature review. It does not include an original case study, field measurements, calibrated building-energy modelling, or independent simulation of retrofit scenarios. Accordingly, the results should be interpreted as a comparative synthesis of the findings reported in existing scientific and professional literature rather than as building-specific quantitative predictions.

The review focused on literature addressing energy renovation of existing and heritage buildings, Passive House and EnerPHit principles, passive retrofit scenarios, and technical challenges associated with the improvement of existing building performance. Priority was given to studies discussing one or more of the following aspects: thermal insulation, thermal bridges, airtightness, ventilation, windows and doors, solar gains and shading, moisture-related risks, and the technical applicability of high-performance retrofit measures [1–8].

The selected sources were classified according to the principal retrofit measures addressed and the building-performance aspects discussed. Because the reviewed studies were conducted for different building types, climates, and methodological conditions, their results were not combined into a single quantitative dataset.

2.2 Criterion-based assessment framework

The analysis considers nine principal measures: continuous thermal insulation, thermal bridge reduction, airtightness improvement, high-performance windows and doors, mechanical ventilation with heat recovery, solar shading, daylighting and controlled solar gains, moisture management, and efficient domestic hot water heating and distribution.

Each measure was comparatively assessed according to five performance criteria:

- Energy efficiency – contribution to reducing energy demand and heat losses;
- Thermal comfort – contribution to stable and acceptable indoor thermal conditions;
- Indoor air quality – contribution to controlled air exchange and indoor environmental quality;
- Moisture protection – contribution to reducing condensation and excessive moisture accumulation;
- Building durability – contribution to preserving the long-term functional performance of building components.

A three-level qualitative scale was used: 1 – limited or indirect contribution; 2 – moderate or context-dependent contribution; and 3 – high and direct contribution. Ratings reflect the directness and relative significance of each measure's contribution to the assessed performance criterion.

Table 1. Analytical framework used for the comparative synthesis

Analytical component	***Assessment focus***
Retrofit measure	Principal technical intervention
Primary function	Main building-performance problem addressed
Energy efficiency	Reduction of energy demand and heat losses
Thermal comfort	Improvement of indoor thermal conditions
Indoor air quality	Contribution to controlled air exchange
Moisture protection	Reduction of condensation and moisture risks
Building durability	Contribution to long-term component performance
Interactions	Relationship with other retrofit measures
Constraints	Building-specific and implementation limitations

3. PASSIVE HOUSE RETROFIT STRATEGIES AND TECHNICAL SOLUTIONS

The principal retrofit measures considered in the application of Passive House principles to existing masonry buildings are illustrated in Figure 1. The measures include improvements to the thermal envelope, thermal bridge reduction, airtightness, high-performance windows, shading, controlled ventilation, daylight utilization, moisture management, and efficient domestic hot water distribution.

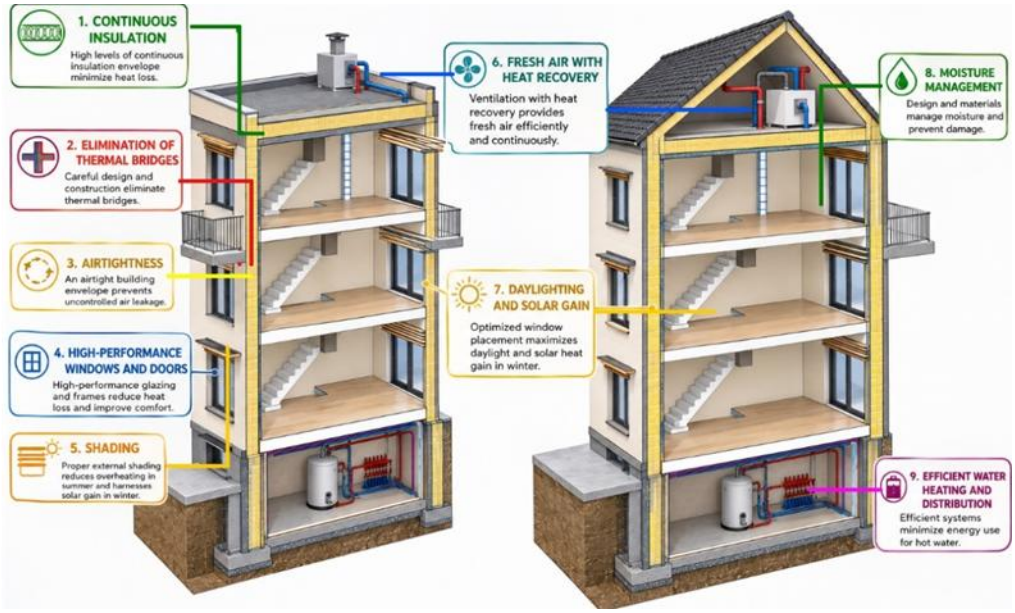


Figure 1. Comparative schematic illustration of Passive House design strategies for flat- and pitched-roof buildings (Author's own illustration, created with the assistance of AI-based tools)

3.1 Thermal envelope and thermal bridge reduction

Improvement of the thermal envelope is one of the primary strategies for reducing transmission heat losses in existing buildings. Continuous thermal insulation can improve the thermal resistance of walls, roofs, and floors while increasing internal

surface temperatures and contributing to improved thermal comfort. Its effectiveness, however, depends on the continuity of the insulation layer and its compatibility with the existing construction [3–6,8].

Thermal bridges represent localized areas of increased heat transfer caused by geometric conditions, material discontinuities, or interruptions in the insulation layer. In existing masonry buildings, they commonly occur at floor and roof junctions, structural elements, balconies, and window reveals. Their reduction is important not only for lowering heat losses but also for increasing internal surface temperatures and reducing the risk of surface condensation and mold growth [5–8].

The position of insulation is particularly important in existing masonry construction. External insulation generally protects the original wall from external temperature variations, whereas internal insulation may be necessary where façade alterations are restricted. However, internal insulation can modify the temperature and moisture conditions within the existing wall and reduce its drying potential. Its application therefore requires careful consideration of material compatibility and moisture-related risks [3–5].

High-performance windows and doors form an integral part of the improved thermal envelope. Their contribution depends on glazing and frame properties, airtightness, installation quality, and the treatment of the connection between the opening and the surrounding wall. Poorly designed installation details may create thermal bridges or air leakage paths that reduce the effectiveness of otherwise high-performance components [6–8].

3.2 Airtightness and controlled ventilation

Airtightness limits uncontrolled air leakage through joints, cracks, penetrations, and construction interfaces. Its primary contribution is the reduction of ventilation-related heat losses and uncontrolled drafts. In existing buildings, achieving a continuous air barrier can be particularly challenging because of irregular surfaces, existing cracks, multiple material junctions, and service penetrations [5,6].

Airtightness should not, however, be considered independently of ventilation. Reducing uncontrolled infiltration increases the importance of a designed strategy for supplying fresh air and removing indoor pollutants and moisture. Mechanical ventilation with heat recovery is therefore a key complementary measure in high-performance retrofits. It enables controlled air exchange while recovering part of the thermal energy from the outgoing air, contributing simultaneously to energy efficiency and indoor air quality [6,7].

The interaction between airtightness and ventilation illustrates the integrated character of Passive House-oriented renovation. Airtightness alone does not improve indoor air quality; its benefits in this respect depend on the implementation of adequate ventilation. Similarly, the effectiveness of mechanical ventilation may be reduced where excessive uncontrolled air leakage remains present. The feasibility of installing heat recovery ventilation in existing buildings may also be constrained by the space required for ducts and equipment, service-routing possibilities, noise control, and access for maintenance.

3.3 Solar control and daylight utilization

Windows provide access to daylight and solar energy but may also increase overheating risk. Appropriate use of daylight can reduce the demand for artificial lighting, while controlled solar gains may contribute to reduced heating demand during suitable periods. These effects depend strongly on orientation, glazing characteristics, window size, climate, and building geometry [2–4].

Solar shading is therefore an important complementary measure. Its primary role is to limit unwanted solar gains and reduce overheating risk, particularly during periods of high solar exposure. External shading can be especially effective because it intercepts solar radiation before it enters the building. However, shading must be coordinated with daylight requirements and beneficial winter solar gains. Excessive shading may reduce useful daylight, while insufficient solar control may compromise thermal comfort [2,3].

In existing buildings, modifications to windows or the installation of external shading may be limited by façade geometry and architectural or heritage restrictions. Consequently, the potential for optimizing daylight and solar performance must be assessed in relation to the characteristics of the individual building.

3.4 Moisture management and building durability

Moisture management is a cross-cutting requirement in the renovation of existing masonry buildings. The introduction of insulation, improved airtightness, and changes in ventilation conditions can alter the original heat and moisture balance of the building envelope. If these changes are not appropriately assessed, they may increase the risk of surface or interstitial condensation, mold growth, and material deterioration [3–5].

This issue is particularly relevant for internally insulated masonry walls. Although internal insulation can significantly reduce heat losses, it may lower the temperature of the existing masonry and alter its drying potential. The suitability of the proposed assembly therefore depends on the characteristics and initial condition of the wall, climatic exposure, moisture sources, and the properties of the new retrofit layers [3–5].

Moisture protection is closely connected with building durability. Repeated or persistent exposure to moisture can affect the functional performance of masonry and other building materials. Appropriate treatment of thermal bridges, airtightness, ventilation, and insulation should therefore be considered together as part of a moisture-safe and durable retrofit strategy. The EnerPHit and Passive House criteria also recognize moisture-related protection and the prevention of excessive indoor humidity as relevant aspects of high-performance building design [7].

3.5 Efficient domestic hot water systems

Efficient domestic hot water systems contribute primarily to the reduction of operational energy consumption. Their effectiveness may be improved through efficient water-heating equipment, reduced distribution losses, insulated pipework, and appropriate system design. Unlike envelope and ventilation measures, their direct influence on thermal comfort, indoor air quality, and moisture protection is limited.

Nevertheless, they form part of the overall strategy for reducing the operational energy demand of renovated buildings and should be coordinated with other building services measures [2,7].

4. COMPARATIVE SYNTHESIS AND DISCUSSION

The findings presented in Section 3 were synthesized using the assessment framework described in Section 2.2. The ratings presented below do not represent measured or simulated performance values. They provide a comparative qualitative interpretation of the primary and secondary effects of individual retrofit measures based on the reviewed literature and their technical function, presented in Table 2.

Table 2. Qualitative assessment of the principal Passive House retrofit measures

Retrofit measure	Energy efficiency	Thermal comfort	Indoor air quality	Moisture protection	Building durability
Continuous insulation	3	3	1	2	3
Thermal bridge reduction	3	3	1	3	3
Airtightness improvement	3	3	3*	3	2
High-performance windows and doors	3	3	1	2	2
Mechanical ventilation with heat recovery	3	2	3	2	2
Solar shading	2	3	1	1	1
Daylighting and controlled solar gains	2	2	1	1	1
Moisture management	2	2	2	3	3
Efficient domestic hot water systems	3	1	1	1	1

Assessment scale: 1 – limited or indirect contribution; 2 – moderate or context-dependent contribution; 3 – high and direct contribution.

**Airtightness alone does not provide fresh air. Its contribution to indoor air quality depends on integration with an adequate controlled ventilation strategy.*

The assessment indicates that continuous insulation and thermal bridge reduction have the strongest combined influence on energy efficiency, thermal comfort, moisture protection, and the durability of the building fabric. This is consistent with their direct role in reducing heat transfer and preventing low internal surface temperatures. However, insulation cannot be considered independently of moisture behaviour, particularly in existing masonry walls and internally insulated assemblies [3–6].

Airtightness and mechanical ventilation with heat recovery form another closely interconnected group. Airtightness reduces uncontrolled air leakage and associated

heat losses, while controlled ventilation provides the required air exchange and enables heat recovery. Their combined application is therefore more important than the performance of either measure considered in isolation [6,7].

High-performance windows and doors also contribute directly to energy efficiency and thermal comfort, but their overall effectiveness depends on installation details and their integration with the surrounding insulation and airtightness layers. Solar control and daylighting have a more context-dependent contribution because their effects vary according to orientation, climate, glazing characteristics, and the balance between beneficial and unwanted solar gains [2–4].

Moisture management has a distinct role within the framework. Its strongest contribution is to moisture protection and building durability, but it also interacts with energy efficiency, thermal comfort, and indoor air quality. This confirms that moisture safety should not be treated as a separate final-stage check but as a condition that must be considered throughout the development of the retrofit strategy [3–5].

Efficient domestic hot water systems have a different functional profile. Their primary contribution is to reducing operational energy demand, whereas their direct influence on envelope performance and indoor environmental quality is limited.

Overall, the results demonstrate that high-performance renovation should be based on the coordinated selection of complementary measures. The improvement of one component may be insufficient or may even create new technical risks when considered separately. For example, increased insulation without adequate thermal bridge treatment may leave localized areas vulnerable to condensation, while increased airtightness without controlled ventilation may adversely affect indoor air quality. Similarly, internal insulation must be evaluated in relation to the moisture behaviour of the existing wall.

The feasibility of achieving the full Passive House standard therefore depends on building-specific conditions. Existing structural configurations, architectural or heritage restrictions, irregular construction details, moisture-related risks, limited space for technical systems, and the cost or complexity of interventions may restrict the application of some measures [1,3–7]. In such cases, the application of Passive House principles through an EnerPHit-oriented renovation approach may provide a realistic pathway for achieving substantial performance improvements while accounting for the limitations of the existing building [6,7].

5. LIMITATIONS OF THE REVIEW

This study is based on a structured analytical review and qualitative synthesis of existing literature. It does not include a primary case study, field measurements, or independent simulation of retrofit scenarios; therefore, the findings should not be interpreted as building-specific quantitative predictions. The qualitative ratings represent a comparative interpretation of the reported effects and technical functions of retrofit measures and may vary according to climate, building geometry, wall composition, the condition of the existing fabric, and the detailed design of the intervention. In addition, the reviewed literature includes different building types and

methodological approaches, which prevents the direct aggregation of reported numerical results. The proposed framework is intended to support the preliminary comparison of retrofit measures and does not replace project-specific energy, hygrothermal, structural, or economic assessment. Future research should apply and validate the framework through representative case studies and quantitative analyses of alternative retrofit scenarios.

6. CONCLUSION

The renovation of existing masonry buildings according to Passive House principles requires an integrated approach in which individual measures are selected and designed in relation to the existing building fabric and their interaction with other interventions. The application of high-performance components alone cannot ensure an effective retrofit if the continuity of the thermal envelope, treatment of thermal bridges, airtightness, ventilation, solar control, and moisture behaviour are not considered together.

This study provided a structured analytical review and criterion-based qualitative synthesis of the principal retrofit measures relevant to existing masonry buildings. The assessment considered their relative contribution to energy efficiency, thermal comfort, indoor air quality, moisture protection, and building durability. The results indicate that continuous insulation and thermal bridge reduction have a particularly broad influence on building performance, while airtightness and mechanical ventilation with heat recovery form a complementary system for reducing uncontrolled energy losses and maintaining controlled indoor air conditions. High-performance windows and doors, solar control, and daylight utilization must be coordinated according to orientation and climatic conditions.

The analysis further confirms that moisture management represents a cross-cutting requirement. Changes to insulation, thermal bridges, airtightness, and ventilation can modify the temperature and moisture conditions of existing masonry assemblies and influence their long-term durability. This is particularly important where internal insulation is applied because of façade or architectural restrictions.

The main contribution of the study is the development of a common analytical framework that enables the principal retrofit measures to be compared across multiple performance criteria. The framework highlights that the effectiveness of a retrofit strategy depends on the interaction between measures rather than on the isolated performance of individual components.

Finally, the findings indicate that the full Passive House standard may not be technically feasible for every existing masonry building. Building-specific structural, architectural, hygrothermal, spatial, and economic constraints must therefore be considered when defining retrofit targets. Nevertheless, substantial improvements in energy performance and indoor environmental quality can be achieved through the systematic and coordinated application of Passive House principles. Where full compliance is not feasible, an EnerPHit-oriented approach may provide an appropriate strategy for adapting high-performance renovation principles to the specific limitations of the existing building.

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Research paper

IMPROVING ENERGY EFFICIENCY AND REDUCING CO_2 EMISSIONS AT THE NIŠKA BANJA SITE

Ana Mitrović[1]

Abstract

This paper considers a specific example of the application of heat pumps at the "Niška Banja" Institute, with the possibility of expanding the capacity to other commercial facilities. The advantages of using geothermal water as an energy source for space heating and domestic hot water preparation are presented. Given that geothermal water is a renewable energy source, such a system can reduce delivered and primary energy consumption compared with the existing fuel-oil-based heating system and has both environmental and economic benefits. The installed heat pumps are water-to-water systems that use exploited geothermal water as the energy source. The paper also presents the possibility of using the pumps at the Institute, or rather the advantages of further distributing hot water to private guest accommodation facilities, such as villas in Niška Banja. All relevant data related to the calculation of energy consumption in buildings were prepared based on a reference example, based on current domestic regulations and standards, and using the URSA Building Physics 2 software.

Key words: *Energy efficiency, Heat pumps, CO_2 emission reduction, Geothermal water, Renewable energy*

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1. INTRODUCTION

More than a third of all consumed high-quality energy, mainly obtained from fossil fuels, is used for space heating and heating of domestic hot water. This energy source has a negative impact on the environment, a low utilization rate, requires large storage spaces, emits harmful gases into the atmosphere when burned and has a longer renewal period compared to its rate of consumption.

The future of energy efficiency lies in the use of renewable energy sources such as: air, solar energy, water, wind, biomass energy and geothermal energy. These energy sources are all around us and are free. This is evidenced by research studies that investigate the performance of heat pumps utilizing renewable energy sources from the environment as an energy source, implemented in buildings [1, 2, 3], as well as by studies that provide comparative analyses of the results obtained for various types of heat pumps [4].

The justification for using these energy sources includes reducing emissions of harmful gases into the atmosphere, reducing global warming and the greenhouse effect and, consequently, climate change as well as reducing dependence on imported energy raw materials and electricity.

The above facts support a better future and sustainable development, both from an ecological and economic perspective.

Given that the energy sources that are most widely used on the market today are becoming more expensive and will eventually become less accessible due to the depletion of resources, or rather their long renewal period, a solution can be found in the application of heat pumps based on the use of renewable sources. Nowadays, a wide range of heat pump types is available, offering different performance levels depending on the energy source used [5, 6].

The problem with the acceptance and implementation of these new technologies is the high cost of new facilities and installations [7].

2. METHODOLOGY

The analysis and systematization presented in this paper concern the subject facilities based on data obtained from the “Niška Banja” Institute regarding their previous and current state. General issues related to guest accommodation facilities were analyzed, with particular emphasis on the input parameters required for the assessment of their energy efficiency. This paper also presents the calculation of the energy performance of the reference facility in its existing state, together with an analysis of the obtained results.

3. THERMAL SPRINGS AND LOCATIONS

Niška Banja, Niš, and the entire district of Niš are known for the existence of geothermal waters, which is not recognized as a significant factor in the sustainable development of the region, despite modern technology having advanced considerably.

If we look back through history, settlements were built in this territory precisely thanks to the existence of geothermal springs. One example is Niška Banja itself, which is one of the city municipalities of the City of Niš.

Even in the distant past, these sites were used, indeed with technology that is primitive for today. In the area that includes Niš and Niška Banja, there are many archaeological sites that, through their architecture, testify to the use of these geothermal springs even during the time of the Roman Empire.

During the construction of the Radon Hotel in Niška Banja, an early Byzantine tomb was discovered, while the Old Bath dates back to the time of Hadrian (1st century AD). Some settlements were also used during the Ottoman Empire.

There are two primary sources of geothermal water in Niška Banja.

One source is the Glavno vrelo (Main Spring) of Niška Banja (Fig. 1), which erupts from a rock about 2.5 m below ground level, with an original Roman captation in the form of a dome-shaped well, where hot water erupts from below and rises to the top of the dome. Among the homeothermal Serbian spa springs, the Glavno vrelo of Niška Banja is one of the most generous ones. The water belongs to radioactive homeothermal springs and its healing effect comes from radon and microelements. The minimum water flow is 35 l/s, the water temperature ranges from 38.2 °C to 38.5 °C, with insignificant mineral content.

This spring supplies water to the following: the Staro kupatilo (Old Bathhouse) (Pool no. 3) dating from the seventeenth century; the Glavno kupatilo (Main Bathhouse) (Pools no. 1 and 2), built in 1932; as well as the facilities "Ozren", "Zelengora", "Radon" and "Terme", dating from the mid-20th century.



Figure 1. View of the facility Glavno vrelo (Main Spring) of Niška Banja, Source: Intermedichbo (2022), Wikimedia Commons, licensed under CC BY-SA 4.0.

The second spring is Suva Banja (Dry Spa), or Prince Tomislav's Spring (Fig. 2), which is located at the intersection of the Nišava and Studena faults, 300 m southeast of the Glavno vrelo (Main Spring) of Niška Banja. This spring was given its name because the

water from the cave spa appeared as a lukewarm spring only after the snow melted or heavy rain, giving the impression that it dried up during other periods.

In 1931, through hydraulic works, the entrance to the cave was opened and the overflow level was lowered to about 70 m below the spring's outlet level, making it a permanent spring. That year, the Hladno kupatilo (Cold Bath) (Pool no. 5) was built, receiving water from this spring for the treatment of patients with a labile nervous system. The characteristics of the water from this spring are low radioactivity, with a temperature and mineral composition similar to those of other springs in Niška Banja.

The Suva Banja spring dried up again after World War II. In 1956, based on the project of Professor Pećinar, the spring inlet was lowered by an additional 8.5 m. The newly created hydrological regime of the spring is characterized by a minimum water inflow during dry periods of 25 l/s, when the water temperature is around 39 °C. During the rainy season and after snowmelt, the water flow increases to about 500 l/s and the water temperature drops to about 11 °C.



Figure 2. View of the building Suva Banja (Dry Spa), Source: Đorđe Marković (2017), Wikimedia Commons, licensed under CC BY-SA 4.0.

4. HEAT PUMPS OF THE INSTITUTE "NIŠKA BANJA"

The "Niška Banja" Institute has recognized the importance of energy efficiency and the value of sustainable development since 1986, when it installed eight heat pumps (Figs. 3, 4) from the manufacturer "Termofriz", split-system type-pwcl/hp-600/180, each of which had a heat capacity of 600 kW and a maximum water outlet temperature of 55 °C. They used the refrigerant – Freon 12, with a primary inlet water temperature at 28 °C. The existing heat pumps were used to heat the Institute's buildings to a minimum external temperature of 0 °C, with a maximum of three pumps operating but with reduced heating capacity due to the insufficient flow of geothermal wastewater.

The operation of the existing heat pumps was very difficult due to very frequent breakdowns, as well as extremely expensive servicing and repairs. The lack and inability to procure spare parts to put the pumps into operation forced the Institute's buildings to continue being heated its buildings with hot water boilers using fuel oil as an energy source.





Figures 3 and 4. Appearance of the old heat pumps manufactured by "Termofriz", Source: Archive of the "Niška Banja" Institute

In 2018, the Institute replaced the obsolete heat pumps with two new units (Figs. 5, 6). The new heat pumps are water-to-water systems equipped with inverter-driven screw compressors capable of adjusting their operating speed according to the instantaneous heating demand. This enables precise control of the condenser outlet water temperature up to 65 °C. The system consists of two identical water-to-water heat pumps. The main technical specifications of a single heat pump are presented in Table 1.





Figures 5 and 6. View of the heat pumps in the power plant of the "Niška Banja" Institute, Source: Archive of the "Niška Banja" Institute

Following the installation of modern heat pumps that utilize discharged geothermal water as an energy source, the Institute was able to provide heating for its own facilities, as well as one private facility.

In 2025, the Institute received funding for a third heat pump. This expansion not only increases heating capacity for the facilities; it also makes it possible to provide domestic hot water for the Institute.

Table 1. Main technical specifications of the water-to-water heat pumps

Type	**ewwd610vzxsa1+op111- "daikin"**
Heating capacity (condenser)	646.5 kW
Temperature regime	water 60/65° C
Flow	31.78 l/s
Compressor type	screw inverter
Refrigerant	r-134 a
COP	minimum 3.2 at the designed temperature regime
Cooling capacity (evaporator)	612 kW

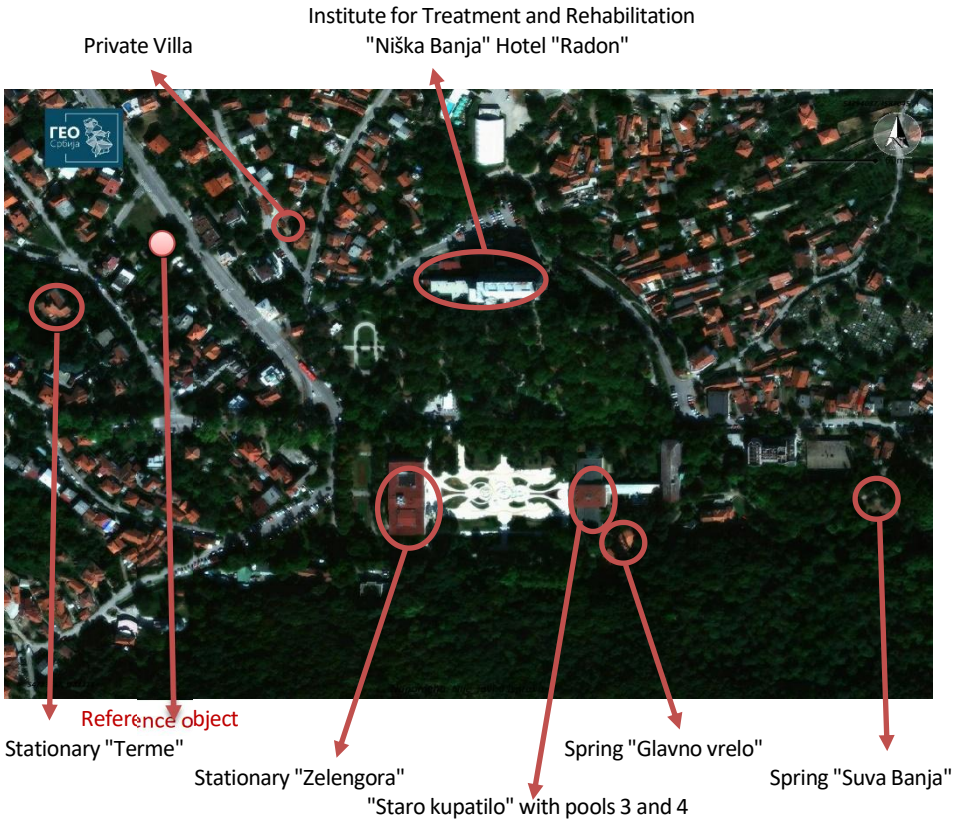


Figure 7. Orthophoto image with a schematic representation of the heat source and the buildings supplied by the district heating network of the "Niška Banja" Institute , Adapted from Satellite ortophoto mosaic (2020–2021 epoch), by Republic Geodetic Authority, n.d., GeoSrbija (geosrbija.rs). In the public domain

5. REFERENCE EXAMPLE OF A BUILDING – VILLA

The reference example for this work is a villa building with a basement, a ground floor and two upper floors, with a total net area 519.53 m^2, located in the central area of Niška Banja. The building in question is newly constructed, which means that it meets the requirements of current domestic regulations [8], so that the calculation of energy efficiency was not affected by poor insulation of the thermal envelope or poor-quality transparent elements.

The energy performance report of the building was prepared based on the 2011 Rulebook on the Energy Efficiency of Buildings [8] and applicable standards. The calculation was performed using the URSA Building Physics 2 program, which uses the thermophysical properties of materials given in the Rulebook [8], Table 3.4.1.2 and URSA thermal insulation materials, whose quality and thermophysical properties are controlled in accordance with the ISO 9001:2000 standard and for which valid IMS certification documentation is available.

The following basic climate data were used for the calculation:

Place: NIŠ

External design temperature $Q_{H,e}$: -14.5 °C

Number of heating degree days HDD: 2613 K-days

Number of heating days: 179 days

Mean temperature of the heating period $Q_{H,mn}$: 5.4 °C

The input parameters for heating for the calculation of the energy performance of the reference building are a local system with an individual boiler and extra-light heating oil as an energy source.

Based on the data obtained from the Tourist Information Center of Niška Banja, which operates as part of the Tourist Organization of the City of Niš, there are 12 registered guest accommodation facilities in the territory of Niška Banja, that are approximately similar to this reference example.

6. RESULTS

In 2017, the Institute consumed over 500 tonnes of fuel oil (more precisely, 562 tonnes) for heating the Institute's facilities, with an area of approximately 27,000 m^2. During the same period in the following heating season, after the installation of two heat pumps, fuel oil consumption dropped to approximately 120 tonnes, which means that consumption was reduced by more than four times [9].

The results obtained from the energy efficiency study for the reference facility (Table 2) show that the specific total annual energy demand for heating is 81.28 kWh/m^2, and carbon dioxide emissions into the atmosphere are 7,194.22 kg/a.

In this work, the actual state of the existing building stock in Niška Banja was not taken into account, as it would affect the calculation of energy classes and performance. However, the theoretical assumption is that all buildings (similar to the reference building) have satisfactory characteristics of their thermal envelope and transparent elements.

In this work, the actual state of the existing building stock in Niška Banja was not taken into account, as it would affect the calculation of energy classes and performance, but the theoretical assumption is that all buildings (similar to the reference building) have satisfactory characteristics of their thermal envelope and transparent elements.

Table 2. Energy balance for heating the reference building

Annual required heat for heating $Q_{H,nd}$	17060.48 kWh
Annual heat losses of the heating system $Q_{H,ls}$	5562.85 kWh
Annual Delivered heat, Q_H	22623.33 kWh/a
Annual required heat for the preparation of DHW Q_W	0.00 kWh
Annual heat losses of the system for the preparation of DHW $Q_{W,ls}$	0.00 kWh
Annual heat requirement for cooling Q_C	0.00 kWh
Annual cooling system losses $Q_{C,ls}$	0.00 kWh
Annual required energy for ventilation and air conditioning Q_{Ve}	0.00 kWh
Annual required energy for lighting E_l	0.00 kWh
Total annual delivered energy E_{del}	27148.00 kWh
Specific total annual delivered energy E'_{del}	**81.28 kWh/m²**
Permitted annual use of primary energy $E_{prim, max}$	0.00 kWh
Annual emission CO_2	**7194.22 kg/a**

Based on the above assumption, for all 12 reference-type buildings combined, the annual heating energy demand is 981.84 kWh/m^2, while the annual carbon dioxide emissions into the atmosphere is 86,330.64 kg/a, i.e. 86.33 t/a.

In the case of heating the reference building using a water-to-water heat pump where the energy source is used thermal water, the electrical energy for heating would be reduced to 0, as would the carbon dioxide emissions. The electricity consumption required to operate the heat pump for the reference facility would be 5,190 kWh. Based on specific CO_2 emissions for different energy carriers from the Rulebook on the Energy Efficiency of Buildings [8] (Table 6.13), the resulting carbon dioxide emissions are reduced to 2,750.70 kg/a. For the 12 reference type facilities, the total electricity demand would be 62,280 kWh, and accordingly the CO_2 emissions would be 33,008.40 kg/a or 33 t/a.

7. DISCUSSION

The "Niška Banja" Institute has an existing energy plant with water-to-water heat pumps that utilize recovered thermal water as an energy source, as well as a developed existing infrastructure network that distributes thermal water to its inpatient facilities and one privately owned facility. By installing additional heat pumps in the Institute, it would be possible to provide hot water for heating the reference guest accommodation villas. Such a measure would achieve a significant reduction in both heating energy demand and carbon dioxide emissions into the atmosphere.

In this paper, a detailed economic analysis of the investments required for this type of intervention was not conducted, considering that the already existing thermotechnical systems and infrastructure network have an significant influence on the investment cost, as well as the availability of donations, the budget from which the Institute is financed, etc.

As a measure to further improve energy efficiency and reduce carbon dioxide emissions at the site, the installation of an on-site photovoltaic system could be considered to provide the electricity required for the operation of the heat pump systems. The use of photovoltaic generation could reduce electricity consumption from the grid and the associated operational CO_2 emissions, thereby reducing dependence on electricity from non-renewable sources.

8. CONCLUSION

By installing water-to-water heat pumps that use recovered thermal water as an energy source, at the "Niška Banja" Institute, the following benefits can be achieved:

- A highly efficient system that is easier to maintain (it almost does not require any special maintenance);
- The proposed system results in a reduction of approximately 61.8% in CO_2 emissions, corresponding to emissions about 2.6 times lower than in the reference case;
- Reduction of the greenhouse effect and improved environmental protection;
- Reduction in the use of non-renewable energy sources;
- Possibility of distribution to other facilities that are not part of the Institute.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

TYPICAL THERMAL BRIDGES IN LARGE-PANEL PREFABRICATED RESIDENTIAL BUILDINGS OF THE OS-68-GL SYSTEM

Lachezar Hrischev[1], Georgi Ivanov[2], Andrey Telbishki[3]

Abstract

This paper presents the results of a thermal assessment and diagnostics of the façade elements of a large-panel prefabricated residential building located in Sofia, Bulgaria. The investigated structure is a representative example of buildings constructed using the OS-68-GL system, which has traditionally been used for various types of dormitories. The investigation was carried out using infrared thermography, with surface temperatures measured both externally and internally on the façade elements, including prefabricated panels and monolithic basement walls. Based on the analysis of the results, conclusions were drawn regarding the presence of areas of increased heat transfer and thermal bridges.

It was established that, in buildings of this type, characteristic thermal bridges occur along the perimeter of blind façade panels (without openings), where no intermediate thermal insulation layer is incorporated into the panel. Thermal bridges were also identified at the horizontal and vertical joints between the façade panels and in the areas of the balconies. Façade panels containing window and door openings, as well as spandrel panels (beneath windows), are also characterized by significant heat transfer. In addition, the building's window and balcony door systems are in unsatisfactory condition, resulting in substantial heat losses through these elements.

The obtained results could serve as a basis for further detailed investigations, including the determination of heat transfer coefficients for the identified building elements. These data could subsequently be used to support the design and implementation of energy renovation measures for buildings of this type.

Key words: l*arge-panel prefabricated residential buildings, thermal bridges, infrared thermography*

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1. INTRODUCTION

The construction of large-panel residential buildings (LPRBs) in Bulgaria has a history of more than 60 years. Following the experimental stage, the period from 1965 to 1975 marked the beginning of the large-scale construction of buildings using industrial technologies and the comprehensive industrialization of the construction sector. As a result of the policies implemented and the production activities of the prefabricated housing construction plants, to date, 860 000 panel dwellings have been constructed in the Republic of Bulgaria, distributed among 18 900 large-panel residential buildings, with 82,3% of LPRBs located in cities serving as regional administrative centers [1]. Some of the most widely used systems for this type of building in Sofia are the BS-69-SF and BS-69-SF-UD systems, with buildings constructed using these systems accounting for approximately 71% of all LPRBs in the city [2]. To meet the demand for student and workers' dormitories, a separate system, OS-68-GL, was developed [3]. As shown in *Figure 1*, LPRBs constructed using the OS-68-GL system were built predominantly during the period from 1968 to 1978.

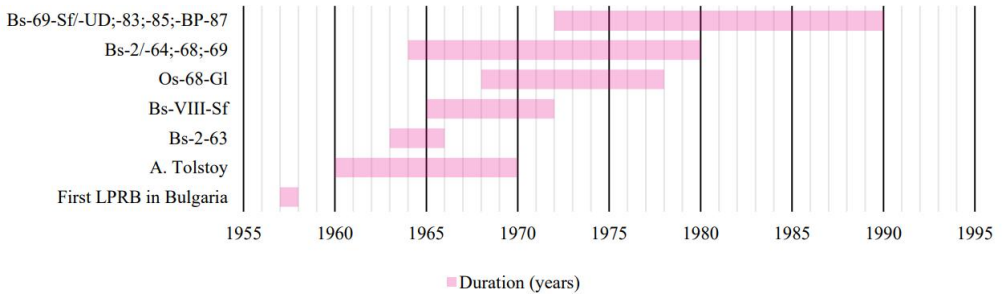


Figure 1. Timeline of LPRB construction periods by system in Sofia, Bulgaria [4]

Current trends are focused on the renovation of large-panel residential buildings (LPRBs) [5], the implementation of measures to improve their energy efficiency [6–9], and the modernization of their building services [10]. Renovation should be carried out on the basis of a detailed evaluation of the serviceability of these buildings, based on both a structural investigation involving destructive and non-destructive testing [11,12] and a thermal performance assessment [13].

According to the current regulatory framework in Bulgaria, and more specifically Ordinance No. 5 on the Technical Passports of Constructions [14], technical passports are required to be prepared for all existing constructions. An important stage in the preparation of technical passports is the structural assessment and the evaluation of energy performance. Similar regulatory requirements exist in other countries, and the data collected and analyzed through the technical passporting process can be used to assess the reliability of buildings [15]. The thermal insulation measures and insulation systems of LPRBs should be designed taking into account the results of the thermal performance assessment conducted for the building and, accordingly, the recommendations documented in the building's Technical Passport.

Also, according to the Energy Efficiency Act in Bulgaria [16], an energy audit must be carried out for all existing buildings, resulting in a report and an energy performance

certificate. The energy audit must determine the thermal performance characteristics of the building and its building elements. Following reconstruction or renovation of the building, the energy performance certificate must be updated.

This paper presents the results of a thermal performance assessment and infrared thermographic investigation of selected facade elements of an LPRB constructed using the OS-68-GL system and located in Sofia, Bulgaria, with the aim of identifying typical thermal bridges. The obtained results may be considered preliminary and could serve as a basis for more detailed investigations at a later stage, which may supplement and further develop the findings, including the determination of heat transfer coefficients to be used in the design and energy renovation of buildings.

2. MATERIALS AND METHODS

2.1. General characteristics of the investigated building

The building investigated in this study is a student dormitory constructed using the OS-68-GL system and located in the Studentski Grad district of Sofia, Bulgaria. It is part of the earlier development of the complex and is a large-panel residential building dating from 1977. The OS-68-GL system was developed based on precast reinforced concrete panels originally designed for frameless-panel residential buildings, with axes spaced at 3,60 m and 5,10 m in plan and a floor-to-floor height of 2,80 m. The system was primarily used for the construction of dormitories ranging from four to eight storeys. The building has a frameless structure consisting of wall and floor panels, with a gross floor area (GFA) of 8334,37 m² and a building footprint of 1177,82 m². A general perspective and plan view of the building are shown in *Figure 2*.



a) *b)*

Figure 2. General view of the building: a) perspective; b) plan [17]

The blind façade panels (panels without openings) are made of three-layer reinforced concrete with an intermediate layer of expanded polystyrene (EPS), while the façade panels with window and door openings are made of expanded clay perlite concrete, and the spandrel panels (panels beneath the window openings) are made of ordinary reinforced concrete [3]. Some of the main characteristics of the façade elements of buildings constructed using the OS-68-GL system are presented in *Table 1*.

Table 1. Characteristics of façade elements of buildings constructed using the OS-68-GL system, based on [3] and [18]

№	Façade element	Element type	Thickness, cm	Main characteristics
1	Basement reinforced concrete walls	Monolithic reinforced concrete	40 cm	Ordinary concrete, grade M 200 (approximately Class C12/15)
2	Façade panels without openings along the end transverse axes of the building (blind panels)	Precast panels	20 cm	Three-layer panels made of ordinary reinforced concrete with an intermediate 5 cm thick EPS layer
3	Façade panels with window and door openings	Precast panels	20 cm	Single-layer panel made of expanded clay perlite concrete, grade M75
4	Spandrel panels (panels beneath the window openings)	Precast panels	20 cm	Ordinary concrete, grade M 200 (approximately Class C12/15)
5	Elements between window openings (inter-window elements)	Layer-by-layer assembly	7 cm	Consist of a wooden board on the exterior side, a 40 mm thick mineral wool layer in the middle, and a wooden board on the interior side

2.2. Research methodology

The identification of characteristic thermal bridges along the building façade was carried out using infrared thermography. The use of a thermal imaging camera for building diagnostics enables the visualization of energy losses, detection of missing or defective insulation, identification of moisture in insulation, roofs, and walls, and localization of thermal bridges, among other applications [19]. The method can be successfully applied to both insulated and uninsulated façades [20,21].

In this study, a FLIR i7 thermal imaging camera was used, with the following technical characteristics: thermal sensitivity of 0,1 ℃, image resolution of 140×140 pixels, spectral range of 7,5–13 μm, temperature range from -20 ℃ to +250 ℃, and accuracy of ±2% [22].

The procedure for detection of thermal bridges in this study is outlined below:

- a visual inspection and an overall digital photograph of the façade were taken;
- an overall thermographic image of the same façade was obtained using the FLIR i7 thermal imaging camera to visualize areas with different surface temperatures;
- detailed thermographic imaging was performed on the areas where higher surface temperatures, indicative of thermal bridges, were identified, from the exterior side of the building;
- the same areas were imaged from the interior side of the building.

The time interval between the capture of the internal and external images was a maximum of 15 minutes. A general view of the building, including the areas selected for detailed infrared thermographic measurements, is presented in *Figure 3*.

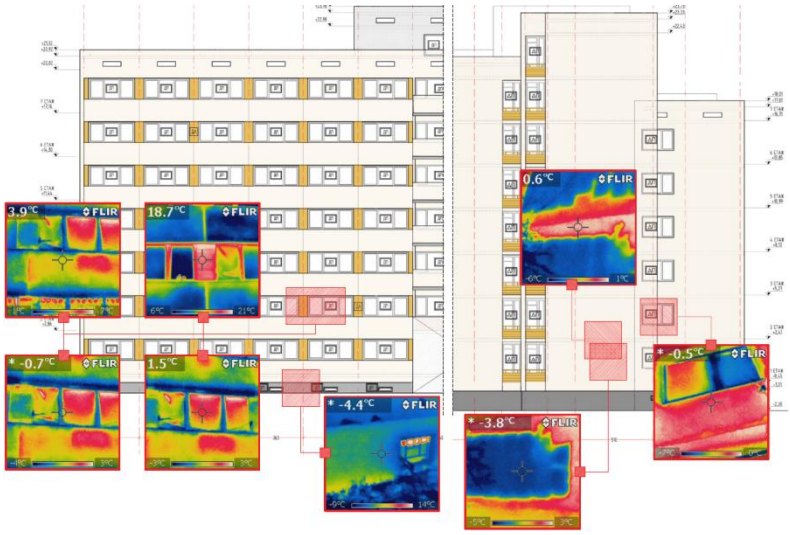


Figure 3. Areas of the building selected for detailed infrared thermographic measurements. Source: Authors

3. RESULTS AND DISCUSSION

Following the initial comprehensive visual inspection of the building façades, detailed infrared thermography was performed on a façade panel incorporating a thermal insulation layer, examined both in the insulated area and in the area without thermal insulation. The investigation also included a façade spandrel panel beneath a window, an inter-window timber element, a façade panel with a window opening and without a thermal insulation layer, and a monolithic reinforced concrete basement wall. It should be noted that the thermographic images of the façade elements on the second floor were captured from ground level.

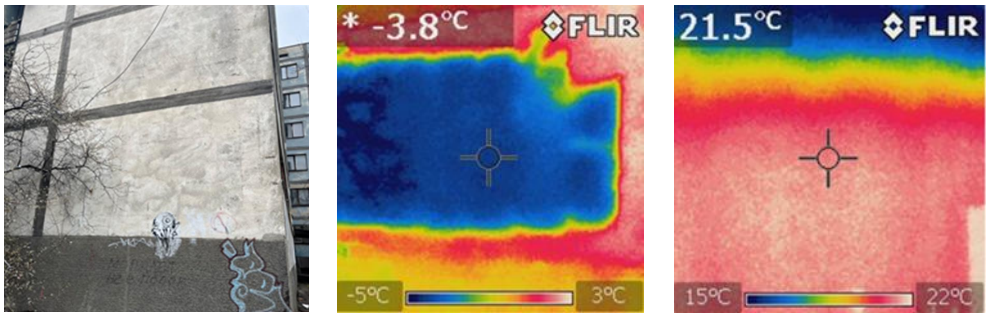
The thermographic investigation was conducted on 16 February 2023, during the period from 09:00 to 11:00. As the aim of the study is to provide a preliminary qualitative assessment of thermal bridges, measurements of humidity and air velocity were not performed.

Table 2 below and the thermographic images summarize the results obtained from the investigation of selected characteristic building elements. The measured surface temperatures on the internal and external sides of the elements are presented.

Table 2. Measured internal and external surface temperatures of the façade elements

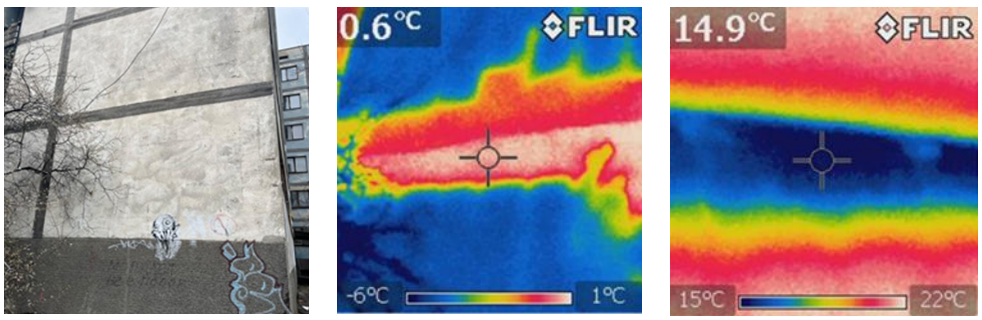
№	Façade element	Internal surface temperature, °C	External surface temperature, °C
1	Façade panel without openings along the end transverse axes of the building (blind panel)		
	a) in the area of the thermal insulation layer	21,5	-3,8
	b) in the area without the thermal insulation layer	14,9	0,6
2	Façade panel with a window opening	9,4	-0,5
3	Spandrel panel	19,5	3,9
4	Inter-window element	26,9	18,7
5	Basement reinforced concrete wall	7,0	-4,4

The digital and thermographic images of the façade elements listed in *Table 2* are presented in the figures below. Each figure includes a digital photograph of the investigated element and thermographic images taken from the exterior and the interior.



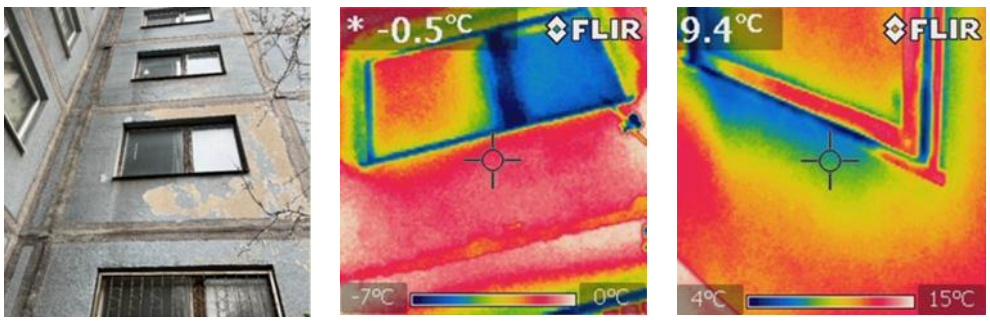
a) *b)* *c)*

Figure 4. Digital photograph and thermographic images of the façade panel without openings along the end transverse axes of the building (blind panel), in the area of the thermal insulation layer: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors



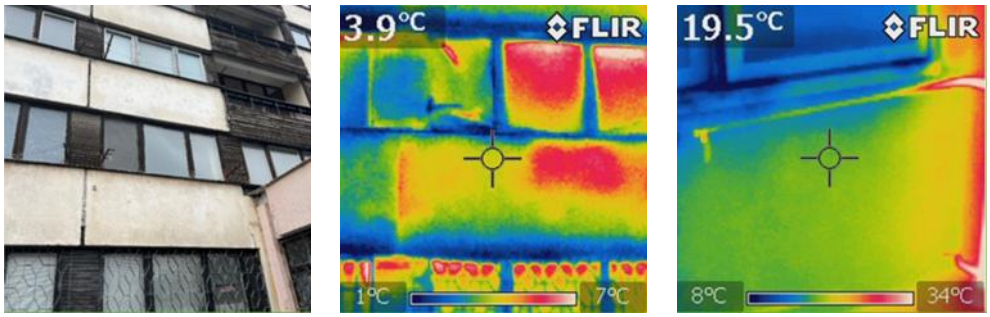
a) *b)* *c)*

Figure 5. Digital photograph and thermographic images of the façade panel without openings along the end transverse axes of the building (blind panel), in the area without the thermal insulation layer: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors



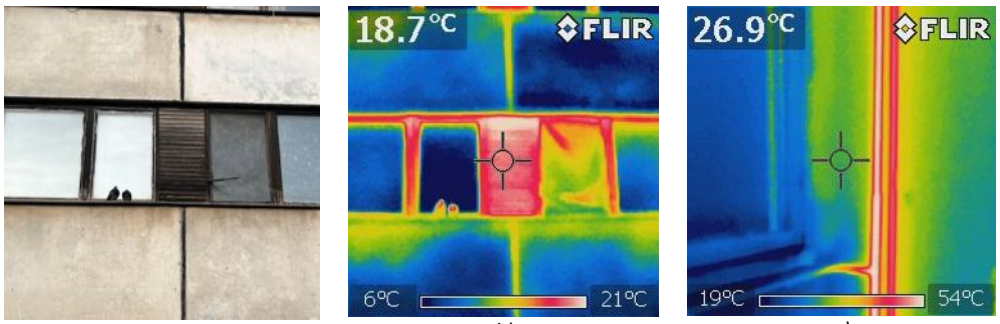
a) *b)* *c)*

Figure 6. Digital photograph and thermographic images of the façade panel with a window opening: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors



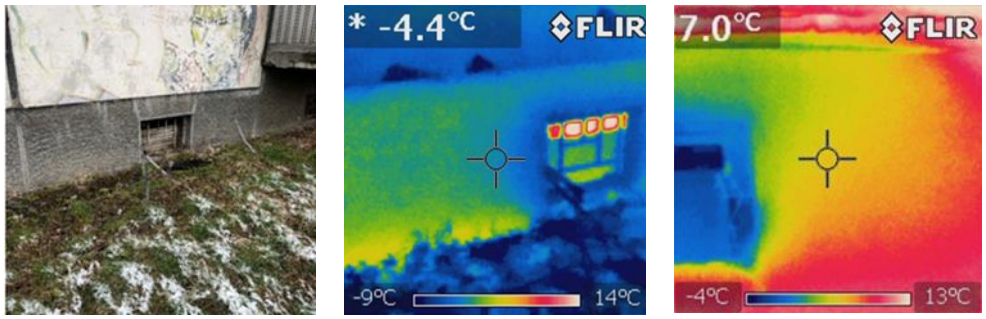
a) *b)* *c)*

Figure 7. Digital photograph and thermographic images of the spandrel panel: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors



a) *b)* *c)*

Figure 8. Digital photograph and thermographic images of the inter-window element: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors



a) *b)* *c)*

Figure 9. Digital photograph and thermographic images of the basement reinforced concrete wall: a) digital photograph; b) exterior thermographic image; c) interior thermographic image. Source: Authors

The results presented in *Table 2*, together with those shown in *Figures 4–9*, indicate the presence of areas of significant heat transfer and thermal bridges in the façade elements of the building. For example, in the façade panel without openings along the end transverse axes of the building (blind panel), the temperature difference between the internal and external surfaces in the area with the incorporated thermal insulation layer is approximately 25,3 °C. In the same panel, but in the area without the thermal

insulation layer, the temperature difference between the two surfaces (internal and external) is approximately 14,3 °C. The thermographic images presented in *Figures 4* and *5* clearly show the area with the thermal insulation layer and the characteristic thermal bridge outside this area.

A temperature difference of a similar magnitude (approximately 15,6 °C) is also observed between the internal and external surfaces of the spandrel panel. These values are consistent with the fact that both panels are made of ordinary concrete and have a thickness of 20 cm. The poor thermal performance of the spandrel panel can also be inferred from the higher-temperature area visible on its external surface, corresponding to the location of a heating radiator belonging to the building's heating system (see *Figure 7b*).

For façade panels with window openings, the differences between the measured surface temperatures are smaller, at approximately 10 °C. This can be attributed to the lower heat transfer coefficient of this type of panel, which is made of expanded clay perlite concrete. A characteristic linear thermal bridge is also observed at the joints between the panels. Similar characteristic linear thermal bridges are observed at the vertical joints between the spandrel panels.

Areas of significant heat transfer are also observed at the inter-window elements (see *Figure 8*) and at the monolithic reinforced concrete basement walls (see *Figure 9*). Despite the presence of a 40 mm thick thermal insulation layer within the inter-window element, a relatively high temperature is observed on its external surface, which may be attributed to compromised integrity of the thermal insulation.

Based on an analysis of the structure of the various façade elements (see *Table 1*) and the thermographic results, it can be concluded that the main reasons for the differences in external surface temperatures are the characteristics of the façade elements and, consequently, the different values of their heat transfer coefficients.

Although not presented in detail in this paper, thermal bridges were also identified at the internal corners between the façade panels and in the balcony areas. These findings indicate that, in future energy renovation of buildings of this type, specific measures for the installation of effective thermal insulation systems should also be considered for these elements.

Since the measurements refer only to individual façade elements, the relationship between the measured temperatures and the numerical data used for energy efficiency and thermal performance calculations has not been determined. It is therefore planned to investigate this relationship more comprehensively by assessing a larger number of elements of the same type under comparable conditions.

4. CONCLUSIONS

This paper presents the results of an infrared thermographic investigation of the façade elements of a large-panel residential building constructed using the OS-68-GL system and located in Sofia, Bulgaria. Based on the measured surface temperatures on the internal and external sides of the façade elements, areas of significant heat transfer and characteristic thermal bridges were identified.

It was established that, in buildings of this type, characteristic thermal bridges occur along the perimeter of blind façade panels, in areas where no intermediate thermal insulation layer is incorporated, at the horizontal and vertical joints between façade panels with openings, at the vertical joints between spandrel panels, and at other locations. Façade panels with window openings, spandrel panels, as well as monolithic basement reinforced concrete walls, are also characterized by significant heat transfer.

The results indicate that specific measures should be taken to implement effective thermal insulation systems in future energy renovation of buildings of this type.

The present study provides an preliminary qualitative assessment rather than a complete assessment of the thermal performance of buildings of this type. Directions for future research include a comprehensive and detailed thermographic investigation of all building envelope elements, aimed at quantitatively evaluating their thermal performance and determining the overall heat transfer coefficients based on established methodologies [21,23]. The overall heat transfer coefficients determined in this way could be effectively used in the design of energy efficiency measures and the energy renovation of buildings.

ACKNOWLEDGMENT

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Research paper

ONE ARCHITECTURAL PROGRAMME, TWO CIRCULAR CONSTRUCTION STRATEGIES: A COMPARATIVE EVALUATION OF ADAPTIVE REUSE AND CONTAINER REPURPOSING

Despina Parpas[1]

Abstract

The construction sector is increasingly required to transition from linear models of resource consumption towards circular approaches that extend the lifespan of existing materials and structures. Among the various circular construction strategies emerging within contemporary practice, the practice of adaptive reuse and shipping container repurposing represent two distinct approaches based on the principle of resource conservation. However, limited research has comparatively examined these strategies when applied to the same architectural programme. This study investigates the economic, technical and contextual implications of adaptive reuse and container repurposing through a comparative analysis of two café developments in Cyprus. The first case study examines the transformation of an existing commercial unit into a café, while the second investigates the conversion of three shipping containers into a café structure. A Multi-Criteria Decision Analysis (MCDA) framework is employed to evaluate the two approaches according to criteria including construction cost, implementation time, regulatory complexity, environmental performance, design flexibility and contextual integration. The findings demonstrate that neither strategy consistently outperforms the other across all evaluation criteria. The adaptive reuse project presents advantages in terms of construction cost, project duration and integration within the existing urban fabric, while the container-based project provides greater opportunities for architectural identity, modular flexibility and material repurposing. The comparison further investigates the common perception that container architecture represents an inherently low-cost circular solution, demonstrating that economic performance depends on the extent of transformation required. The study argues that circular construction strategies should not be evaluated through a single sustainability indicator, but through a holistic assessment of environmental, economic, technical and architectural considerations. By providing empirical insights into the decision-making process between alternative reuse approaches, this research contributes to the broader discussion on context-sensitive circular design strategies.

Key words: *Adaptive Reuse, Shipping Container Architecture, Circular Economy, Multi-Criteria Decision Analysis*

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1. INTRODUCTION

The construction sector generates significant environmental impacts through resource extraction, material production, construction activities and construction and demolition waste. Its predominantly linear model of extraction, use and disposal has intensified pressure on natural resources, encouraging approaches that extend the useful life of existing resources and reduce new material consumption [1,2].

Circular economy principles promote value retention through reuse, adaptation, repurposing and recovery. At the building scale, adaptive reuse extends the functional life of existing structures by introducing new uses while retaining existing fabric [3-5]. At the material and component scale, repurposing transforms existing objects into new architectural applications [6]. Shipping container repurposing combines industrial artefact reuse with modular architectural applications, although its environmental performance depends on the extent of adaptation [7,8]. Similarly, adaptive reuse depends on existing conditions, proposed use, regulations and intervention requirements [3,5,9]. Thus, circular reuse strategies do not necessarily produce equivalent economic, technical or architectural outcomes.

Despite growing research on both approaches, they are generally examined separately. Limited attention has been given to their direct comparison when accommodating the same architectural programme, although different circular strategies may preserve different forms of value and produce different economic, technical, regulatory and spatial outcomes. This study addresses this gap through a comparative analysis of two café developments in Cyprus.

2. LITERATURE REVIEW

2.1. Circular Economy in Construction

The construction sector has traditionally followed a linear model of extraction, production, use and demolition, contributing to resource depletion, waste and environmental degradation. Circular economy principles provide an alternative by retaining the value of buildings and materials through reduction, reuse, adaptation and recovery [1,2]. In construction, this transition prioritises retaining and adapting existing structures and materials, which can preserve more material value and embodied energy than demolition and replacement. Adaptive reuse is therefore a high-value circular strategy, enabling existing buildings to accommodate new functions while reducing demand for new materials [10,11].

Circular construction can also reduce embodied carbon from material extraction, processing, transportation, construction and end-of-life treatment. As operational buildings become more energy efficient, embodied impacts have gained importance, reinforcing the value of retaining existing structures where feasible [2]. Reuse, adaptation and repurposing can further reduce waste while promoting adaptability, durability and future transformation [12].

These principles are increasingly relevant amid material pressures, supply-chain disruptions and environmental demands, as circularity can reduce reliance on virgin resources while improving the efficiency and resilience of existing assets [11].

2.2. Adaptive Reuse as a High-Value Circular Strategy

Unlike conventional renovation, adaptive reuse establishes a new relationship between an existing structure and contemporary programme requirements, potentially involving changes to spatial organisation, services, environmental performance and structural components. Its principal circular value lies in extending building life rather than replacing existing structures. Retaining building fabric reduces demand for new materials, demolition waste and loss of embodied resources [2,10]. It can also preserve architectural, social, cultural and urban values while accommodating contemporary uses [3,13].

However, adaptive reuse is not inherently economically advantageous. The condition and configuration of existing buildings, alongside structural, functional and regulatory requirements, can strongly influence feasibility [3,9]. Decision-making therefore requires consideration of physical, functional, economic and regulatory criteria rather than a single performance measure, consistent with research on adaptive reuse and sustainable development [5,9].

Repurposing further distinguishes adaptive reuse from other circular transformations. This distinction is central to the present study, which compares an existing commercial unit with shipping containers accommodating the same architectural programme. The feasibility of adaptive reuse remains context-dependent, with structural, spatial, environmental and planning constraints potentially limiting new uses [3,9].

2.3. Shipping Container Repurposing as Material Circularity

Shipping container repurposing extends the life of industrial artefacts by transforming decommissioned freight containers into architectural spaces. Its potential contribution to recycling, sustainability and green architecture has been examined in previous research [7], alongside more recent studies of the carbon implications of container-based construction [8].

Containers offer standardised dimensions, structural characteristics, modularity and transportability, allowing units to be combined for different applications. Their reuse has been explored for temporary accommodation, housing, commercial uses and other forms of construction [7,14].

However, containers were designed for freight transportation rather than human occupation. Their conversion therefore requires interventions addressing structural, environmental and functional requirements. New openings may require strengthening, while the steel envelope requires appropriate insulation and treatment for thermal performance, condensation and occupant comfort. These interventions can significantly affect environmental and economic performance [7,8]. Although reuse can avoid disposal and reduce demand for some new

materials, conversion introduces additional materials, energy and construction processes, requiring a lifecycle perspective.

Container architecture may also provide a distinctive identity through its industrial character, particularly in commercial applications. Its suitability nevertheless depends on its relationship with the surrounding context and applicable planning and building regulations. Thus, shipping-container repurposing should not be considered inherently low-cost or low-carbon; its performance depends on the existing container, required interventions, intended programme and environmental and contextual conditions.

3. METHODOLOGY

This study adopts a comparative case study methodology supported by Multi-Criteria Decision Analysis (MCDA) to examine how adaptive reuse and container repurposing perform across economic, environmental, regulatory, construction and architectural dimensions. MCDA was selected because circular construction decisions involve multiple and competing criteria that cannot be adequately assessed through a single indicator. Comparative evaluation matrices therefore provide a structured means of identifying the relative strengths and limitations of each strategy.

The research combines quantitative and qualitative data. Quantitative data include construction costs, cost per square metre, project duration and intervention requirements, while qualitative data derive from the literature review, site observations and semi-structured interviews with the owners of the two establishments. This mixed-method approach captures both measurable performance and less quantifiable factors, including architectural identity, user perception, urban integration and implementation challenges. The final methodological stage involves evaluating both case studies against criteria derived from the literature, project analysis and observed challenges. The resulting MCDA matrix provides a structured comparison of the advantages and limitations of each strategy and supports the subsequent analysis of circular construction decision-making.

Table 1. Evaluation Criteria

Criterion	Description	Source
Economic performance	Construction Cost and Cost Efficiency	Case Study Data & Analysis
Construction Duration	Time Required until operation	Owner Interviews
Regulatory Complexity	Permit requirements and Challenges	Legislation Review
Environmental performance	Retention of Embodied Resources	Literature
Design Flexibility	Ability for Spatial Transformation	Case Study Data & Analysis
Urban Integration	Compatibility with Context	Site Observation, Legislation Review
Architectural Identity	Contribution to Place Character	Qualitative Assessment

4. COMPARATIVE CASE STUDIES

4.1. Case Study Selection and Context

The empirical investigation examines two café developments in the Nicosia district of Cyprus representing distinct circular construction approaches: adaptive reuse of an existing commercial unit and repurposing of shipping containers into a new café. The cases were selected to isolate the influence of construction strategy from differences in function, climate and geography. Both accommodate the same public use, operate within the same climatic context and have comparable spatial requirements, while differing in initial conditions, construction processes and relationship with their surroundings.

4.2. Case Study A: Adaptive Reuse of an Existing Commercial Unit into a Café

4.2.1 Project Overview and Context

The first case study is an existing ground-floor retail unit near Nicosia city centre, within a relatively dense area characterised by mixed urban activities and moderate pedestrian and vehicular movement. The project retained the existing building shell and adapted its spatial configuration for café use, representing adaptive reuse through functional, technical and aesthetic modifications.





Figure 1. Case study A: The unit is located near Nicosia, City Centre, Source ©Google Maps,
Figure 2. The Adaptively Reused Unit, Source © DP+Architectural Office (design), Deplot(render)

4.2.2 Transformation Process

The intervention focused on upgrading the unit to meet contemporary café requirements. Works included electrical and mechanical upgrades, new plumbing, modifications to openings and external interfaces, interior finishes, café equipment and service infrastructure, and an external seating area. The existing structural framework was retained, while building services and functionality were substantially upgraded. The refurbishment period was approximately eight months.

4.2.3 Economic Analysis

The cost breakdown of the adaptive reuse intervention, as calculated by the Quantity Surveyor (DP+ Architectural Office), is presented below.

Table 2. Case Study A: Cost Breakdown

Works	Design, Consultancy & Permits	Masonry & Plastering	Electrical Works	Mechanical Works	Plumbing	Networking	Flooring
Cost (€)	4 000,00	8 500,00	7 000,00	6 000,00	2 500,00	1 500,00	6 000,00
Works	Aluminum Openings	Carpentry	Painting	Equipment	Landscaping	TOTAL	Cost per m^2
Cost (€)	14 000,00	9 500,00	4 000,00	25 000,00	5 000,00	93 000,00	808,70

4.2.4 Regulatory Considerations

The project required compliance with planning, building and operational regulations for café developments, including consultation with the Deputy Ministry of Tourism, Public Health Services and Fire Prevention Department.

Compared with introducing a new independent structure, approval was facilitated by the existing building and its established relationship with the planning framework, making the process relatively straightforward where proposed alterations complied with applicable regulations.

4.2.5 Environmental Considerations

The principal environmental benefit derives from retaining the existing building structure, avoiding demolition and substantial new structural construction. This reduced demand for new materials and preserved embodied energy, while the limited concrete and steel interventions reduced construction-related emissions compared with new-build alternatives.

4.3. Case Study B: Shipping Container Repurposing into a Café

4.3.1 Project Overview and Context

The second case study is located on the outskirts of Nicosia, near a major transport corridor connecting Nicosia with Larnaca and Limassol. The lower-density surroundings comprise mainly residential units and undeveloped land, with limited public uses. The project converts three shipping containers into a café, introducing a new architectural object rather than adapting an existing building.





Figure 3. Case study B: The unit is located in the outskirts of Nicosia, Source ©Google Maps,

Figure 4. The Repurposed Containers, Source © Andreas Trisveis Architecture

4.3.2 Transformation Process

The conversion required substantial interventions, including structural reinforcement for new openings, mechanical, electrical and plumbing systems, thermal and environmental improvements, interior finishes, café equipment, landscaping and external seating. Although container modularity offers spatial flexibility and potential for rapid assembly, extensive intervention was required to achieve the desired comfort, functionality and architectural quality. The total construction period was approximately eighteen months.

4.3.3 Economic Analysis

The cost breakdown, as calculated by the Quantity Surveyor (DP+ Architectural Office), is presented below.

Table 3. Case Study B: Cost Breakdown

Works	Design, Consultancy & Permits	Container Purchase	Structural Modificat.	Electrical Works	Mechanical Works	Plumbing	Networking
Cost (€)	10 000,00	12 000,00	10 000,00	10 000,00	9 000,00	5 000,00	1 500,00
Works	Flooring and Finishes	Aluminum Openings	Carpentry	Equipment	Landscaping	TOTAL	Cost per m²
Cost (€)	20 000,00	17 000,00	9 000,00	25 000,00	10 000,00	138 000,00	1 631,33

4.3.4 Regulatory Considerations

The approval process was more complex than for the adaptive reuse case. The introduction of an unconventional building form required additional consideration of spatial dimensions, material performance, fire safety and building regulations. Consultation with tourism, public health and fire prevention authorities was required in both cases; however, the container project involved additional scrutiny concerning fire safety, structural modifications and compliance with building standards.

4.3.5 Environmental Considerations

The environmental rationale of container repurposing lies in extending the useful life of existing steel structures that might otherwise require recycling or disposal. Their modular characteristics also allow adaptation and integration of renewable technologies such as photovoltaic systems. However, these benefits must be considered alongside the additional materials, energy and interventions required to transform containers into comfortable and compliant architectural spaces.

5. MULTI-CRITERIA DECISION ANALYSIS & COMPARATIVE ANALYSIS

The evaluation criteria were derived from the literature review, case-study observations and practical considerations encountered during construction. They reflect key factors influencing architectural decisions between alternative circular strategies. The resulting MCDA matrix, derived from the two case studies, is presented below.

Table 4. Evaluation Criteria- MCDA Matrix

Criterion	Adaptively Reused Unit	Container Repurposing
Economic performance	●●●●●	●●●●○
Construction Duration	●●●●●	●●●○○
Regulatory Complexity	●●●○○	●●●●○
Environmental performance	●●●●●	●●●●●
Design Flexibility	●●●○○	●●●●●
Urban Integration	●●●●●	●●●●○
Architectural Freedom	●●●○○	●●●●○
Future Expansion-Potential	●●●○○	●●●●●

The comparison demonstrates that adaptive reuse and container repurposing represent distinct pathways towards circular construction. While both extend the useful life of existing resources, they preserve different forms of value. Adaptive reuse prioritises existing spatial and contextual value, whereas container repurposing creates new architectural value through the reuse of industrial artefacts and their distinctive identity.

Economically, adaptive reuse required approximately €93,000 (€808.70/m²), compared with €138,500 (€1,631.33/m²) for the container café. Although both remain below the estimated €2,000/m² cost of new construction in Cyprus, the container project was more expensive due to structural modifications, services, thermal improvements, finishes and regulatory requirements. This indicates that container repurposing may be economical compared with new construction, but its performance depends on the extent of transformation. Construction duration similarly favoured adaptive reuse, at approximately eight months compared with eighteen months for the container project, demonstrating that modular construction does not necessarily ensure faster delivery when extensive modifications and external works are required.

The strategies also differ in flexibility and contextual integration. Container repurposing provided greater freedom to combine units and create new spatial arrangements, although their narrow dimensions imposed functional constraints. Adaptive reuse was more restricted by the existing configuration but achieved stronger integration with the surrounding urban fabric. The peripheral location of the container café nevertheless supported its distinctive architectural expression.

Both strategies contribute to resource conservation by extending the life of existing buildings or materials. However, reuse must be assessed alongside the resources required for transformation, including additional materials, energy and construction processes. Overall, adaptive reuse performed better in cost, implementation time and urban integration, while container repurposing offered greater architectural freedom, design flexibility and future expansion potential. Neither strategy therefore consistently outperforms the other, reinforcing the need for multi-criteria and context-sensitive evaluation.

6. DISCUSSION

The findings demonstrate that circular construction strategies should be understood as context-dependent design decisions rather than inherently superior solutions. Both approaches extend the useful life of existing resources, but their performance depends on the relationship between the available resource, required interventions and intended architectural outcome.

A key finding is that circularity does not automatically ensure economic efficiency. The container case demonstrates how structural modifications, environmental improvements, services and finishes can increase costs, while adaptive reuse remains subject to existing spatial, structural and regulatory constraints. The comparison therefore highlights a trade-off between retaining existing building fabric and introducing greater modular and architectural flexibility.

Context also influences the suitability of each strategy. Adaptive reuse benefits from continuity with the existing urban fabric, whereas container repurposing can establish a distinctive identity through reused industrial elements, particularly where contextual constraints are less restrictive. The MCDA framework makes these trade-offs explicit and supports more informed decisions rather than identifying a universally superior approach.

7. CONCLUSIONS

This study compared adaptive reuse and shipping-container repurposing as alternative circular strategies for achieving the same architectural programme. The findings show that they are complementary approaches that preserve different forms of value: adaptive reuse demonstrated advantages in cost, implementation time and urban integration, while container repurposing provided greater design flexibility, architectural distinctiveness and modular potential.

The study also investigates the assumption that reuse is inherently economical or efficient, as transformation requirements can substantially affect project feasibility. MCDA demonstrates that circular construction involves trade-offs between economic, environmental, regulatory, spatial and architectural objectives. Consequently, strategy selection should remain context-sensitive, aligning available resources, project requirements and site conditions. Circular architecture is therefore defined not by a specific construction method, but by recognising existing value and transforming it into meaningful and resilient future use.

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Review paper

APPLICATION OF PHASE CHANGE MATERIALS IN PASSIVE SOLAR ARCHITECTURE

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Abstract

This paper presents a review of the application of phase change materials (PCMs) in passive solar architecture, with particular emphasis on their integration into Trombe walls, building envelopes, and interior building components. The study examines the fundamental thermal properties of PCMs, their classification, thermal energy storage mechanisms, and the most common integration techniques used in buildings. Special attention is given to the role of PCMs in improving thermal comfort, enhancing energy efficiency, and increasing the utilization of solar energy through latent heat storage. The paper also discusses the advantages and limitations of different PCM types, including organic, inorganic, and eutectic materials, as well as current challenges related to thermal conductivity, long-term stability, fire safety, and economic feasibility. Furthermore, recent developments and future research directions, including bio-based PCMs, advanced encapsulation methods, and intelligent energy management systems, are reviewed. The findings indicate that PCM integration can significantly improve thermal regulation, reduce indoor temperature fluctuations, and decrease heating and cooling energy demand. Studies reviewed in this paper report energy savings of up to 30% in PCM-enhanced building systems, highlighting their considerable potential for sustainable and energy-efficient building design.

Key words: *Phase Change Materials, Passive Solar Architecture, Thermal Energy Storage, Energy Efficiency, Trombe Wall*

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1. INTRODUCTION

The building sector plays a key role in addressing climate change due to its high energy consumption and environmental impact. Buildings account for 36% of global energy use, while the construction industry is responsible for approximately 37% of annual CO_2 emissions [1]. Therefore, improving energy efficiency and increasing the use of renewable energy sources have become essential strategies for reducing carbon emissions and mitigating climate change [2].

Among renewable energy technologies, solar energy has attracted significant attention. However, its intermittent nature requires effective thermal energy storage (TES) systems to ensure continuous utilization. TES technologies enable the storage of excess thermal energy and its release during periods of higher demand, contributing to load balancing, improved energy efficiency, and reduced reliance on fossil fuels [3].

Phase change materials (PCMs) have emerged as one of the most promising TES solutions. These materials store and release large amounts of latent heat during phase transitions, helping to regulate indoor temperatures and reduce energy consumption [4]. Although the application of PCMs in buildings dates back to the 1970s, interest in this technology has grown considerably in recent years. PCMs can be incorporated into building envelopes, including walls, ceilings, and floors, where they increase thermal inertia, improve thermal comfort, and reduce temperature fluctuations and peak energy demand, contributing to more sustainable building operation [5].

Numerous studies have demonstrated the effectiveness of PCMs under different climatic conditions, with reported energy savings of up to 30% and further performance improvements achieved through conductivity-enhancing additives such as graphite [6,7]. Besides improving energy efficiency, PCMs contribute to sustainability by reducing dependence on mechanical heating and cooling systems and lowering greenhouse gas emissions. However, challenges related to thermal conductivity, long-term stability, fire safety, and economic feasibility still limit the widespread implementation of PCM technologies in buildings.

The aim of this paper is to review recent research on the application of phase change materials in passive solar architecture and to evaluate their potential and limitations regarding building energy efficiency and thermal comfort.

2. PHASE CHANGE MATERIALS (PCMS)

Phase change materials regulate temperature by storing and releasing latent heat during phase transitions. When temperatures rise above the phase change point, PCMs absorb heat and melt, while cooling causes them to release stored energy and solidify. If the phase change temperature corresponds to indoor comfort conditions, PCMs can stabilize indoor temperatures, improve thermal comfort, and reduce peak heating and cooling demands [8]. Their ability to enhance heat storage capacity, particularly in buildings with low thermal mass, makes them well suited for building applications.

2.1 Types of Phase Change Materials

Phase change materials are commonly classified according to their chemical composition, phase transition behavior, and application area [9]. Depending on the phase transition mechanism, PCMs may undergo solid–solid, solid–liquid, solid–gas, or liquid–gas transformations. Among these, solid–liquid PCMs are the most widely used in building applications due to their high latent heat storage capacity, effective thermal performance, and cost-effectiveness [10].

The selection of a suitable PCM primarily depends on its melting temperature and latent heat capacity, which should correspond to the operating conditions of the intended application. Based on their chemical composition, PCMs are generally categorized as organic, inorganic, or eutectic materials [11].

2.1.1. Organic PCMs

Organic phase change materials (PCMs) are generally divided into two categories: paraffin and non-paraffin materials. Owing to their favorable thermal and chemical characteristics, they are among the most commonly used PCMs in thermal energy storage applications. Organic PCMs possess relatively high latent heat storage capacity and suitable phase change temperature ranges, which makes them particularly effective for building applications [12]. Furthermore, they are chemically stable, non-corrosive, and typically do not experience phase segregation, while exhibiting little or no supercooling during the solidification process, contributing to reliable thermal performance [13]. However, their relatively low thermal conductivity remains one of the main limitations affecting heat transfer efficiency in building applications.

2.1.1.1. Paraffins. Paraffins are petroleum-derived saturated hydrocarbons with melting temperatures typically ranging from 20 °C to 70 °C, depending on carbon chain length [14] . They exhibit good thermal reliability, low vapor pressure, and minimal phase separation during repeated thermal cycles [15] . However, their relatively low thermal conductivity (approximately 0.2 W/(m·K)), moderate flammability, and limited compatibility with certain plastic containers represent important drawbacks [16].

2.1.1.2. Non-paraffins. Non-paraffin organic PCMs comprise a diverse group of materials, including fatty acids, esters, fatty alcohols, glycols, and other organic compounds. Among them, fatty acids have received particular attention for building thermal energy storage applications due to their renewable origin, environmental compatibility, and lower flammability compared to paraffin-based PCMs [17,18].

2.1.2. Inorganic PCMs

Inorganic PCMs are widely used in building applications due to their high latent heat storage capacity, superior thermal conductivity, and relatively low cost compared to organic PCMs. Common inorganic PCMs include salt hydrates, metallic materials, and other inorganic compounds. Despite their advantages, these materials may experience corrosion and phase separation during repeated thermal cycling, which can negatively affect their long-term performance.

2.1.2.1. Salt hydrates. Salt hydrates are the most widely used inorganic PCMs in building applications. They undergo reversible phase transitions between salt and

water during heating and cooling cycles. Owing to their high latent heat capacity and thermal conductivity, they can store larger amounts of energy and provide efficient heat transfer compared to organic PCMs [19]. In addition, their low cost, non-flammability, and environmental compatibility make them attractive materials for sustainable building applications [20]. However, their practical application may be affected by phase segregation and stability issues during long-term operation.

2.1.2.2. Metallics. Metallic PCMs are rarely used in buildings, despite their high thermal conductivity, rapid thermal response, and high energy storage density [21]. Their application is limited by high phase change temperatures, greater weight, and higher costs compared to other PCM types. Nevertheless, they remain promising for hybrid and high-temperature thermal energy storage systems [22].

2.1.3. Eutectic

Eutectic materials are mixtures of two or more components that melt and solidify simultaneously at a specific composition and temperature without phase separation. This stable phase transition behavior makes them suitable for thermal energy storage applications. Eutectic PCMs can consist of organic–organic, organic–inorganic, or inorganic–inorganic mixtures. Although they generally exhibit high thermal conductivity and density, their latent heat storage capacity is typically lower than that of other PCM types, which limits their wider application [23].

2.2 Properties of PCMs

The effectiveness of PCMs in building applications largely depends on their thermal properties, which determine their ability to store and release heat, regulate temperature fluctuations, and improve building energy performance [24].

2.2.1. Latent heat capacity

During phase transitions, PCMs absorb and release latent heat at nearly constant temperatures. Therefore, latent heat capacity is a key parameter in evaluating PCM thermal storage performance, as higher values enable greater energy storage and more effective temperature regulation in buildings.

2.2.2. Phase transition temperature

The phase change temperature is another critical selection criterion, as it should match the building's operating temperature range. For residential applications, PCMs with phase transition temperatures between 20 °C and 30 °C are generally preferred to maintain indoor thermal comfort [25].

2.2.3. Thermal conductivity

Thermal conductivity is a key parameter affecting PCM performance, as it determines the rate of heat absorption and release during phase transitions. Higher thermal conductivity enables faster responses to temperature changes and improves efficiency under dynamic thermal conditions [26].

2.2.4. Specific heat capacity

Specific heat capacity describes the amount of heat required to increase the temperature of a material by one degree Celsius and is particularly relevant during sensible heat storage, when no phase transition occurs.

2.2.5. Thermal cycling stability

Thermal cycling stability describes the ability of a PCM to retain its thermal properties after repeated heating and cooling cycles. Since PCMs undergo numerous phase transitions during operation, long-term stability is essential for maintaining performance. Repeated cycling may cause phase separation, reduced latent heat capacity, and material degradation, making thermal stability a key criterion for assessing PCM durability and reliability in building applications [27].

3. APPLICATIONS OF PCMS IN PASSIVE SOLAR ARCHITECTURE

PCMs have attracted considerable attention in passive solar architecture due to their ability to enhance thermal energy storage and indoor thermal comfort. Their integration into Trombe walls and building envelopes improves energy efficiency and reduces indoor temperature fluctuations.

3.1 PCM-Enhanced Trombe Walls

The Trombe wall is a passive solar heating system consisting of a massive dark-colored wall covered by glazing, with an air cavity between them. Solar radiation passes through the glazing and is absorbed by the wall, where thermal energy is stored and gradually released to the indoor space through conduction and convection [28].

Despite its advantages, the traditional Trombe wall may exhibit unstable heating performance in winter and overheating during summer. To overcome these limitations, various improvements have been proposed, including the integration of phase change materials, photovoltaic systems, advanced ventilation strategies, and venetian blind technologies [29]. Among these approaches, PCM integration has attracted particular attention due to its ability to increase thermal storage capacity, regulate indoor temperatures, shift peak thermal loads, and reduce building energy consumption [30].

The performance of PCM-enhanced Trombe walls (Fig. 1) depends on factors such as solar radiation intensity, PCM properties, air gap dimensions, glazing characteristics, and indoor temperature conditions [32]. Studies reviewed in this paper reported energy savings ranging from 15% to 30%, demonstrating the potential of PCM-integrated Trombe walls to improve thermal storage performance and indoor thermal comfort. The reported performance varies considerably depending on climatic conditions, PCM characteristics, and wall configuration, which makes direct comparison between studies difficult.

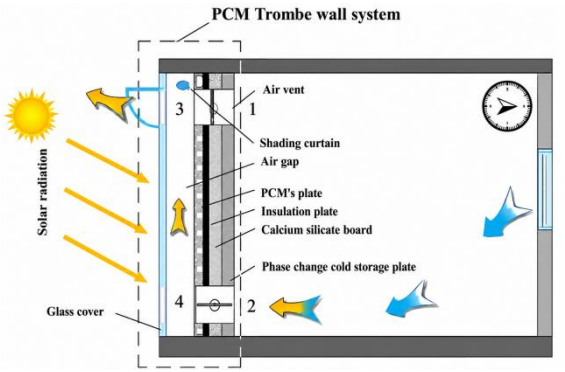


Figure 1. Trombe wall integrated with PCMs [31]

3.2 Building Envelope Integration

The integration of PCMs into building envelopes improves thermal performance, energy efficiency, and indoor thermal comfort by regulating heat transfer through walls, roofs, and facades [33]. Bio-based PCMs offer a sustainable alternative to petroleum-based materials, contributing to lower energy consumption and greenhouse gas emissions [34].

By absorbing excess heat and releasing it when temperatures decrease, PCMs help reduce indoor temperature fluctuations and improve thermal stability [35]. They can be incorporated into various building components, including wallboards, roof tiles, and facades, where they enhance thermal performance and reduce solar heat gains [36]. The effectiveness of PCM integration depends on both the thermal properties of the selected material and the architectural characteristics of the building.

Studies have reported reductions in heating and cooling energy demand ranging from 10% to 25%, while cooling load reductions in hot climates can reach up to 30%, highlighting the potential of PCMs to improve building energy efficiency and thermal comfort. However, challenges such as limited thermal stability, relatively low latent heat capacity, and leakage during phase transitions still restrict their wider application [37]. In addition, the effectiveness of PCM-enhanced building envelopes is highly dependent on climate conditions and proper material selection, indicating that a universal solution for all building types is unlikely.

4. CHALLENGES AND LIMITATIONS

Despite significant progress in PCM development, several challenges continue to limit the large-scale implementation of PCM-based thermal energy storage systems. Low thermal conductivity, particularly in organic PCMs, reduces heat transfer efficiency, although approaches such as nanoparticle additives, graphene enhancement, and nano-encapsulation have shown promising results [38]. Long-term performance may also be affected by phase segregation, supercooling, and material degradation during repeated thermal cycles [9]. Additional concerns include the flammability of some paraffin-based PCMs, insufficient assessment of environmental impacts throughout

their life cycle [39], integration challenges within building components, and the lack of standardized performance evaluation methods. Furthermore, economic constraints remain a significant barrier to commercialization.

Although numerous technical solutions have been proposed to address these challenges, their effectiveness often depends on specific climatic conditions, building characteristics, and PCM properties, which complicates large-scale implementation and comparison of research results.

These limitations highlight the need for climate-responsive PCM system design that balances thermal performance, durability, safety, and cost-effectiveness.

5. FUTURE PERSPECTIVES

Future developments in the application of PCMs in buildings are focused on improving their heat transfer performance, expanding their operating temperature range, and ensuring long-term stability through a large number of charge-discharge cycles. In particular, enhancing thermal conductivity remains one of the primary research objectives. This can be achieved through techniques such as the use of extended surfaces, microencapsulation methods, and the incorporation of nanoparticles to improve heat transfer efficiency [40].

Further efforts are also needed to evaluate the economic and environmental impacts of PCM applications, particularly through the development of bio-based and waste-derived PCMs that can reduce costs and environmental burdens [7]. In addition, artificial intelligence, digital twin technologies, sensors, and advanced control algorithms offer new opportunities for optimizing PCM performance and supporting dynamic energy management in smart buildings [9].

Future developments should also include the establishment of standardized testing procedures and performance criteria, as well as the integration of PCM technologies into building regulations and sustainability assessment frameworks. Greater emphasis should be placed on developing climate-specific PCM solutions, since thermal performance may vary considerably under different environmental and operational conditions.

Finally, long-term field studies and large-scale demonstrations are essential for validating laboratory findings and assessing the long-term reliability and effectiveness of PCM-based systems under real operating conditions [41].

6. CONCLUSION

Phase Change Materials represent a promising solution for improving the thermal performance and energy efficiency of passive solar buildings. Their ability to store and release latent heat allows more efficient thermal regulation compared to traditional construction materials.

Applications of PCMs in Trombe walls, building envelopes, and interior elements demonstrate considerable potential for reducing energy consumption and improving indoor comfort. Although several technical and economic challenges remain, ongoing

research and technological development are expected to accelerate the adoption of PCM systems in sustainable architecture.

The findings of this review indicate that the effectiveness of PCM integration depends not only on material properties but also on climatic conditions, building characteristics, and system design. Therefore, careful selection and optimization of PCM solutions are essential for achieving the desired thermal and energy performance.

The integration of PCMs into passive solar design strategies can play an important role in achieving future energy-efficient and environmentally responsible buildings.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

CONTRIBUTION OF BUILDING MATERIALS TO LEED, BREEAM, AND DGNB CERTIFICATION

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Abstract

The construction industry plays an important role in satisfying the needs of society, enhancing the quality of life, and contributing to the economic growth of a country. It has been widely criticized for significantly contributing to carbon emissions, environmental degradation, generating a large amount of construction and demolition waste and global warming due to the use of a significant portion of natural resources and energy consumption. As an indispensable need, green building rating systems (GBRSs) have been launched to optimize the consumption of natural resources and control pollution. BREEAM (Building Research Establishment Environmental Assessment Method) was the first to appear among them, and then others followed. Today we can single out GBRSs, which is widely adopted internationally, or play a dominant role at the regional and national level in Europe, such as HQE (Haute Qualité Environnementale or High Environmental Quality), DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen, or the German Sustainable Building Council) and LEED (Leadership in Energy and Environmental Design). The assessment of building materials is an important component of the GBRSs. In order to better understand their impact on the overall certification outcome, it is necessary to analyze the weighting factors and the share of points assigned to material-related criteria within the different certification frameworks. Although all major GBRSs recognize the importance of building materials, the extent to which they contribute to the final certification score varies significantly and is not so easy to define. This paper analyzes the contribution of materials to the overall GBRSs rating, choosing LEED, BREEAM and DGNB as the most widely used and widespread certificates in Europe. Based on the obtained results, we can conclude that DGNB v2023 gives the greatest importance to the choice and performance of building materials, while BREEAM v7 and LEED v5 place a strong emphasis on reducing embodied carbon, but with a smaller overall share in the final rating.

Key words: *Green building rating systems (GBRSs), BREEAM, LEED, DGNB, building materials*

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1. INTRODUCTION

The construction industry plays an important role in satisfying the needs of society, enhancing the quality of life, and contributing to the economic growth of a country [1]. At the same time, it has been widely criticized for significantly contributing to carbon emissions, environmental degradation, generating a large amount of construction and demolition waste and global warming due to the use of a large portion of natural resources and energy consumption [1].

Recognizing the importance of sustainable building practices, the "green approach" and "environmental sustainability" have been introduced for many years. Despite this, the construction industry is still the main consumer of energy according to official statistics. One reason for this could be the passive attitude of construction professionals towards the adoption of sustainable solutions. Faced with rising energy costs, energy shortages, and growing environmental concerns, the demand for sustainable buildings with minimal environmental impact has recently grown even more significantly [1].

As a logical consequence of that, governments and numerous organizations have launched green building rating systems (GBRSs) to minimize/optimize the consumption of natural resources and control pollution. We can consider GBRSs as a new building philosophy, encouraging the use of more environmentally friendly materials, the implementation of techniques to save resources and reduce waste consumption, and the improvement of indoor environmental quality [2]. Or we can consider it as a tool for measuring the environmental performance of buildings [3] that can assess the sustainability of buildings throughout their life cycle that enables the transition towards a sustainable built environment, from an environmental, social and economic perspective [4]. Buildings certified under these rating systems consume less energy and contribute to the overall reputation and value of the property [1]. Today, there are a large number of GBRSs around the world.

The paper shows the contribution of building materials in the certification process through the allocation of weights or points.

2. GREEN BUILDING RATING SYSTEMS (GBRSS)

The first real attempt to "establish comprehensive means of simultaneously assessing abroad range of environmental considerations in buildings" was the Building Research Establishment Environmental Assessment Method (BREEAM). It is the first commercially available tool for assessing the environmental impact of buildings, based on specific target values for various criteria, and was established in 1990 in the United Kingdom. Since then, many different tools have been launched around the world, Figure 1 [3]. GBRSs also called ''Whole building assessment frameworks or systems"- are used to assess building performance based on standard quantitative and qualitative basis for the whole building or specific phases of its life cycle [5].

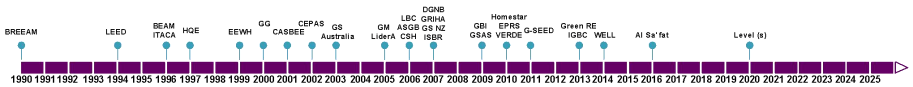


Figure 1. Timeline of GBRSs [3]

The principle behind these tools (Figure 1) includes environmental categories divided into credits, each addressing an issue and assigning a weighting of points that indicates the perceived level of sustainable performance of the building and, in summary, determining its corresponding certification level [5]. We can say that they are a multi-criteria evaluation tool based on multidimensional targets and that they are divided into the following four levels: categories, criteria, sub-criteria, and indicator levels [6]. All of these systems are not only applicable at the local level, but can also be applied internationally [7]. Each system includes a certain number of schemes that are chosen depending on the scope covered by the certification or the stage in which the facility is located.

After BREEAM, the most used GBRSs in Europe are HQE (*Haute Qualité Environnementale*) developed in France in 1997, LEED (*Leadership in Energy and Environmental Design*) developed in US in 1998 and DGNB (*Deutsche Gesellschaft für Nachhaltiges Bauen*) developed in Germany in 2007. These systems are widely adopted internationally or play a dominant role at regional and national levels in Europe [7][8].

For the analysis in this paper, 3 systems with their latest versions and a certain scheme were chosen: LEED v5 - Building Design and Construction, BREEAM v7 - New Construction and DGNB v2023 - System for New Construction.

2.1. BREEAM

This system considers and analyses ten different macro-areas and each is then divided into indicators, which include different credits reaching the maximum possible score depending on the purpose of the building. The maximum score is 100% and an additional 1% to 10% can be added to the final score as an “innovation credit”. When calculating the rank, the credit weighting factor is also taken into account. Based on the final score achieved, it is possible to earn one of the following rating levels: Unclassified (< 30 points), Pass (≥ 30 points), Good (≥ 45 points), Very Good (≥ 55 points), Excellent (≥ 70 points) and Outstanding (≥ 85 points), Figure 2 [9][10][11].

2.2. LEED

LEED is a system that requires certain prerequisites which needed to qualify for the certification. The protocol is divided into nine macro-areas that address key aspects of green buildings. These areas are the same for all the project types and are made up of credits. Points can be awarded for meeting criteria, which are grouped into credit categories. The maximum number of achievable points is 100 but 10 extra points can be obtained in the “Innovation” and “Regional priority” categories [9]. LEED often offers more pathways or options to meet certain credit criteria, so that the design can be flexible and adjusted to local conditions [11]. The final ranking is obtained by simply adding up the points assigned to certain categories. Based on the total number of building points, new construction can be classified into four groups: Certified (40–49 points), Silver (50–59 points), Gold (60–79 points), and Platinum (80+ points), Figure 2 [12].

2.3. DGNB

DGNB, in contrast to BREEAM and LEED, is more in line with the triple bottom line approach, addressing the social, economic, and environmental dimensions in a more balanced manner [8]. DGNB is organized into six categories according to six quality area [13]. DGNB is also the only method aligned to United Nations' Sustainable Development Goals (UN SDG's) and to Level(s), a European Union's (EU) voluntary reporting framework created to improve buildings sustainability, in line with the EU's Circular Economy Action Plan [8]. The number of points achieved in each topic is weighted differently to give the overall score. The final building grade (bronze, silver, gold, platinum, Figure 2) is awarded based on the total performance index and minimum performance index. The total performance index is calculated using all six topics, while the minimum performance index must be achieved in the three main topics (environment, economy and socio-cultural quality) to ensure a certain level of quality [14].

BREEAM rating		% score
Outstanding	★★★★★★	≥85
Excellent	★★★★★☆	≥70
Very good	★★★★☆☆	≥55
Good	★★★☆☆☆	≥45
Pass	★★☆☆☆☆	≥25
Unclassified	★☆☆☆☆☆	<25



	DGNB Platinum	DGNB Gold	DGNB Silver	DGNB Bronze*
Total performance index	80% and higher	65% and higher	50% and higher	35% and higher
Minimum performance index	65%	50%	35%	-- %

Figure 2. Rating levels of GBRSs [11][12][13]

LEED, BREEAM, and DGBN all award credits, points, or percentages when the designer satisfies designated levels of performance for each indicator. Nevertheless, LEED, BREEAM, and DGBN differ in the weight they award specific indicators and in the choice of relevant indicators in each category, which means that these methods view the importance of sustainability areas differently [8]. Additionally, DGNB was chosen for being a system that intends to assess the whole building's life cycle, giving more balanced weights to the environmental, social, and economic dimensions, thus closing the gap left by LEED and BREEAM regarding this matter [8].

In BREEAM, the final score is factored by a given coefficient, whereas in LEED, credits are simply added to the final score. DGNB attributes different coefficients to each of the indicators within the categories (referred to as "share") that are further adjusted with an additional weighting factor [8].

3. BUILDING MATERIALS IN GBRSS

All GBRSs schemes are voluntary, for now. As stated, these systems measure the performance of green buildings by assigning credits and weights to environmental topics, sorted into appropriate categories which comprise a set of indicators to evaluate buildings throughout their life cycle.

We can see how important materials are from the base, a careful design process and a comprehensive material selection method, rather than an elevated investment in technology, may be enough to achieve desired environmental goals at a lower cost [2].

Analyzing the systems, we can observe that energy, water and materials are the most common categories analyzed by rating systems, followed by location and the qualities of the indoor and outdoor environment [15]. Although the tools appear to cover the same phases of the building life cycle, they may cover the phases differently.

3.1. Sertifications of building materials

The choice of materials, in addition to directly affecting energy consumption through production, installation and use, also affects the energy consumption of the entire building and the overall rating of the building in the GBRSs.

For this reason, it is very important to know all this information when choosing and applying materials in buildings. The best and easiest way is the existence of certain tools, documents, standards and etc. that would unify all this data. At GBRSs, when assessing the impact of materials on the environment and the level of certification, we use some of the following:

1) **Life Cycle Assessment (LCA)** - compilation and evaluation of the inputs, outputs and potential environmental impacts of a product or system throughout its life cycle [5].
2) **Environmental Product Declarations (EPDs)** - provides objective, transparent, and third-party verified information about the environmental performance of a product or service throughout its life cycle [16].
3) **Responsible Sourcing Certification** - verification process that proves a company's products and materials are obtained in an ethical, sustainable, and socially responsible manner [17].
4) **Material Health Declarations (HPD)** - standardized technical document that transparently discloses the chemical ingredients in a product and their associated health impacts [18].

Here are only some of the documents that include the most important data on the materials used and the aspects of impact on the environment, energy consumption and human health.

3.2. Importance of materials in certification systems

In the following analysis “credit” means each issue taken into account in each macro area and characterized by a certain amount of points; “weight” stands for the importance given to each credit; “score” represents the sum of the total credit points, which have been previously multiplied for their specific weights. As mentioned, each

tool is characterized by credits achievable on the basis of the building characteristics in specific areas and each rating system allows to obtain a building labelling, according to the reached total score, Figure 2. Despite their extensive use and proven benefits, GBRSs exhibit significant methodological differences that complicate direct and objective comparisons [19].

The assessment of construction materials constitutes an important component of GBRSs. To better understand their influence on the overall certification outcome, it is necessary to analyze the weighting factors and the proportion of points allocated to material-related criteria within different certification frameworks. Although all major GBRSs recognize the importance of construction materials, the extent to which they contribute to the final certification score varies considerably and it is not so simple to define. The following section examines the weighting of material-related criteria and their contribution to the overall assessment in LEED, BREEAM, and DGNB certification systems.

In all three choosen systems materials are not rated in just one „simple“ category, but are distributed across several areas — but there is one dominant „main“ category.

BREEAM- The main category in which the material is evaluated is Materials (Mat). Materials are primarily assessed through LCA analysis of the building; responsible procurement (sourcing); EPD declarations; lifetime of the material/durability. Also, material related with Waste (Wst) and Innovation (Inn) [11]. In BREEAM, materials are not evaluated with a single number of points, but through multiple credits (Table 1). In order to obtain points, the project is compared with a reference object and points are determined based on the reduction of impact. The credits achieved are then multiplied by the weighting factor of the category. It contributes about ~ 15 -21 % of the total score (depending on the scheme), Table 2 [11].

LEED - The main category in which the material is evaluated is Materials and Resources (MR). Through it we observe the following: choice of building materials; EPD (Type III); LCA; recycled and regional materials; material composition (eg. cement, steel, concrete). The impact of materials is also felt across the areas of energy and atmosphere (EA) and innovation (IN). In LEED there are points that simply add up. Similar like in BREEAM, the project is compared with a reference object and points are determined based on the reduction of impact. It contributes max 18 points out of a total of 110 (in category Material) or ~ 16%. The distribution of points by items for material in the New Construction is given in Table 1 [12].

DGBN - There is no single category in these GBRSs for materials, but rather it is viewed through several of them, but the one that most encompasses this topic of materials is Environmental Quality. It evaluates: GWP (CO_2 emissions); LCA analysis (EN 15978); consumption of primary resources; recycling potential; the overall impact of the structure (including concrete and cement). There are no fixed material points, materials influence through several criteria and are evaluated through the degree of fulfillment. Each criterion that includes DGNB in the field of materials carries a certain weight (Table 1). The total contribution is calculated as Σ (weight × percent filled). It contributes around 22–25% of the total grade in the area in the area closest to the materials (Environmental Quality), depending on the chosen scheme [13].

For easier mutual comparison of systems, the number of final points or weights has been reduced to percentages, i.e. it is normalized. Table 1 gives the points and weighting factors for BREEAM, points for LEED in the material category, while for DGNB the percentage contribution of materials in various categories.

Table 1- Schedule of points, weighting factors and participation of materials in the selected GBRSs [11][12][13]

BREEAM			**LEED**		**DGNB**	
Issues	Points	Weight (%)	Credit	Points	Criterion	Contribution %
Mat 01 (LCA)	≤7-10	15,5-21,0	**MRc1** (Building and Mat. Reuse)	≤3	**ENV1.1** – Climate action and energy (LCA)	22,5
Mat 02 (EPD)	≤1		**MRc2** (Reduce Emb. Carbon)	≤6	**ENV1.2** – Local environmental impact	
Mat 03 (Resp. Sourc.)	≤4-5		**MRc3** (Low-emitting materials)	≤2	**ENV1.3** – Responsible resource extraction	
Mat 04 (Durability and resilience)	≤1		**MRc4** (Build. Product Selection and Procurement)	≤5	**TEC1.6** – Circular construction (Design for disassembly and recyclability)	2-4
Mat 05 (Efficien.)	≤1		**MRc5** (Demolition Waste)	≤2		

Table 2 gives the contribution of materials in certificates expressed in % and normalized for easier comparison. The values shown are estimated directly through credits and weighting factors that are assigned through the material category (BREEAM, LEED) or the category closest to the materials (DGNB), as well as an assessment that takes into account other categories that the materials indirectly affect (Figure 3).

Table 2- Contribution of materials in the final rate of selected GBRSs [11][12][13]

System	Version	Maximum contribution of the material to the overall grade	Estimated total impact and out-of-category material
BREEAM	Version 7	~15,5-21%	20-30%
LEED	Version 5	~16,4%	20-25%
DGNB	2023	~22-25%	25-30%

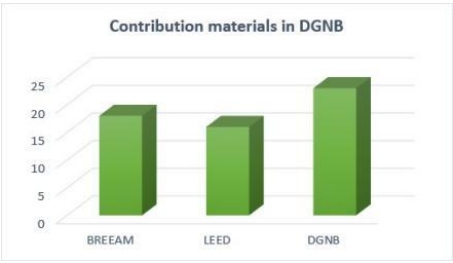


Figure 3. Contribution of materials in the final rate of selected GBRSs

4. DICSUSION

Understanding the complexity of the problem of identifying and assessing the environmental characteristics of building materials requires attention to the different aspects from which this problem could be analyzed. Consequently, it is necessary to take many things into consideration such as, among others, the capacity of environmental resources, the various environmental impacts of materials, energy consumption, life cycle assessment of materials and buildings, etc.

The assessment of material contribution within certification systems is complex due to differences in methodologies, data requirements, and evaluation frameworks. One of the main challenges is the availability and quality of data.

Another difficulty lies in the inconsistent valuation of the same materials across systems. LEED uses a threshold-based point system, BREEAM applies weighted credits, while DGNB uses percentage-based scoring with multiple interconnected criteria. As a result, identical materials can have significantly different impacts on the final certification score depending on the system. Additionally, regional differences in supply chains complicate the assessment, as materials with similar technical properties may have different environmental impacts due to transportation distances and local production conditions. Likewise, the interpretation of LCA results is challenging because different databases and software tools can produce varying outcomes for the same material, making consistent and comparable evaluation difficult across projects and certification schemes. To reduce transport-related emissions, GBRSs emphasized the adoption of local materials for buildings [20].

The most common materials highlighted in the GBRSs are concrete, cement, steel, aggregates and timber. For example, the adoption of Supplementary Cementitious Materials (SCMs) for cement replacement is common in the GBRSs, where points are allocated based on the percentage of replacement [20]. Other materials should be included here, but the availability of SCM should also be taken into account. Also, timber materials are highly emphasized across, and they valued timber sourcing from certified sustainable parties, which require that the timber be legally harvested. Otherwise, the adoption of uncertified wood in buildings may have a negative effect on carbon emissions reduction, promoting forest restoration and biodiversity [20]. All of this shows that caution and care should be taken, as certain green materials cen lead to longer transportation distances and increase carbon emissions over the life cycle of a building.

Also, in the GBRSs, the treatment of carbon throughout the life cycle remains uneven, with operational carbon generally given greater emphasis than carbon associated with material production, transport and end-of-life phases. However, the embodied carbon associated with building materials is becoming increasingly significant. This shift highlights the need for integrated strategies that address both operational and embodied carbon throughout the life cycle of a building [20]. Of the systems analyzed, the DGNB comes closest to the idea of covering the entire life cycle of a material.

Based on the results obtained in Tables 1 and 2 and Figure 2, we can conclude that DGNB v2023 gives the greatest importance to the choice and performance of building

materials, while BREEAM v7 and LEED v5 place a strong emphasis on reducing embodied carbon, but with a smaller overall share in the final rating.

5. CONCLUSION

All three selected systems BREEAM, LEED and DGNB apply the LCA approach, but with different valuation methods and weighting factors, leading to different effects of the same materials on the final assessment. In the modern versions of these systems, the circular economy, the reuse of materials and the reduction of the overall ecological footprint, especially through the reduction of incorporated carbon, are becoming increasingly important, especially in the latest version. The focus is on the reduction of embodied and operational carbon, but also on broader aspects such as resource consumption, the possibility of recycling and the impact on human health and the environment.

In BREEAM and LEED, there is a defined category for materials and it is much easier to define the contribution of materials to the overall ranking, and there is also a smaller contribution of materials through other categories. In DGNB, it is not easy to define materials because there is no specific category, but rather it is assessed based on the category that is most closely related to which the material has the greatest impact. Based on the analysis, it was found that materials have the greatest contribution in DGNB and we can say that this system promotes the transition to a circular economy and life cycle thinking the most.

We can certainly say that the contribution of the material and, therefore, the importance of choosing an adequate material during the certification of facilities is extremely important. The recommendation would be to try to find some common framework in order to make the certification simpler, more acceptable by users, at least in the domain of documents that are used as bases.

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Review paper

PUBLIC–PRIVATE PARTNERSHIPS FOR GREEN INFRASTRUCTURE: THE ROLE OF RENEWABLE ENERGY

Aleksandar Đorđević[1], Milan Gocić[2], Vuk Milošević[3], Milica Ćirić[4]

Abstract

Financing green infrastructure requires arrangements capable of addressing high initial capital needs and long-term performance requirements. This paper examines the application of Public–Private Partnerships (PPPs) to renewable energy, energy-efficient buildings, and related forms of green infrastructure. The study combines a structured qualitative review of scientific and institutional sources with selected international and Serbian project cases. The analysis identifies risk allocation, life-cycle management, regulatory predictability, institutional capacity, and contractual design as important factors affecting PPP performance. International cases include energy-efficient public lighting, solar-energy development, and waste-to-energy infrastructure, while Serbian examples cover public-lighting and biomass-based heating projects in Niš, solar generation in Vranje, and the Vinča waste-management PPP in Belgrade. These applications are interpreted through an integrated conceptual framework linking infrastructure investment needs and project risks with PPP mechanisms and economic, environmental, and social outcomes. For Serbia, the findings also indicate potential for further application in public-building energy renovation, renewable-energy systems, low-carbon district heating, and urban green and blue infrastructure.

Key words: *public–private partnerships; green infrastructure; renewable energy; sustainable development; infrastructure financing.*

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1. INTRODUCTION

The transition toward low-carbon and resource-efficient infrastructure is increasing demand for renewable energy systems, energy-efficient buildings, and other forms of sustainable public infrastructure. These projects often combine high initial capital requirements with long implementation periods and benefits realized over a longer horizon, creating financing challenges where public budgets are constrained [1–5].

Public–Private Partnerships (PPPs) can combine public-sector objectives with private financing, technical expertise, innovation, and long-term asset management. In green infrastructure, their relevance also lies in risk allocation, life-cycle considerations, and performance-based contractual mechanisms, which are particularly important where project viability depends on long-term efficiency, regulatory stability, and technological performance [6–10].

Existing research often treats PPP financing and governance, renewable-energy investment, and green-building performance separately. An integrated perspective is therefore useful for linking PPP financing characteristics with the specific requirements of sustainable infrastructure projects [7–12].

Accordingly, this paper examines the role of PPPs in financing green infrastructure, with particular emphasis on renewable energy systems and green buildings. It organizes these relationships within an integrated framework linking financing constraints, risk allocation, institutional capacity, and sustainability outcomes, and interprets selected international applications together with cases from Niš, Vranje, and Belgrade to identify further opportunities for green-oriented PPPs in Serbia.

2. LITERATURE REVIEW

The review combines peer-reviewed publications with reports, guidelines, and policy documents from UNEP, the European Union, IEA, IRENA, OECD, the World Bank Group, and EPEC. Sources span 2012–2026 and were selected for relevance to three interconnected areas: green infrastructure and green buildings, renewable-energy development and financing challenges, and PPP models for sustainable infrastructure. Earlier sources were retained where they provide relevant theoretical foundations or documented project experience.

2.1. Green Infrastructure and Green Building

Green infrastructure integrates environmental protection, resource efficiency, climate resilience, and long-term economic considerations into infrastructure planning and urban development. Compared with conventional infrastructure approaches, it places greater emphasis on reducing environmental impacts throughout the project life cycle and on improving the resilience and efficiency of infrastructure assets. Governments and international organizations increasingly incorporate these principles into policies aimed at climate neutrality, urban resilience, and the transition toward a low-carbon economy [1–4].

Within this broader concept, green buildings represent an important component of sustainable infrastructure. Green buildings are designed, constructed, and operated to minimize energy consumption, reduce greenhouse gas emissions, optimize water use, improve indoor environmental quality, and promote the efficient utilization of construction materials. Their performance is evaluated not only through environmental criteria but also through economic and social indicators, including operational cost savings, occupant health, and long-term asset value [1, 2].

International certification systems such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and the German Sustainable Building Council (DGNB) provide standardized frameworks for assessing building sustainability. These systems incorporate criteria related to energy efficiency, resource use, environmental performance, and life-cycle considerations, thereby supporting more consistent evaluation of green building projects [2].

Green building projects may require higher initial investment than conventional buildings because energy-efficient systems, sustainable materials, and advanced building technologies often increase upfront costs. However, part of this additional expenditure may be offset over the project life cycle through lower energy consumption, reduced operating costs, and improved asset performance. This investment profile creates a particular financing challenge, especially for public authorities facing budget constraints, and increases the relevance of financing models capable of combining public and private resources and considering long-term project performance [5, 9].

2.2. Renewable Energy Development and Financing Challenges

Renewable-energy investment has expanded as energy systems incorporate solar, wind, hydropower, biomass, and geothermal technologies. These technologies support emissions reduction, energy-supply diversification, and long-term energy security, while international climate and energy policies further encourage investment [3, 4].

Renewable-energy projects nevertheless face high upfront costs, long recovery periods, technological uncertainty, regulatory and market risks, permitting and grid-connection requirements, and dependence on public-support mechanisms [3, 4, 8]. Predictable legal frameworks, transparent procurement, appropriate contracts, and balanced risk allocation can improve bankability and private-sector participation [8, 11].

These characteristics increase the relevance of financing structures that combine public objectives with private capital and expertise. PPPs are one possible approach where renewable-energy projects include a clear public-service or infrastructure component, but their suitability depends on project characteristics, revenue mechanisms, regulatory stability, and public-sector capacity [6, 8, 11].

2.3. Public–Private Partnerships in Green Infrastructure

PPPs are long-term contractual arrangements in which public and private partners share responsibilities for financing, design, construction, operation, or maintenance of

infrastructure and public services. Their sectoral structure varies across countries and levels of development [13], while the central objective is to combine public supervision with private financing, technical expertise, and operational capacity [6, 10].

Risk allocation is central to PPP design. Construction, operational, technological, financial, regulatory, and demand risks should be assigned to the party best able to manage them; poor allocation can increase costs and reduce value for money, whereas balanced responsibilities can improve long-term performance [6, 8, 10, 14, 15].

Although PPPs have traditionally been used in transport, water, healthcare, education, and utilities, their application has expanded to renewable energy, energy-efficient public buildings, district heating, waste management, and public lighting [7–9]. In green infrastructure, long-term contracts can support life-cycle cost management, performance-based maintenance, energy-efficient technologies, and specialized operational responsibilities [6, 10, 14].

PPP effectiveness depends on project preparation, procurement quality, regulatory predictability, public-sector capacity, and contract management. Weak institutions or poorly specified obligations can reduce expected economic and environmental benefits, so PPPs should be compared with alternative procurement and financing models before implementation [6, 10, 15]. Figure 1 summarizes the conceptual framework applied in this paper.

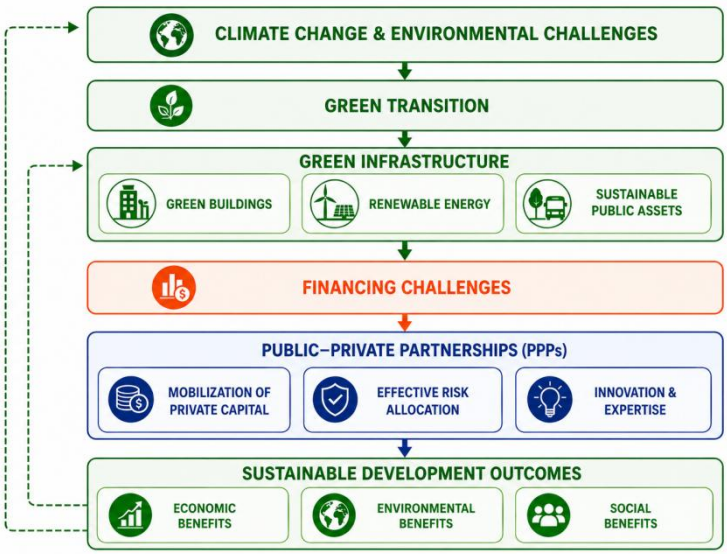


Figure 1. Conceptual framework illustrating the role of Public–Private Partnerships in financing green infrastructure development. Source: Authors' illustration based on the reviewed literature.

Figure 1 links green-infrastructure demand, financing constraints and project-specific risks with PPP mechanisms and sustainability outcomes. PPPs are positioned as an intermediary contractual and financing mechanism through which private capital, technical expertise, risk allocation, and long-term asset management may be combined with public-sector objectives. Their contribution depends on whether the selected structure addresses the project's financing, technological, operational, and institutional constraints.

The resulting outcomes can be assessed across economic, environmental, and social dimensions, including life-cycle efficiency, environmental performance, service quality, and long-term infrastructure sustainability. This framework provides the analytical basis for the financing mechanisms and project cases discussed below.

3. PUBLIC–PRIVATE PARTNERSHIPS AS FINANCING MECHANISMS FOR GREEN INFRASTRUCTURE

3.1. Benefits of PPPs in Green Infrastructure Development

The financing of green infrastructure often requires contractual arrangements capable of addressing high initial investment costs together with long-term operational and performance requirements. PPPs can support this process by combining public-sector objectives with private financing and by distributing financing, construction, operational, and technological responsibilities across the project life cycle [6, 12].

Risk allocation represents one of the main channels through which PPP structures can influence project performance. Where individual risks are assigned to the party with the greater capacity to manage them, PPP arrangements may improve cost control and reduce the probability that construction or operational problems are transferred entirely to the public sector. However, risk transfer does not automatically generate value for money; its effectiveness depends on contractual design, project preparation, and the ability of both partners to manage their allocated responsibilities [6, 10, 14, 15].

The long-term structure of PPP contracts may also create incentives to consider operating and maintenance costs during project design and construction. This is particularly relevant for energy-efficient buildings, public lighting, heating systems, and renewable-energy infrastructure, where project performance over time can determine both financial and environmental outcomes. Private partners may additionally contribute specialized technical expertise, energy-management systems, digital monitoring, and other technologies that improve asset performance during operation [3, 7, 11].

The potential benefits of PPPs therefore depend less on the formal designation of a project as a PPP and more on whether the contractual structure improves financing conditions, risk management, life-cycle performance, and service delivery compared with alternative procurement approaches. At a broader level, PPP investment may also generate economic benefits through infrastructure provision and the mobilization of private capital, particularly in developing economies [16]. The following examples illustrate how these mechanisms have been applied in practice.

3.2. Selected PPP Applications in Green Infrastructure: International and Serbian Experience

PPP arrangements have been applied to energy-efficient public lighting, renewable-energy generation, waste management, and urban energy systems. Table 1 combines

selected international and Serbian cases to show how private financing, risk allocation, and operational responsibility can be adapted to different technologies and project scales.

In the United Kingdom, public-lighting PPPs have supported replacement of inefficient equipment with energy-efficient lighting, reducing electricity use and operating costs [17]. In India, PPP-related approaches have supported large-scale solar development by combining public infrastructure and coordination with private investment and technical capacity [18]. In China, waste-to-energy PPPs combine municipal waste treatment, private financing, long-term contracting, and energy recovery [19].

Table 1. Selected PPP Applications in Green Infrastructure

Country / City	**Selected PPP application**	**Green dimension / relevance**
United Kingdom (Croydon)	Street-lighting modernization [17]	Energy efficiency; lower electricity consumption and operating costs.
India	Solar parks program [18]	Large-scale renewable-energy deployment through solar infrastructure.
China	Waste-to-energy PPP projects [19]	Waste treatment combined with energy recovery.
Serbia, Niš	Replacement, rationalization and maintenance of public lighting [20]	Municipal energy efficiency and reduced electricity demand.
Serbia, Niš	Substitution of fossil-fuel heat production with wood biomass [21]	Renewable heat, lower fossil-fuel use and reduced emissions.
Serbia, Vranje	Two solar power plants in the Vranje Free Zone [22]	Local solar-energy generation and renewable infrastructure.
Serbia Belgrade (Vinča)	Waste-management and waste-to-energy PPP [23]	Landfill remediation, modern waste treatment and energy recovery.

Serbian cases show green-oriented PPP applications at different local-infrastructure scales. In Niš, public-lighting modernization targets lower electricity demand and maintenance requirements [20], while a district-heating proposal substitutes fossil-fuel production with wood biomass, with the private partner financing equipment and assuming relevant technical and financial risks [21]. This is consistent with broader recommendations for private-sector participation in district-heating modernization [24].

A further Niš project replaces fuel-oil boilers in schools and preschool facilities with biomass, pellet, or natural-gas systems [25]. In Vranje, a concession proposal covers financing, design, construction, connection, management, and maintenance of two solar power plants [22]. At a larger scale, the Belgrade Vinča PPP combines landfill remediation, waste treatment, and energy recovery, mobilizing substantial private and institutional financing [23].

Together, the cases illustrate PPP applications in energy efficiency, solar generation, renewable heating, and waste-to-energy infrastructure, while also showing the role of local authorities in identifying projects suitable for long-term public–private cooperation.

Further Serbian applications could include ESCO-type renovation of public buildings, rooftop photovoltaics and storage, low-carbon district heating, and urban green and blue infrastructure. Recent public-building initiatives already combine envelope

measures, photovoltaics, heat pumps, efficient lighting, and automated energy management [26], while district-heating modernization can incorporate biomass, heat pumps, solar thermal systems, and waste-heat recovery [24]. These directions align with Serbia's broader decarbonization investment needs [27].

3.3. Challenges and Future Perspectives of PPPs in Green Infrastructure

The implementation of PPP projects in green infrastructure is affected by financial, regulatory, institutional, and political risks that can influence project costs and private-sector participation. High transaction costs, lengthy procurement procedures, regulatory uncertainty, and changes in public policy are particularly relevant in developing and emerging markets, where they may weaken project bankability and increase implementation risks [6, 8, 11].

Financial sustainability represents an additional challenge because green infrastructure generally combines high initial investment requirements with long operating and repayment periods. Private participation therefore depends on credible revenue mechanisms, predictable regulatory conditions, and, where justified, appropriate public support. Inadequate project preparation, unrealistic demand assumptions, or poorly structured financial obligations can undermine long-term project performance [6, 14, 15].

Institutional capacity is equally important. Public authorities must be able to prepare feasibility studies, structure procurement procedures, allocate risks, and monitor long-term contracts. Limited technical and administrative capacity may result in delays, inappropriate risk allocation, contract renegotiation, or additional fiscal exposure [10, 12].

Future PPP structures may increasingly be combined with complementary financing instruments, including green bonds, blended finance, climate funds, and other sustainability-oriented sources of capital [3, 4, 11]. Digital technologies may also support project preparation and contract management. Building Information Modelling (BIM), digital twins, smart monitoring systems, and data-based performance assessment can improve the monitoring of energy use, operating conditions, and life-cycle asset performance.

The further application of PPPs to green infrastructure will therefore depend on the quality of project preparation, institutional capacity, contractual design, and the ability to measure long-term performance. For Serbia, the cases discussed in the previous section indicate potential in municipal energy efficiency, renewable heating, solar energy, public buildings, and environmental infrastructure, while broader application will require continued strengthening of project-development capacity and financing conditions [24, 27].

4. CONCLUSION

Green infrastructure projects, particularly renewable-energy systems and energy-efficient buildings, combine substantial initial investment requirements with long operating periods and performance objectives that extend beyond conventional

infrastructure delivery. The reviewed literature indicates that PPPs can address some of these characteristics by combining private financing and technical capacity with long-term risk allocation, operation, and asset-management responsibilities. Their suitability, however, depends on project characteristics and on whether the selected contractual structure provides advantages over alternative procurement and financing approaches.

The analysis implies that regulatory stability, transparent procurement, appropriate risk allocation, institutional capacity, and consistent long-term project management remain central to PPP performance. These factors are particularly relevant in green infrastructure, where financial outcomes are often linked to energy savings, technological performance, environmental requirements, and life-cycle costs. PPP arrangements should therefore be assessed not only according to their ability to mobilize private capital, but also according to their capacity to improve long-term project performance and allocate responsibilities effectively.

The international and Serbian cases presented in this paper demonstrate the diversity of possible applications. International experience includes energy-efficient public lighting, solar-energy development, and waste-to-energy infrastructure, while Serbian practice provides examples of public-lighting modernization, biomass-based district heating, improvements to heating systems in public buildings, solar generation in Vranje, and the large-scale Vinča waste-management PPP in Belgrade. These cases indicate that green-oriented PPPs in Serbia are already being applied at different project scales, with local authorities playing an important role in identifying suitable infrastructure needs.

Based on this experience, further application in Serbia could extend toward comprehensive energy renovation of public buildings, rooftop photovoltaic systems and energy storage, low-carbon district-heating solutions, and urban green and blue infrastructure. The viability of such projects will depend on careful project preparation, measurable performance requirements, appropriate financing structures, and sufficient institutional capacity rather than on the PPP model alone.

By linking green-infrastructure investment requirements, renewable-energy financing constraints, project risks, and PPP mechanisms within a common analytical framework, the paper provides a basis for comparing different applications of public–private cooperation in sustainable infrastructure. Future research should assess the actual financial, energy, and environmental performance of completed green PPP projects and compare their outcomes with alternative infrastructure-delivery models.

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Review paper

LIFE CYCLE ASSESSMENT OF CONSTRUCTION MATERIALS: A REVIEW OF ENVIRONMENTAL PERFORMANCE AND FUTURE DIRECTIONS

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Abstract

The increasing demand for sustainable and resource-efficient buildings has intensified the need for comprehensive environmental assessment tools in the construction sector. Construction materials play a crucial role in determining the environmental performance of buildings throughout their life cycle, influencing energy consumption, resource depletion, waste generation, and greenhouse gas emissions. As the construction industry seeks to reduce its environmental footprint and support sustainable development goals, Life Cycle Assessment (LCA) has emerged as a widely accepted methodology for evaluating environmental impacts and supporting informed decision-making. This review paper examines the application of Life Cycle Assessment (LCA) to the evaluation of construction materials, with a particular focus on their environmental performance and recent developments in sustainable construction. The study reviews the life cycle impacts of commonly used materials, including concrete, steel, timber, aluminium, glass, and other structural and non-structural materials. The findings demonstrate that no construction material is environmentally superior in all situations and emphasize the importance of context-specific material selection based on comprehensive life cycle assessment. Integrating environmental, technical, and functional considerations through LCA can support more sustainable decision-making and contribute to the development of low-carbon, resource-efficient buildings and infrastructure.

Key words: *Life Cycle Assessment, Construction materials, Sustainability, Environmental impact*

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1. INTRODUCTION

The building sector contributes significantly to resource consumption, energy use, and greenhouse gas emissions, all of which have an adverse effect on the environment. Approximately 34% of energy-related CO_2 emissions and more than 32% of energy demand in 2023 came from the buildings and construction industry, making it a crucial sector for reaching global net zero carbon and resilience goals [1]. Rapid urbanization, infrastructure expansion, and population growth intensify pressure on natural resources and ecosystems [2]. Consequently, the transition toward sustainable construction practices has become a strategic priority at global, national, and industry levels. Construction materials have a significant impact on CO_2 emissions because their production often requires large amounts of energy [3]. Materials such as cement, steel, and concrete are among the largest sources of carbon emissions in the construction industry. Choosing sustainable, recycled, or low-carbon materials can greatly reduce the environmental impact of buildings. Therefore, the selection of construction materials plays a key role in reducing greenhouse gas emissions and supporting sustainable development.

Sustainability in construction refers to designing, building, and operating structures in a way that reduces environmental impact while promoting economic and social benefits. It involves using energy-efficient technologies, sustainable materials, and renewable energy sources. Sustainable construction helps conserve natural resources, reduce waste and carbon emissions, and create healthier living and working environments. As a result, it plays an important role in achieving long-term environmental and economic goals. Traditional approaches to environmental evaluation in construction focused primarily on operational energy consumption. However, growing evidence highlights the importance of embodied impacts associated with material extraction, production, transportation, construction, maintenance, and end-of-life processes. These embodied impacts can represent a substantial share of total life cycle emissions, particularly in energy-efficient buildings.

Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental impacts throughout the entire life cycle of a product or system [4]. In the context of construction materials, LCA enables quantitative comparison of alternative materials and supports evidence-based decision-making. This paper reviews methodological foundations, applications, limitations, and future directions of LCA in construction material assessment. It offers a comprehensive and methodical way to evaluate a material's environmental performance and find areas for improvement. Impacts including carbon emissions, energy use, water use, air pollution, waste production, and ecosystem depletion are measured by life cycle assessment (LCA) studies [5, 6]. In the construction industry, LCA is widely applied to assess the sustainability of building materials and construction systems by considering all stages, from raw material extraction and manufacturing to transportation, use, maintenance, and end-of-life treatment [4]. The concept of LCA is based on life cycle thinking, which recognizes that environmental impacts occur at every stage of a product's existence [7]. Rather than focusing only on the production phase, LCA evaluates the complete chain

of activities and material flows. It also considers the potential benefits of reuse, recycling, and resource recovery, emphasizing the circular nature of modern sustainable construction practices. LCA follows several fundamental principles that ensure consistency and reliability of the assessment. These include considering the entire life cycle of the system, defining clear system boundaries, maintaining transparency in data collection and methodological choices, evaluating all relevant environmental impacts, and applying consistent assessment procedures. By following these principles, LCA enables objective comparisons between alternative materials and construction solutions while supporting sustainability-oriented decision-making.

2. METHODOLOGY

This review was conducted to provide a comprehensive overview of the environmental performance of construction materials through the application of Life Cycle Assessment (LCA). A structured literature search was performed to identify relevant scientific publications addressing the environmental impacts of construction materials, LCA methodologies, embodied carbon, circular economy strategies, and emerging trends in sustainable construction. The literature search was carried out using four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. The review primarily considered peer-reviewed journal articles published in English between 2006 and 2025, with particular emphasis on recent publications reflecting current advances in LCA methodology and sustainable construction.

The selection process focused on studies that (i) applied Life Cycle Assessment to construction materials or buildings, (ii) evaluated environmental impacts using recognized LCA methodologies, (iii) investigated embodied carbon, energy consumption, resource efficiency, or circular economy approaches, and (iv) presented findings relevant to sustainable material selection and environmental decision-making. Following the screening and evaluation process, references were selected for qualitative synthesis. The selected literature was analyzed comparatively to identify the environmental characteristics, advantages, limitations, and sustainability potential of major construction materials, as well as current research trends and future directions in Life Cycle Assessment within the construction sector.

3. ENVIRONMENTAL IMPACTS OF MAJOR CONSTRUCTION MATERIALS

Construction materials play a crucial role in determining the overall environmental performance of buildings. According to the Global Status Report for Buildings and Construction 2024–2025, buildings consumed 32% of global energy and contributed 34% of global CO_2 emissions in 2023 [8]. Emissions associated with building operations accounted for around 26% of total global emissions, primarily due to heating, cooling, lighting, and other energy-related activities. In addition, the production of construction materials such as cement, steel, and aluminium contributed approximately 5% of global emissions, while materials such as glass and bricks accounted for a further 3% [9]. Operational emissions from buildings reached nearly 9.8 gigatonnes of CO_2 in 2023,

highlighting the continued dependence of the sector on energy-intensive processes [10]. Although embodied carbon emissions related to construction materials decreased slightly to approximately 2.9 gigatonnes of CO_2, the overall reduction remains insufficient to meet global climate targets [11]. The main environmental characteristics of the most commonly used construction materials are summarized in Table 1.

Table 1. Environmental characteristics of major construction materials

Material	Main Advantages	Main Limitations	Environmental Characteristics	References
Cement	Excellent mechanical performance	High clinker-related CO_2 emissions	Highest contribution to embodied carbon	[12], [13], [14], [15]
Concrete	High durability; thermal mass	Cement production dominates impacts	Environmental performance improves using SCMs and recycled aggregates	[6], [16], [17], [18]
Steel	High strength; fully recyclable	Energy-intensive primary production	High embodied energy but excellent recyclability	[15], [18], [19], [20]
Brick	Long service life	Energy-intensive firing	Moderate environmental impacts over long service life	[21], [22]
Timber	Renewable resource; carbon storage	Moisture sensitivity and durability issues	Lowest embodied carbon among structural materials	[18], [22]
Glass	High daylight utilization	High melting temperatures	High manufacturing energy demand	[20], [22]
Aluminium	Lightweight; corrosion resistant	Very high electricity demand during primary production	Recycling significantly reduces impacts	[23], [24]
Recycled construction materials	Resource conservation; waste reduction	Variable quality	Lower embodied carbon than virgin materials	[23], [24], [25], [26]

Concrete is the most widely used construction material in the world due to its durability, versatility, and relatively low cost [12]. However, its environmental impact is considerable, primarily because of cement production. The manufacturing of cement requires high-temperature kilns and releases large amounts of carbon dioxide (CO_2) both from fuel combustion and from the chemical process of limestone calcination. As a result, cement production is one of the largest industrial sources of global CO_2 emissions [13]. In addition to greenhouse gas emissions, concrete production consumes significant quantities of natural resources such as limestone, sand, gravel, and water. Nevertheless, concrete offers advantages such as long service life, thermal mass benefits, and the potential incorporation of recycled aggregates and supplementary cementitious materials that can reduce its environmental footprint [14, 15].

Steel is another fundamental construction material widely used in structural systems due to its high strength, durability, and flexibility. The production of steel is energy-intensive and generates substantial greenhouse gas emissions, particularly when manufactured using traditional blast furnace technology. Environmental impacts also include the extraction of iron ore and coal, resource depletion, and air pollution [15]. Despite these challenges, steel has one of the highest recycling rates among construction materials. Recycled steel requires significantly less energy than primary steel production, making circular economy strategies particularly effective in reducing its environmental impact.

Timber is often regarded as one of the most environmentally friendly construction materials because it is renewable and capable of storing carbon throughout its service life. Timber production generally requires less energy compared to concrete and steel manufacturing. However, the sustainability of timber depends on responsible forest management practices. Unsustainable logging can contribute to deforestation, biodiversity loss, and ecosystem degradation. Certified wood products sourced from sustainably managed forests offer significant environmental advantages and are increasingly promoted in green building projects. In a study of a residential building in Scotland, Asif et al. assessed the embodied CO_2 emissions of several commonly used construction materials [16]. The results indicated that concrete was the dominant contributor to embodied energy, accounting for 61% of the total, while ceramic tiles and timber contributed 15% and 14%, respectively [15]. These findings highlight the significant environmental impact of concrete compared with other building materials [15, 17].

Bricks and masonry products are widely used for walls and façades due to their durability, thermal performance, and fire resistance. Their production typically involves the extraction of clay and high-temperature firing processes, which consume considerable amounts of energy and generate CO_2 emissions. Although brick manufacturing can have notable environmental impacts, masonry structures often have long service lives and low maintenance requirements, which can partially offset their initial environmental burden over the building life cycle. In this context, alternative bricks are manufactured using either organic (ABO) or inorganic (ABI) additives, which are typically derived from industrial waste streams. A key distinction in their production process is the elimination of the firing stage, although this approach is not applicable to all types of alternative bricks [18]. According to Galan-Marin et al. (2016), the evaluation of alternative brick types should include comparisons not only with traditional brick (TB) but also with other construction systems, such as precast concrete, wood, bamboo, and similar materials [19].

Glass is an essential material in modern architecture, providing natural lighting, transparency, and aesthetic value. However, glass manufacturing requires high temperatures and substantial energy consumption, resulting in greenhouse gas emissions. Large glazed surfaces can also increase operational energy demand if not properly designed. On the other hand, advanced glazing technologies, such as low-emissivity (Low-E) coatings and double or triple glazing systems, can significantly improve building energy efficiency and reduce operational environmental impacts [20].

Aluminium is valued in construction for its lightweight properties, corrosion resistance, and durability. Nevertheless, primary aluminium production is highly energy-intensive and associated with significant greenhouse gas emissions. The extraction and processing of bauxite ore also contribute to environmental degradation. Despite these impacts, aluminium can be recycled repeatedly without substantial loss of quality, and recycled aluminium requires only a fraction of the energy needed for primary production, making recycling a key strategy for improving sustainability. One special quality of aluminium is that it can be recycled endlessly without losing its qualities. In comparison to the first mining and processing, recycling aluminium only

consumes 5% of the energy and 10% of the initial capital equipment expenditures [21]. Melting or casting and solid-state recycling are the two main processes used to recycle aluminium [22].

4. OVERVIEW OF LIFE CYCLE ASSESSMENT RESEARCH ON CONSTRUCTION MATERIALS

Life Cycle Assessment (LCA) provides a scientific basis for comparing the environmental performance of different construction materials and building systems. The comparison of LCA results is typically based on a range of environmental indicators, including greenhouse gas (GHG) emissions, energy consumption, water use, resource depletion, waste generation, human health impacts, and ecosystem effects. Since no single material performs best in every category, LCA helps identify trade-offs between different environmental objectives and supports balanced decision-making.

Studies consistently show that concrete and steel generally have higher embodied carbon emissions than timber-based materials [23, 24]. Cement production is a major contributor to the environmental impact of concrete, while steel manufacturing requires substantial energy and generates significant greenhouse gas emissions [25, 26]. In contrast, timber products often exhibit lower embodied energy and carbon footprints due to their renewable nature and carbon storage capacity [27, 28]. For example, timber structures can significantly reduce life-cycle carbon emissions compared to equivalent concrete or steel structures [29]. However, timber may require additional considerations regarding durability, fire resistance, and sustainable forest management practices. Therefore, environmental advantages should always be evaluated alongside technical and functional requirements. Aluminium often exhibits one of the highest embodied energy values among construction materials because of the energy-intensive extraction and refining processes involved in primary production. Nevertheless, its environmental performance improves substantially when recycled aluminium is used [21, 22]. Similarly, glass production can be energy-intensive, but high-performance glazing systems can reduce operational energy consumption throughout a building's service life, compensating for part of the initial environmental burden.

LCA comparisons frequently distinguish between embodied impacts and operational impacts. Embodied impacts include emissions and resource consumption associated with material extraction, manufacturing, transportation, construction, maintenance, and disposal. Operational impacts result from energy and water consumption during the use phase of a building [30, 31]. Traditionally, operational energy dominated the environmental footprint of buildings. However, improvements in energy-efficient building design have reduced operational impacts, making embodied carbon increasingly important. Consequently, material selection now plays a more significant role in the overall sustainability performance of buildings.

Comparative LCA studies reveal several consistent trends [30, 31]. Timber generally exhibits the lowest embodied carbon footprint among major structural materials, whereas concrete is associated with relatively high CO_2 emissions because of cement

production [32]. Steel is characterized by high embodied energy and greenhouse gas emissions but offers significant environmental advantages due to its high recyclability [33]. Primary aluminium production has one of the highest embodied energy requirements among construction materials; however, recycling substantially reduces its environmental impacts [34]. In general, recycled and secondary materials demonstrate lower environmental impacts than virgin materials across most impact categories [35].

5. FUTURE DIRECTIONS OF LCA IN CONSTRUCTION

Life Cycle Assessment (LCA) is continuously evolving in response to new sustainability goals, technological progress, and increasing environmental awareness in the construction industry. Future developments are strongly linked to circular economy principles, digital tools, standardized environmental data, and the use of low-carbon materials [36]. One of the most important future directions is the integration of LCA with circular economy strategies. Instead of the traditional linear model (take–make–dispose), the circular approach focuses on reducing waste, reusing materials, and recycling resources. LCA helps evaluate the environmental benefits of circular practices such as material reuse, component recovery, and recycling loops. By quantifying environmental savings, LCA supports the design of buildings that minimize resource depletion and extend material life cycles [37]. The use of digital technologies, especially Building Information Modelling (BIM), is transforming how LCA is applied in construction [38, 39]. BIM enables the integration of material quantities, building design data, and environmental databases in a single digital environment. When combined with LCA software, BIM allows for real-time environmental impact assessment during the design phase [39]. This integration improves decision-making, reduces errors, and enables designers to optimize buildings for lower environmental impact before construction begins. Environmental Product Declarations (EPDs) are becoming increasingly important as standardized and transparent sources of environmental data for construction materials [39]. EPDs provide verified information on the life cycle environmental impacts of products, based on LCA methodology. The growing availability of EPDs improves data quality in LCA studies and supports more reliable and comparable environmental assessments in the construction sector.

Several European countries, including Germany, France, and the Netherlands, have promoted the use of low-carbon cement, recycled steel, and sustainably sourced timber, which has contributed to lower embodied carbon emissions within the construction sector [40]. These materials help reduce greenhouse gas emissions while maintaining the required structural and functional performance of buildings [41]. Similar initiatives have emerged in North America. In the United States, the Federal-State Buy Clean Initiative encourages the procurement of lower-carbon construction materials for publicly funded projects [42]. Participating states prioritize environmentally responsible material selection, supporting market demand for products with reduced life-cycle emissions. Such policies demonstrate the growing role

of sustainable procurement strategies in accelerating the transition toward a low-carbon built environment.

6. CONCLUSION

Construction materials differ significantly in their environmental performance throughout their life cycle, making material selection a key aspect of sustainable construction. The reviewed literature shows that no single material is environmentally superior in all situations. Timber generally exhibits the lowest embodied carbon footprint, while concrete and steel are associated with higher greenhouse gas emissions due to cement production and energy-intensive manufacturing. Although aluminium and glass require considerable energy during primary production, their environmental performance can be significantly improved through recycling and efficient use. Life Cycle Assessment (LCA) remains the most comprehensive tool for evaluating the environmental impacts of construction materials by considering their entire life cycle. Future developments, including the integration of circular economy principles, Building Information Modeling (BIM), Environmental Product Declarations (EPDs), and digital technologies, are expected to improve the reliability and practical application of LCA. Overall, sustainable construction requires context-specific material selection based on comprehensive life cycle assessment that considers environmental, technical, and functional performance to support the transition toward a low-carbon and resource-efficient built environment.

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Research paper

THE INFLUENCE OF VENTILATION OPENING CONTROL STRATEGIES ON THE ENERGY PERFORMANCE OF A TROMBE WALL

Jelena Jović[1], Anđela Stojiljković[2], Dušan Ranđelović[3]

Abstract

Trombe wall is passive solar system that can reduce heating energy demand by storing and transferring solar gains to the interior space. However, their energy performance depends strongly on the operation of ventilation openings, particularly because uncontrolled airflow may lead to reverse thermosiphoning and nocturnal heat losses. This study investigates the effect of different ventilation opening control strategies on the energy performance of a Trombe wall under winter conditions in Niš, Serbia. A dynamic simulation model was developed for a 40 m³ room equipped with a south-oriented Trombe wall with an effective solar area of 6.7 m². Six operating scenarios were analysed: a reference case without a Trombe wall, continuously open ventilation openings, two manually scheduled control strategies, temperature-based intelligent control, and a Trombe wall without ventilation openings. The analysed performance indicators included mean indoor temperature, heating energy demand, and night-time heat losses. The results show that the intelligent control strategy achieved the highest heating-energy saving of 26.02 %, while also producing the lowest night-time heat losses. Although the continuously open configuration achieved a similar overall heating-energy saving, it resulted in substantially higher nocturnal losses. The findings indicate that adaptive control of Trombe wall ventilation openings can improve the balance between solar heat utilisation and unwanted heat losses. The results are limited to the analysed winter day and provide a basis for further investigation over longer simulation periods.

Key words: *Trombe wall, ventilation openings, energy efficiency, thermal comfort*

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1. INTRODUCTION

Since the building sector accounts for the largest share of energy consumption, experts worldwide are actively investigating opportunities to improve the energy efficiency of buildings and promote sustainable construction. Consequently, particularly in recent years, an increasing number of buildings have incorporated renewable energy sources, as well as active and passive systems, to reduce heating and cooling energy demand. Solar energy is one of the cleanest and most widely available renewable energy sources. One of the approaches to its passive utilisation is the application of a Trombe wall, which uses solar energy to heat indoor spaces without the need for complex mechanical equipment.

A conventional Trombe wall consists of a massive wall with a dark surface oriented towards the south, glazing, and an air space between them. During the day, the wall absorbs solar energy and stores it within its thermal mass, while the accumulated heat is gradually released into the interior during the evening hours through conduction. When ventilation openings are provided at the top and bottom of the wall, additional heat transfer occurs through natural air circulation - convection. Although a Trombe wall can significantly contribute to reducing heating energy consumption, its performance depends on numerous factors, such as climate, materials, wall dimensions, glazing, orientation, and the way in which the ventilation openings are operated. Open ventilation channels during the night or periods of low solar radiation may lead to an adverse effect, i.e. a significant increase in heat losses and a reduction in system efficiency due to the release of stored heat to the exterior [1,2,3]. Therefore, contemporary research pays particular attention to the development of ventilation-opening control strategies that enable maximum utilisation of solar gains while minimising heat losses.

The aim of this study is to investigate, using dynamic simulation, the influence of different ventilation-opening control strategies of a Trombe wall on energy efficiency and thermal comfort during a winter day under the climatic conditions of the city of Niš, Serbia.

2. METHODOLOGY

The study was conducted using a dynamic simulation model developed in MATLAB to analyse the influence of different ventilation-opening control strategies on the energy performance of a Trombe wall during the winter period. The model accounts for the interaction between outdoor climatic conditions, the Trombe wall, the indoor space, and the auxiliary heating system, enabling the assessment of the system's energy performance under different operating regimes.

The reference space has a volume of 40 m^3 and a south-oriented Trombe wall with an effective solar area of 6.7 m^2. The thermal storage part of the wall is made of reinforced concrete with a thickness of 0.30 m, while double glazing is positioned 0.10 m from the wall, forming an air gap between the glazing and the wall. The remaining simulation parameters are given in Table 1.

Table 1. Parameters of the simulated Trombe wall system

Parameter	**Value**
Room volume	40 m^3
Trombe wall area	6.7 m^2
Wall thickness	0.30 m
Wall mass	4820 kg
Specific heat capacity	880 J/kgK
Glazing type	Double glazing (4 - 12 - 4 mm)
Solar transmittance of glazing (τ)	0.60
Air gap thickness	0.10 m
Vent opening area	0.04 m^2
Indoor set-point temperature	20°C

Characteristic climatic conditions for a January day in Niš were used for the simulation. The outdoor temperature during the analysed period ranged approximately from −2 °C to +4 °C, while the maximum solar radiation intensity on the south façade reached 450 W/m². The simulation accounted for solar gains through the glazing, heat storage in the wall, heat transfer between the wall and the room, and heat losses through the building envelope. An auxiliary heating system with an indoor set-point temperature of 20 °C was also implemented, and the required heating energy was used as one of the main indicators of the energy performance of the analysed scenarios.

Six operating scenarios were analysed to assess the influence of ventilation-opening control. The first scenario represents the reference case without a Trombe wall, while the remaining scenarios represent different ventilation-opening control strategies, including continuously open openings, predefined opening schedules, intelligent temperature-based control, and a Trombe wall without ventilation openings (Table 2).

Table 2. Description of the simulation scenario

Scenario	Description of the simulation scenario
S0	Reference case without a Trombe wall
S1	Trombe wall with continuously open ventilation openings
S2	Manual control of the Trombe wall ventilation openings from 08:00 to 18:00 h
S3	Manual control of the Trombe wall ventilation openings from 09:00 to 19:00 h – user delay
S4	Trombe wall with an intelligent ventilation-opening control system based on the temperature difference between the wall and the room
S5	Trombe wall without ventilation openings

For each scenario, key system performance indicators were determined, including mean indoor temperature, required auxiliary heating energy, night-time heat losses,

ventilation-opening operating time, and the degree of solar energy utilisation. Particular attention was paid to the occurrence of the reverse thermosiphon effect, which can lead to unwanted cooling of the indoor space during night-time hours. The different control strategies were analysed to determine the extent to which this phenomenon can be reduced or completely eliminated through the application of simple control algorithms. The obtained results enabled a comparison of the effectiveness of the individual control strategies and the identification of the solution providing the most favourable balance between energy efficiency and indoor thermal comfort.

3. RESULTS AND DISCUSSION

The simulation results are presented in Table 3. The main indicators used to assess the energy performance of the system were the mean indoor temperature, heating energy demand, and night-time heat losses. These parameters were selected to evaluate the influence of different ventilation-opening control strategies on the energy performance of the Trombe wall. Scenario S0, representing the room without a Trombe wall, was adopted as the reference case.

Table 3. Simulation results

Scenario	Mean temperature [°C]	Heating [kWh]	Night-time heat losses [kWh]	Savings for heating [%]
S0	17.53	8.897	0.0000	
S1	18.15	6.665	0.1853	25.09
S2	17.90	7.551	0.0672	15.13
S3	17.96	7.343	0.0282	17.5
S4	18.17	6.582	0.0149	26.02
S5	17.66	8.443	0.0330	5.1

In the reference case S0, the required heating energy was 8.897 kWh, with a mean indoor temperature of 17.53 °C. Introducing a Trombe wall reduced the heating energy demand in all analysed scenarios. The smallest improvement was recorded for S5, the Trombe wall without ventilation openings, where the heating energy demand was 8.443 kWh, corresponding to a 5.10 % saving compared with S0. The highest saving was achieved by S4 with intelligent control, reaching 26.02 %, with the heating energy demand reduced to 6.582 kWh.

Changes in indoor temperature during the analysed day for all six scenarios are shown in Figure 1. In the early morning hours, differences between the scenarios are relatively small, while with increasing available solar radiation the influence of the Trombe wall on room temperature becomes more pronounced. Scenarios with active heat transfer through ventilation openings show an increase in temperature during the

solar-exposure period, with S4 achieving the highest mean room temperature of 18.17 °C. A very similar value was obtained for S1, with a mean temperature of 18.15 °C.

In contrast, S5, without ventilation openings, achieved a mean room temperature of 17.66 °C. Although heat is stored in the thermal mass of the wall in this case, its transfer to the indoor space is limited. This result indicates that thermal mass alone is not sufficient to achieve a greater influence on indoor temperature; the way in which stored heat is transferred is also important.

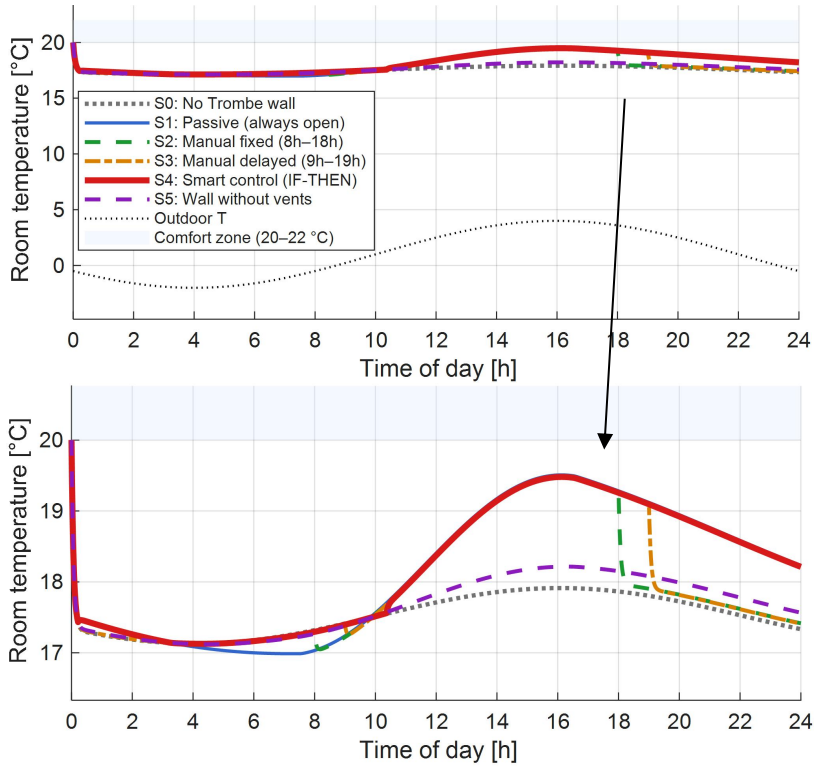


Figure 1. Indoor air temperature - comparison

The operating regimes of the ventilation openings are presented in Figure 2. Scenario S1 represents the case in which the ventilation openings remain open throughout the analysed period. In S2, the openings are open from 08:00 to 18:00, while in S3 the opening period is shifted by one hour, from 09:00 to 19:00. Scenario S4 uses intelligent control based on an IF–THEN algorithm, in which the state of the ventilation openings is determined by the instantaneous temperature difference between the Trombe wall and the room.

The comparison of operating regimes shows that the strategies differ primarily in their ability to adapt the operation of the ventilation openings to current conditions. In the time-based strategies S2 and S3, the openings are operated according to a predefined schedule, regardless of whether the conditions for heat transfer are favourable at a given moment. In contrast, the S4 strategy determines the opening state according to the thermal condition of the system, allowing the operating regime to adapt to changes during the day.

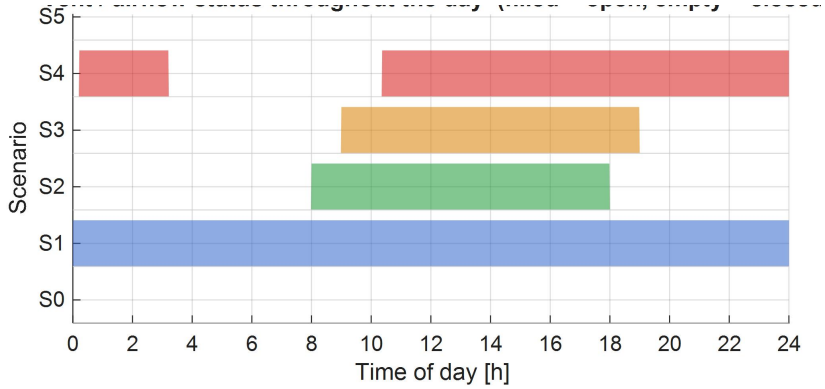


Figure 2. Vent/airflow status throughout the day (filled = open, empty = closed)

Figure 3 presents the heat transfer between the Trombe wall and the indoor space. Positive values represent useful heat transfer towards the room, while negative values indicate heat transfer in the opposite direction, corresponding to unwanted cooling caused by reverse thermosiphon effect. During solar-exposure periods, scenarios with ventilation openings show increased heat transfer towards the room, contributing to a reduction in auxiliary heating demand.

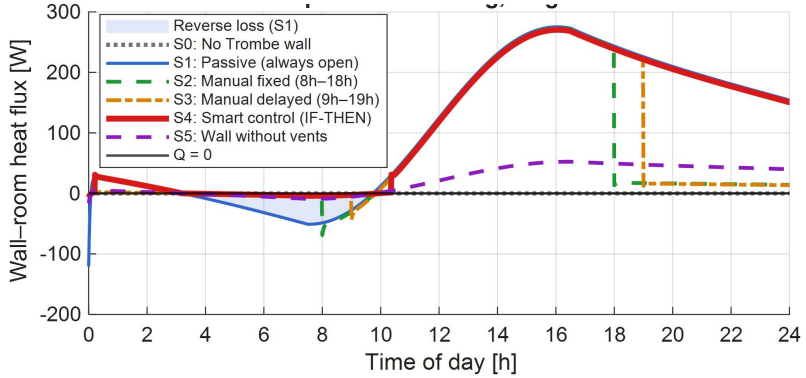


Figure 3. Heat transfer wall → room: positive = heating, negative = nocturnal back-cooling

In S1, where the openings remain continuously open, a pronounced negative heat flux occurs after the solar-exposure period. As the wall cools during the night, the conditions for natural air circulation change and heat is transferred from the room towards the Trombe wall. Consequently, S1 has the highest night-time heat losses, amounting to 0.1853 kWh.

Restricting the operating period of the ventilation openings reduces these losses. In S2, night-time losses amount to 0.0672 kWh, while in S3 they are reduced to 0.0282 kWh. Shifting the opening period from 08:00 - 18:00 to 09:00 - 19:00 therefore reduces night-time losses, while also affecting the amount of heat transferred to the room during the day.

The lowest night-time losses were achieved by S4, amounting to only 0.0149 kWh. In this case, adaptive control enables the ventilation openings to be closed when the temperature conditions are no longer favourable for heat transfer towards the indoor

space. In this way, the possibility of heat transfer from the indoor space towards the Trombe wall during the night is significantly reduced.

Comparison of the energy results shows that the advantage of intelligent control is not limited to reducing night-time losses, but also lies in maintaining a high level of overall energy efficiency. Scenario S4 requires 6.582 kWh of heating energy, while S1 requires 6.665 kWh. The difference between the two scenarios is only 0.083 kWh, or approximately 1.25 %, indicating that their overall energy performance is very similar. However, S4 simultaneously achieves substantially lower night-time heat losses than S1. This result is important when interpreting the effect of automated control. Continuously open ventilation openings allow efficient utilisation of solar gains during periods of solar exposure, which is why S1 achieves a 25.09 % saving compared with S0. However, the same operating regime results in increased losses after solar exposure ends. Intelligent control in S4 achieves a slightly higher overall saving of 26.02 %, while its main advantage is the ability to limit unfavourable operating conditions of the system.

The comparison between S4 and S2 shows a more pronounced difference in the overall heating energy demand. In S2, the required heating energy is 7.551 kWh, corresponding to a 15.13 % saving compared with S0, whereas S4 requires 6.582 kWh, corresponding to a 26.02 % saving. This represents a reduction in heating energy demand of approximately 12.8 % compared with S2. The result indicates that fixed time-based control does not always enable optimal utilisation of the available solar energy, since the ventilation openings may remain closed during periods when heat transfer towards the indoor space would be beneficial.

The comparison of S2 and S3 also shows that even a relatively small change in the opening schedule can affect system performance. Shifting the operating period by one hour reduced the heating energy demand from 7.551 kWh to 7.343 kWh, or by approximately 2.75 %, while night-time losses decreased from 0.0672 kWh to 0.0282 kWh. This result demonstrates that the selection of an appropriate ventilation-opening schedule directly affects the energy efficiency of the Trombe wall.

Based on all analysed scenarios, it can be observed that the application of a Trombe wall alone is not sufficient to achieve maximum energy savings. Scenario S5, without ventilation openings, achieved only a 5.10 % saving compared with the reference case, whereas scenarios with controlled heat transfer through ventilation openings achieved savings of 15.13 - 26.02 %. Continuously open openings provide high energy savings but result in greater night-time losses, while time-based manual control reduces these losses but may limit the utilisation of useful solar gains.

Overall, S4 achieved the best energy performance among the analysed cases, with the highest heating-energy saving, the highest mean indoor temperature, and the lowest night-time heat losses. Nevertheless, the small difference in total heating energy between S1 and S4 indicates that, for the analysed day, the advantage of intelligent control is not a dramatic increase in total energy savings, but rather in its ability to maintain a high level of Trombe wall energy efficiency while simultaneously limiting unfavourable heat-transfer regimes.

4. CONCLUSIONS

The conducted analysis showed that the energy performance of the Trombe wall depends not only on its ability to absorb and store solar energy, but also on the way in which the accumulated heat is transferred to the indoor space. Therefore, the selection of an appropriate ventilation opening control strategy represents an important element in the application of this passive solar system.

The analysed scenarios indicate that time-based control can improve the operation of the Trombe wall compared to its application without ventilation openings, but that a predefined operating schedule is not always consistent with changing thermal conditions. Adaptive control enables the system to respond to the current state of the Trombe wall and indoor space, allowing available solar gains to be utilised while limiting unfavourable heat-transfer regimes.

The significance of the results lies in the potential to achieve high energy efficiency without relying on continuously open ventilation openings. The intelligent control strategy demonstrated the potential to provide more effective system operation and reduce unwanted heat losses, providing a basis for further development of adaptive control strategies for passive solar systems.

The results should be interpreted in the context of the study limitation that the analysis was performed for one characteristic winter day. Therefore, the results represent the behaviour of the analysed system under the adopted conditions rather than a final assessment of its performance over the entire heating season. Further research should focus on longer simulation periods and different climatic conditions in order to further assess the applicability and robustness of the analysed control strategies.

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Review paper

IMPACT OF CLIMATE CHANGE ON INDOOR AIR QUALITY AT SCHOOL

Maja Nikolić[1], Aleksandra Stanković[2], Sonja Novak[3], Nadežda Popović[4]

Abstract

Climate change and urbanization demands have highlighted the importance of indoor air quality (IAQ) as a key component of healthy and sustainable buildings. School environments are of particular concern because children spend a significant portion of their day indoors and are more susceptible to the adverse effects of air pollution than adults. Numerous studies have linked poor IAQ in schools with respiratory diseases, allergic symptoms, reduced cognitive performance, and increased absenteeism.

This paper reviews current evidence on the health and educational impacts of indoor air pollution in schools and discusses opportunities for improvement through green building principles. Special attention is given to ventilation strategies, low-emission building materials, moisture control, air filtration systems, and the role of green infrastructure in reducing pollutant exposure. To illustrate local conditions, indoor air quality measurements were conducted in two primary schools in Niš, Serbia, revealing differences in pollutant presence associated with surrounding traffic intensity.

The findings emphasize the need for continuous IAQ monitoring and the integration of sustainable building solutions to create healthier, more resilient, and energy-efficient educational environments that support both student well-being and academic performance.

Key words: *climate change, indoor air quality, school*

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1. INTRODUCTION

One of the biggest environmental issues threatening human health in the world today is climate change and it poses significant risks to their right to good health. The World Health Organization states that climate change will cause approximately 250,000 additional deaths annually between 2030 and 2050 [1]. These deaths will primarily be caused by malnutrition, malaria, diarrhea, and heat stress. An estimated 3.6 billion individuals live in settings that are particularly susceptible to climate-related hazards. The adverse health effects of climate change are not distributed equally, with low-income nations and small island developing states bearing a disproportionate share of the burden despite their relatively minor contribution to global emissions. Evidence suggests that populations in highly vulnerable regions have experienced significantly higher mortality from extreme weather events, with death rates far exceeding those recorded in less vulnerable areas. Beyond its environmental consequences, climate change affects human health through complex interactions with social, economic, and healthcare systems, thereby influencing both population health outcomes and the resilience of public health infrastructure. In Europe, the spectrum of illnesses and diseases is changing, allergies increased and infectious diseases spread. Heat waves place a great strain in older people with cardiovascular and other chronic diseases.

Climate change can affect the indoor environment through heat and mass transfer between the indoors and outdoors through two fundamental ways. First, a direct response to global warming itself, with extreme weather phenomena such as frequent or violent hurricanes, leads to an increase in indoor air quality (IAQ) problems. Second, IAQ may be impacted by indirect actions taken to reduce emissions of greenhouse gases that can lead to increased concentrations of indoor air contaminants.

Most individuals in Westernized countries spend ~80% of their time indoors [2,3,4], demonstrating the importance of indoor air quality. The composition of indoor air is affected by several factors including outdoor pollutants, the quality/quantity of ventilation, indoor allergens, and activities such as smoking, heating, and cooking [5].

Indoor exposure to air pollutants can influence health, placing women and children in particular at risk of both acute and long-term ill health. Due to physiological characteristics children are more vulnerable to air pollutants than adults. They have higher ventilatory rates per minute (400mL/min/kg body weight in newborns compared to 150mL/min/kg in adults) and on that way increase risk of pulmonary exposure to respirable airborne particles, otherwise filtered in the upper airway. Also, a child aged 7-9 years typically exhales approximately 14 L of CO_2 per hour during normal breathing, whereas adolescents produce substantially higher amounts. Under conditions of moderate physical activity, a 15-year-old student may emit up to 85 L of CO_2 per hour [6]. Moreover, children inhale a larger fraction of air through their mouths than adults. This increased oral breathing allows pollutants to penetrate deep into the lower respiratory tract, which is more permeable. A higher cardiac pulse rate and the extent of tissue perfusion allow more rapid exposure to toxins absorbed into the blood. Although air pollution has long been thought to exacerbate minor acute illnesses in children, there is increasingly strong evidence that air pollution is associated with nontrivial increases

in infant mortality [7] and chronic disease in children [8]. Children's bodies and organs, including their lungs, are also still in development, which further increases risk [9]. Furthermore, children's developing immune systems are weaker than those of adults, strengthening the effects of pollution.

The aim of our study was to indicate the significance of indoor air quality monitoring, with special attention to children as risk population.

2. INDOOR AIR QUALITY IN SCHOOLS: HEALTH AND EDUCATIONAL IMPACT

Schools are among the most important indoor environments for children, as they spend a substantial proportion of their daily lives within classrooms. Classrooms are more crowded than most other workplaces, with roughly four times the occupancy density of typical office buildings [10]. Elevated indoor CO_2 concentrations can contribute to discomfort and reduced air quality in classrooms [11]. Prolonged exposure to indoor air pollutants during childhood has been associated with respiratory symptoms, allergic diseases, asthma exacerbations, impaired cognitive performance and increased school absenteeism. Consequently, ensuring adequate indoor air quality (IAQ) in schools is essential not only for protecting children's health, but also for supporting optimal learning conditions [12]. Numerous international studies have shown that school buildings frequently suffer from inadequate ventilation, poor maintenance, moisture-related problems and accumulation of biological and chemical pollutants [13]. The European Federation of Asthma and Allergy Associations has emphasized that poor IAQ in schools constitutes a widespread and preventable health risk, particularly for children with asthma and allergies, who are disproportionately affected by indoor environmental exposures [14]. Numerous studies have demonstrated a significant association between indoor air quality (IAQ) and students' academic performance. Improved classroom ventilation and lower concentrations of CO_2 and particulate matter have been linked to better cognitive function, higher test scores, improved attendance, and enhanced attention and memory among schoolchildren [11].

As indoor air quality in nonresidential buildings (e.g., schools) plays an important role in respiratory health [15]. The *Schools Indoor Pollution and Health: Observatory Network in Europe* (SINPHONIE) project, funded by the European Parliament, assessed indoor air exposure in schools in 23 countries [16]. The study found that $PM_{2.5}$, some VOCs (e.g., formaldehyde), radon, and allergens (especially molds) were commonly present. Moreover, the *Health Effects of School Environment* (HESE) project [17] reported that 78% and 66% of children attending schools in Norway, Sweden, Denmark, France, and Italy were exposed to PM_{10} over 50 μg/m^3 and to carbon dioxide (CO_2) over 1000 ppm, respectively. Another study from the HESE project investigating the burden of fungi showed that the number of viable molds in indoor air exceeded the maximum standard of 300 cfu/m^3 in 33% of participating classrooms [18]. Very recently, these findings were confirmed in a study conducted in Southern Italy. Importantly, this work observed that the concentration of elements from industrial emission was significantly higher in schools located in

urban/industrial areas as compared to rural areas [19], implying that the penetration of outdoor pollutants further deteriorates the quality of indoor air.

Adverse respiratory and neurological health outcomes associated with exposure to indoor air pollutants can secondarily impact educational attainment both in the short and long term [11].

Few studies succeeded in isolating the effects of exposure in the education environment from exposures in the home, while also accounting for socio-economic confounders (e.g., health inequalities across more deprived communities) [20].

Attributing health effects to individual pollutants can be challenging, which some studies account for by using an index covering multiple pollutants.

A holistic approach of both repairing damage to buildings and improving ventilation should ensure that health effects relating to, e.g., damp conditions or uncontrolled ingress of outdoor pollution are minimized.

Together with source control, the provision of adequate ventilation can achieve optimal IAQ in educational buildings. Increasing classroom ventilation rates often results in better performance (e.g., speed of task completion), but there are inconsistencies relating to, e.g., cognitive performance and task error rate, caused by difficulties delineating the impacts of different pollutants on academic performance. Maintaining indoor temperature between 20 °C and 22 °C through natural or hybrid ventilation can also improve academic outcomes [21].

There is evidence of associations between absenteeism and chronic PM exposure, mould, and low ventilation rates. There is a lack of substantial evidence to confirm the associations of absenteeism with VOC or O_3 exposure [22].

Traffic-related air pollution has been found to impact the executive function through task completion speed, as well as exam grades and language/numeracy testing. There is evidence of negative associations between $PM_{2.5}$ and working memory; NO_2 and UFP with reduced cognitive development compounded by long-term exposure; and VOCs and PAHs with cognitive function.

Mechanical and hybrid ventilation systems systematically outperform natural ventilation strategies in terms of achieving a desired air flow rate to provide adequate conditions for both learning and reducing respiratory infection transmission. However, ventilation standards remain unmet in a concerningly large proportion of educational buildings, especially schools, even when mechanical ventilation is in place. Depending on national or state public school funding, the capital and operating costs of mechanical ventilation and/or air filtration devices to improve indoor conditions can represent a relatively small fraction of a typical state school budget [23].

3. CASE STUDY: INDOOR AIR QUALITY IN SCHOOLS IN NIŠ, SERBIA

3.1. Study area

The city of Niš is situated in Southern Europe (altitude -190 m) and covers a surface area of about 597 km^2. It is the third city in Serbia and according to the latest census from 2022 has about 178,976 inhabitants. The location of the city is unsuitable because the whole city area is located in the valley closed from the three sides. The dominant wind is the North West and its direction diverges so that natural airing is obstructed. Niš has moderate continental climate with average annual temperature of about 11,2^oC. Temperature inversion is frequent. Wet days are present for more than 100 days a year.

Up to the nearly nineties of the previous century, Niš was an industrial city. The dominant sources of air pollution were industry and heating. Nowadays the dominant sources of air pollution in Niš are individual household heating during the winter months, localized road traffic emissions, and operational emissions from industrial facilities within the region.

We investigated two selected school buildings in Nis that represented the building stock of the region in terms of typology, construction technology, age and the natural ventilation type dominant in the country [24]. School 1 is located at an urban area with major traffic roads surrounding the school building and School 2 is located in a residential area, far from main street.

3.2. Methodology

The sampling was carried out in the heating period in each primary school building from Monday morning to Friday afternoon. The samplers took place only when the classroom was occupied in order to provide a better estimate of exposure. Target air quality parameters investigated in this study were sulfur dioxide (SO_2) and black smoke (BS), nitrogen oxides, formaldehyde and carbon monoxide. The samplers was placed at approximately 0.8 m height indoors, which corresponds to the breathing zone of sitting children, not closer than 1 m to the wall. Simultaneously, sampling and monitoring were undertaken outdoors with identical samplers and monitors at each building.

The pollutants were measured daily, during the heating season. The ambient level of BS was measured by reflectance. The sampling was performed by means of a pump operating with flow rate of 1 L/min through Whattman No1 paper filters. The air concentration of SO_2 was determined by spectrophotometer. The sulfur dioxide present in the air stream reacts with the solution to form a stable monochlorosulfonatomercurate complex. During the subsequent analysis, this complex is brought into reaction with acid-bleached pararosaniline dye and formaldehyde yielding intensely colored pararosaniline methyl sulfonic acid. The optical density of this species is determined spectrophotometrically at 548 nm and was directly related to the amount of sulfur dioxide collected. The total volume of the air sample was determined from the flow rate and the sampling time. The concentration of sulfur dioxide in the ambient air was calculated and expressed in $\mu g/m^3$. The lowest limit of detection is 1.7 $\mu g/m^3$. Ambient nitrogen dioxide was collected with a pump containing

triethanolamine in its tube with the exact amount of the reacted nitrogen dioxide using the standard spectrophotometry. The minimum detectable limit of the method had been determined to be 2.0 mg/m^3. The method for formaldehyde air detection involve collecting air samples followed by spectrophotometric analysis using chromotropic acid and measuring the concentration via spectroscopy. Gas samples were collected using the aspiration method with an SKC ltd. pump in corridors, sport halls/gymnasiums and two classrooms in every school. Sampling equipment was placed at 1.5 m above floor level at the sampling sites.

A statistical package SPSS was used for data analysis. Air pollution data were analyzed using Mann-Whitney U test. A P value <0.05 was required for significance.

3.3. Results

The results of the monitoring for the sulfur dioxide and black smoke are reported in Table 1 for the investigated primary school buildings.

Table 1. Mean 24-hour values of sulfur dioxide and black smoke

	School 1		School 2	
Sampling location	SO_2 (μg/m^3)	Black smoke (μg/m^3)	SO_2 (μg/m^3)	Black smoke (μg/m^3)
Corridor	20	4	0	4
Classroom	4	10	0	5
Schoolyard	31	1	20	0
Guideline values	150	50	100	40

Concentrations of SO_2 and black smoke in both schools were below ambient air limit values and occupational exposure limits. In School 2 SO_2 was not detected in the corridor and one classroom while in School 1, SO_2 and black smoke were detected in all sampled rooms.

The results of the monitoring for the gases carbon monoxide, nitrogen dioxide, and formaldehyde are reported in Table 2 for the investigated primary school buildings.

Table 2. Mean values of carbon monoxide, nitrogen dioxide, and formaldehyde

	School 1			School 2		
Sampling location	CO (mg/m^3)	NO_x (μg/m^3)	Formaldehyde (mg/m^3)	CO (mg/m^3)	NO_x (μg/m^3)	Formaldehyde (mg/m^3)
Corridor	2,8	45,7	7,6	0	21,1	0
Classroom 1	0	38,4	5,7	0	20	0
Sports hall/Gymnasium	0	22,5	4,9	0	22,2	0
Classroom 2	0	27	0	0	21,7	0
Guideline values	5	85	0,1	3	70	0,1

Measured concentrations of CO and NO_x in both schools were below the relevant guideline values. Formaldehyde was detected in the School 1, whereas it was not detected in School 2.

4. DISCUSSION AND RECOMMENDATIONS

The findings presented in this study, together with evidence from international research, confirm that indoor air quality (IAQ) in schools remains an important public health concern. Children represent a particularly vulnerable population due to their physiological characteristics, developing respiratory and immune systems, and the substantial amount of time they spend indoors. Our measurements, as well as previous European studies, indicate that elevated concentrations of carbon dioxide, particulate matter, biological contaminants, and other indoor pollutants are frequently present in school environments, potentially affecting both health and educational outcomes.

Improving IAQ in schools should therefore be recognized as an essential component of sustainable school design and operation. Green building principles provide an effective framework for achieving healthier indoor environments while simultaneously reducing environmental impacts and energy consumption. Rather than focusing solely on energy efficiency, modern green school buildings should integrate strategies that balance energy performance with occupant health and comfort [25].

Adequate ventilation should be a key priority in green school buildings. Mechanical ventilation systems with high-efficiency filtration can significantly reduce indoor concentrations of particulate matter, allergens, and airborne pathogens while maintaining acceptable carbon dioxide levels [26]. Where full mechanical ventilation is not feasible, hybrid systems combining natural and mechanical ventilation may provide a sustainable and cost-effective alternative. Continuous monitoring of carbon dioxide concentrations can help assess ventilation performance and identify areas requiring intervention. In addition, incorporating vegetation through green spaces, green walls, or landscaped buffers around schools may further improve environmental quality by reducing pollutant exposure, enhancing occupants' well-being, and supporting broader sustainability goals [27].

Building design and maintenance also play a critical role in IAQ improvement. Moisture control, prevention of water intrusion, and timely remediation of dampness and mold growth are essential for reducing respiratory symptoms and allergic diseases among students. The use of low-emission construction materials, furniture, paints, adhesives, and cleaning products can further minimize indoor exposure to volatile organic compounds and other harmful chemicals [28].

Green school concepts additionally emphasize the importance of reducing the penetration of outdoor pollutants. Schools located near major roads or industrial zones should incorporate appropriate filtration systems, strategic landscaping, and building envelope improvements to limit the infiltration of traffic-related air pollution. Green roofs, vegetation barriers, and surrounding green spaces may provide additional environmental and health benefits while improving thermal comfort [27].

The implementation of smart building technologies represents another promising approach. Real-time monitoring systems capable of measuring carbon dioxide, temperature, humidity, particulate matter, and other environmental parameters can support evidence-based management of indoor environments. Such systems allow rapid identification of problems and optimization of ventilation and energy use [29].

5. CONCLUSION

Improving IAQ requires multidisciplinary collaboration involving public health professionals, engineers, architects, school administrators, and policy makers. National standards and regulations should increasingly incorporate health-oriented IAQ criteria into school building design, renovation, and operation. Investments in healthy school environments should not be viewed solely as infrastructure costs but as long-term investments in children's health, cognitive development, academic achievement, and overall well-being.

Future efforts should focus on integrating IAQ monitoring into routine school management practices and promoting green building strategies that simultaneously support environmental sustainability, energy efficiency, and occupant health. Such an approach is essential for creating resilient and healthy educational environments in the context of climate change and increasing urbanization.

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TOPIC 03

SUSTAINABLE STRUCTURES & CIRCULAR ENGINEERING

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

CIRCULAR ARCHITECTURAL INTERIOR SYSTEMS TRANSFORMATION: MODULARITY, DESIGN FOR DISASSEMBLY AND RECYCLABLE MATERIALS IN THE BUILT ENVIRONMENT

Viktorija Mangaroska[1]

Abstract

The transition to circular economy within built environments has revived the discussion of strategic pathway for reducing resource extraction, lowering embodied carbon, and fostering resilient local economies. Over the last decades there has been increasing research invested in the area of circular construction, in the scale of buildings. However, relatively little attention has been paid to architectural interior systems. The paper investigates the potential role of circular architectural design practices in Macedonia, based on modularity, design for disassembly and use of recyclables in architectural interior systems. It combines a systematic review of available literature from the field of circular architecture with empirical evidence from case studies of the new circular practice in local context. An engineering-based scenario assessment compares conventional practice into engineering circular scenarios. The results emphasize the potential of modular interior architectural design, reversible connections and recyclable components into improved circular performance of architectural interior systems. Architectural interior systems are itself an ideal testing ground for such changes by being replaced more regularly, due to constantly evolving designs. The case studies show that some elements of circular practice are already developing in the local context through community-based upcycling projects, municipal systems of material recovery, and small modular furniture manufacturers. The paper provides a place-based perspective to circular architecture, and offers recommendations which could be applied in the context of other small and medium-sized transitioning economies.

Key words: *Circular architectural interior design, Design for Disassembly, Modular construction, Recyclable materials, Lifecycle assessment*

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1. INTRODUCTION

The transition shift to a circular economy is defined as one of the most important challenges facing the construction sector today. Circular buildings lower resource consumption, waste generation and embodied carbon in buildings. While the operational performance has been significantly improved in the recent years, the construction materials influence during the building lifecycle have not been effectively addressed. This is very evident for the architectural interior systems which tend to be replaced more frequently and have high material flows which are not recovered at maximum potential. Partition systems, furniture, finishes and technically functional building services are often subject to numerous replacements [1].

Over the last decade, Macedonian construction industry has been characterized by a stable growth, urban regeneration, increase of commercial development and slow adaptation to the European environmental standards [2]. However, there has been still a predominance of the linear model of production and consumption in the building sector. This linear model is resulting in material flow in buildings, material extraction, use in buildings and disposal following intervention for renovation or demolition [3]. Secondary material markets remain limited and design for repair is rarely considered during the project development. Modular construction systems have yet to become part of mainstream professional practice [4]. Design for Disassembly defines function of systems circular organization where building elements can be repaired and rejoined without an enterprise loss. In addition, the materials choice is an essential factor in circular system of construction, as opportunities for modular adaptation, reversible construction and material reuse [5]. This paper investigates how the combination of three strategies: modularity, design for disassembly and recycling, can be applied towards circular architectural practice in North Macedonia [6].

Despite the research on circular construction in the building sector, relatively little empirical evidence is available regarding the implementation of circular architectural interior systems in small and medium-sized economies. There is also lack of understanding as to how modularity, design for disassembly and recyclable materials can be adopted in current architectural practice in the context of the developing market, fragmented recovery infrastructure and emergent policy context. Addressing this knowledge gap, the study aims to answer the following research questions:

- To what level can modular architectural interior systems, design for disassembly, and recyclable materials improve the environmental performance of architectural interior design compared to conventional linear approaches?
- How do existing circular design initiatives in Macedonia contribute to material recovery, product longevity, and resource efficiency within interior systems?

These research questions define the basis of the analytical framework for the study and determine the selection of methods, case studies, engineering scenarios, and evaluation criteria presented in the following sections.

2. METHODOLOGY

This research employs a mixed-methods approach, consisting of systematic literature review, an empirical case-study investigation, engineering scenario modelling, and comparative lifecycle assessment [7]. Blending qualitative and quantitative approaches enables this study to examine circular design from engineering and practice-oriented approach [7] [8]. The research was conducted in five sequential stages, each shaping the subsequent stage. The results of the review of literature provided the conceptual framework to examine the engineering principles behind circular designs. This guided the selection of empirical case studies, the construction engineering scenarios and interpretation of environmental performance indicators. The first stage was a systematic review of academic literature, technical guidance documents and European policy concerning circular economy practices in the built environment. Special focus was made to research the modular construction systems, design for disassembly, recyclable and bio-based materials and life cycle assessment. Literature review was based on peer-reviewed journal articles, technical reports, design manuals and policy documents which offered methodological or regulatory background. The second stage drew on empirical evidence from North Macedonia through a multiple case-study technique. Its selection, based on Yin's [9] proposition, was not driven by a statistical representation of construction activity, but on a complete implementation of a circular designs strategy-such as material reuse, modular manufacturing, design for disassembly or municipality material recovery programs. Community-based upcycling schemes, small-scale interior design and furniture manufacturing as modular products, provide material recovery during building refurbishment. They were analyzed using the same analytical framework by material properties, degree of modularity, disassemblarity, maintenance, reuse potential and institutional endorsement. The third stage established an engineering-scenario model to compare architectural interior alternative approaches. Three scenarios of the Case studies were established to represent increasing levels of circular implementation. The scenarios were evaluated using performance indicators commonly reported in circular construction research [10]. Circularity of materials flows was visualized through Sankey-diagrams and comparisons of linear and circular systems represented through engineering graphs distinguishing between modular and traditional interior products. This smart visual presentation enhanced interpretation of the numerical outcomes and exposed the dynamics between interior design choices, material circulation and lifecycle performance [11]. The final stage integrated the engineering findings with empirical case studies and stakeholder consultations with architects, municipal authorities, furniture manufacturers and organizations involved in circular design in order to overcome technical implementation barriers and promote adoption of circular architecture principles [12].

2.1. Case Studies: Circular Architectural Interior Systems in Macedonia

2.1.1. Case Studies Context

The case studies in reveal the context in North Macedonia through which the early adoption of circular architectural design has taken place. Although the country lacks well-established circular construction market like most other European countries, national building sector continues to be structured on traditional linear approaches [13]. The construction sector is comprised of small and medium-sized enterprises, where the wood-processing sector is one of the country's most well-established manufacturing industries. It consists of rapidly growing network of designers, architects, artists, civil and non-governmental organizations that begin to organize and reuse modular production. The cases correspond to the complementary dimensions of the transition: community-based education, public-sector implementation and private-sector innovation. Analyzed together, they provide a broader understanding of technical, institutional and social conditions influencing circular architectural design.

2.1.2. Case Studies of Circular Architectural Interior Systems in Macedonia

Case Study 1: The TUDEC (Through Upcycling to Design of Ecocities) educational program is an example of how community and school workshops can build circular material literacy. TUDEC prototypes small furniture and city fixtures made from upcycled timber, metal drums, and bicycle inner tubes to demonstrate flows of local material [14]. This case study is an example of community upcycling programs run by design collectives in Skopje involved in transforming reclaimed wood, metal, and bio-materials into interior accessories and small furniture. These projects highlight similarities with other worldwide upcycling initiatives to illustrate urban waste flows into circular design practice.

Case Study 2: Municipal pilots in Skopje, reusing modular partition retrofits and reuse programs, presents case study of municipal architectural interior design. These pilots catalogued reclaimed doors, timber panels and modules, reintegrating them into lower-demand public spaces. The pilots illustrate procurement levers and the role of municipal demand in developing reuse markets [15]. This case is a municipality-led circularity pilot in Skopje focusing on material recovery from public buildings. Construction waste such as salvaged wood, metal partitions, glass, and usable interior fittings were documented and partially reintegrated into public buildings. The ecological value of this initiative demonstrates how municipal infrastructure can model circular procurement practices consistent in the EU public procurement guidelines. It represents the volume of materials they reintroduced and the procurement leverage. Local authorities are typically among the largest building clients and their material purchases influence local market circulation.

Case Study 3: Small workshops clusters in Skopje: ModulArt reuses wood offcuts and by-products from industries for their modular furniture kits using reversible fasteners. These kits are designed for local assembly, repairability, and material recovery, demonstrating commercial circular-product pathways. Their objective is local

installation, local rehabilitation and reuse by following commercial circular-product pathways [16]. ModulArt crafts up-cycled modular furniture wood materials form local manufacturers. The modular re-used wood materials are used form local producers. Their modular furniture up-cycled wood joinery and reversible fasteners provide practical examples of design for disassembly adapted to the Macedonian artisan context [17]. Case studies illustrate that transition towards circular architectural interior design is occurring through multiple and interconnected processes rather than through a single policy initiative or technological innovation.

3. RESULTS

3.1. Engineering Scenario Assessment

The scenario analysis demonstrates significant environmental and material benefits from applying modularity, design-for-disassembly, and use of recyclable materials in circular interior design of the case studies. The examination of the case studies revealed upcycling and maket-based approach which increased public awareness, strengthened repair culture, and expanded aesthetic acceptance of reused materials. Municipal pilots demonstrated institutional capacity, though they require scaling through policy reform. The scenario modelling produced quantitative contrasts among the three scenarios. Material recovery rates rose from an estimated baseline of 10–15% in Scenario C1 with the traditional linear ModulArt case study to 35–45% under partial circularity Scenario C2 with the Municipal pilots in Skopje and exceeded 60% under design for disassembly circularity Scenario C3 with the TUDEC case study in Skopje. Product lifespans increased substantially under circular scenarios. Modular components exhibited lifespan extensions of 40–70% due to ease of repair and remanufacture, while circular systems facilitated multiple reuse cycles. *(Table 1).*

Table 1. Scenario Comparison Model Curves among the three Case Studies in Macedonia

Scenario	Case Study Context	Curve Description	Impact Trajectory
Scenario C1: Linear	Traditional, Linear, non-modular construction, minimal reuse/recycling.	The impact line is high with marginal changes over the lifecycle.	Marginal Improvement
Scenario C2: Partial Circularity	Municipal Pilots in Skopje	The impact line is lower than A and shows a faster descent, especially after the Production stage.	Accelerated Reduction
Scenario C3: Fully Circular	TUDEC or integrated Workshop Cluster model (modularity + design for disassembly + upcycling).	The impact line is the lowest, showing the steepest descent impact at lifecycle assessment	Steepest Descent/Compounded Benefits

The Scenario comparison model curves plots environmental impact index was developed by representing the lifecycle stages for the three scenarios. [18] The curves demonstrate that linear systems Scenario C1 with the ModulArt case study show marginal improvements over time due to minor efficiency, while partial circularity in Scenario C2 at the Municipality pilots case study accelerates the impact reductions through targeted modular upgrades and recycled content. Fully circular systems in Scenario C3 at the TUDEC case study achieves the steepest descent in impact, illustrating compounded benefits from combined strategies of modularity, design for disassembly and recyclability. In the selected case Studies, circularity leads to a faster reduction in environmental impacts, re-usable building components and repeated circularity of materials. The comparison of these scenarios implies that cumulative advantages are secured by adopting various circular principles in a rational design model. Adoption of multiple circular practices by comparison effectively facilitates replication and improvement, which supports the overarching systems approach adopted in this study. *(Figure 1)*

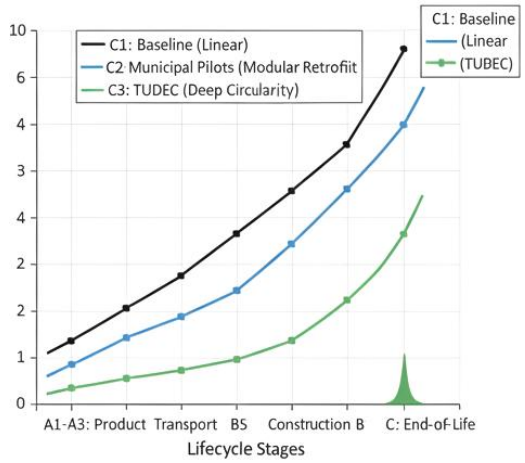


Figure 1. Scenario Comparison Model Curves for selected Skopje Case Studies, North Macedonia

3.2. Sankey Diagram Method

The material flows were investigated with the Sankey-based method analysis, comparing the conventional, linear practice with the proposed circular design scenario. This method illustrates the material flows of wood, metal, plastic and biocomposites within interior architectural systems and compares the two scenarios in terms of potential recovery via reuse, repair, remanufacturing and recycling. The case studies provide practical example of emerging circular practices of selected case studies in Macedonia, where municipal refurbishment projects present potential recovery of architectural components. The repair, upgrading of materials and modular product development represent practical implementation of community and locally owned furniture manufacturing into circular design practice [19]. The circularity of materials: reuse product stream: material flow of wood and metal is directed back into the use phase with modular furniture kits, and recycling stream: material is sent for reprocessing into secondary raw material, residual landfill. The Sankey based analysis

illustrates the impact of more strategic design and recovery actions for a more sustainable resource circulation strategy for interior architectural systems *(Table 2).*

Table 2. Sankey Material Flow Diagram Method

Case Study	Intervention Node in Diagram	Description of Flow
Case Study 1: TUDEC	Non-modular Upcycling Demolition Waste	Informs the initial design phase, promoting the diversion of waste materials (timber and metal drums) and feeding them to upcycling streams.
Case Study 2: Municipal Pilots	Municipal Pilots Modular Reuse	Represents the municipal program where reclaimed doors, timber panels, and modules are reintegrated into public spaces. This interrupts the largest demolition waste flows.
Case Study 3: ModulArt	ModulArt Upcycling	Represents clusters that process smaller fractions like wood offcuts and production residues into new products (modular furniture kits), demonstrating a commercial circular pathway.

3.3. Modular vs Non-modular Comparison Chart Method

The engineering assessment of non-modular versus modular architectural interior systems in the case studies in Macedonia, demonstrates tangible implications of circular design strategies. The following chart directly compares the performance of a non-modular construction and modular scenario representing the specific outcomes of the Skopje case studies. The collected data from the circular interior design case studies of municipal retrofits present the modular design columns. The visual chart compares the case studies environmental performance indicators between the non-modular baseline TUDEC and the circular approach modular scenario that integrates the benefits from the Municipal Pilots, and ModulArt workshop activities in the case studies in the city Skopje, North Macedonia *(Figure 2).*

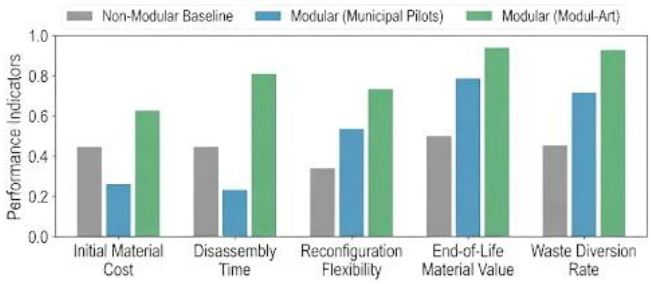


Figure 2. Modular vs Non-Modular Comparison Chart for the selected Skopje Case Studies

The assessed indicators of the circular modular systems in the case studies provided better environmental performance. The maximum savings for the modular systems were reached for embedded carbon and primary energy demand, due to modular reuse design, by increasing its lifetime and reducing replacement measures. The comparison indicates that modular circular interior systems achieve higher material recovery rates than conventional interior assemblies.

4. DISCUSSION

Engineering results demonstrate integrating modularity, design for disassembly, and recyclable materials into architectural interior design practices in the context of an emerging circular economies. The scenario analysis offered a coherent answer for the first research question, by showing how the adoption of modular system solutions, design for disassembly and recyclable materials lead to significant improvements of the environmental performance of architectural interior systems in comparison with traditional linear design [20]. Findings from the case studies of the empirical research, offered answers to the second research question on the critical barriers affecting the development of circular architectural design in Macedonia. These case studies, which include small-scale architectural interior refurbishments, adaptive reuse of commercial spaces, and locally fabricated modular furniture systems, demonstrate that circular practices already exist. The central finding of the municipal pilots in Skopje is that modular architectural interior retrofits significantly increase spatial adaptability while reducing material waste. Offices and public service spaces that adopted demountable partitions were able to reconfigure layouts without demolition of interior systems.

The paper has contribution to the circular construction literature by developing integrated assessments of circular architectural interior systems in diverse Southeast European context [21]. The material flow analysis of the case studies revealed that most interior components in architectural design still enter linear waste streams at the end of their use phase. This finding directly supports the need for policies that promote deconstruction over demolition. Municipal regulations should mandate selective disassembly for interior renovations above a certain scale, and financial support should be provided for the establishment of local material recovery hubs. Policy instruments should explicitly reward modularity and reversibility through tax incentives, or green certification schemes. By linking modularity to environmental performance metrics, these policies would make adaptability a recognized sustainability asset rather than a purely operational choice. In summary, the selected case studies in North Macedonia demonstrate that the policy recommendations articulated here are targeted structural interventions responding directly to observed conditions by reforming procurement systems, stabilizing innovation through public support, restructuring financial mechanisms and reframing architectural education.

5. CONCLUSION

The study explores the potential of the circular modular architectural interior design, design for disassembly and recyclable materials towards the transition to a circular built environment in Macedonia. Towards this aim, a systematic review of existing literature, engineering scenario modelling and empirical case studies were employed. The study demonstrated that architectural interior design is a technically possible as well as pragmatic method for a circular economy in developing countries. The engineering assessment presents the utilization of a modular design solution with Design for disassembly and recyclable materials could significantly enhance environmental

performance through material recovery, prolonging product lifetime and embodied carbon reduction, with these largely delivered via means of maximum material value retention with reuse, repair and adaptation, rather than mainly end-of-life recycling. Although the investigated case studies confirm that circular design solutions are technically achievable, their wider adoption is constrained by fragmented regulations, procurement systems focused on initial cost, limited recovery infrastructure and underdeveloped secondary-material markets. These findings reinforce the view that circular construction should be understood as a socio-technical transition requiring coordinated change across policy, industry and professional practice. The research highlights that with the appropriate policy and professional guidance, North Macedonia has the capacity to change architectural interiors from large-volume consumers of resources into a resource-efficient built environment, by developing larger paradigm change necessary to enable a transition to a sustainable, resilient and resource-efficient built environment.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

OLD SHIPPING CONTAINERS AS A RESOURCE FOR SUSTAINABLE AND CIRCULAR CONSTRUCTION OF MULTI-STOREY BUILDINGS

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Abstract

The construction sector is one of the largest consumers of natural resources and a significant source of carbon dioxide emissions. In recent decades, more and more attention in this sector has been paid to the application of the principles of sustainable construction and the circular economy. In this context, the reuse of existing materials and construction elements becomes an important strategy for reducing the negative impact of the construction industry on the environment. Old shipping containers are one of the potential resources for such an application. Thanks to their structural characteristics, modularity, durability and standardized dimensions, shipping containers can be successfully repurposed into modular building units for the construction of multi-storey buildings of various purposes. Their application contributes to reducing the amount of waste, more rational use of resources, shortening the construction time and reducing the need for the production of new building materials. The aim of this paper is to consider the possibilities of using old shipping containers as a secondary construction resource in accordance with the principles of circular economy and sustainable construction. Special attention is paid to the analysis of environmental benefits, the potential for the integration of Green Building principles, as well as the challenges that accompany the application of this concept in the construction of multi-storey buildings.

Key words: *shipping containers, sustainable construction, circular economy, modular construction, multi-storey buildings*

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1. INTRODUCTION

Contemporary architecture and civil engineering face numerous challenges arising from intensive urbanization, climate changes and increasing consumption of natural resources. World statistics indicate that the impact of buildings and available infrastructure on the environment is manifested through the use of over 40 % of total energy consumption, 35 % of natural resources, 14 % of drinking water and over 39 % of carbon dioxide emissions [1]. Therefore, sustainable construction becomes one of the key priorities of modern society. The concept of sustainable development is based on meeting the needs of current generations without jeopardizing the ability of future generations to meet their needs [2]. In the field of architecture and civil engineering, this means efficient use of space, energy and materials, application of renewable energy sources, reduction of negative impact on the environment and improvement of the quality of life in buildings in general [3]. The concept of the circular economy has acquired a special attention in recent years as well. Achieving the circular economy targets is not an easy task in the construction sector. Concerns have been raised about the availability of materials for future demand of new construction, refurbishment and renovation [4]. However, the construction industry has a great potential for the use of existing construction components and industrial products that can be given a new purpose after the end of their original function. One of such products is shipping containers. Every year, a large number of containers end their working life in the international transport of goods. Instead of energy-intensive recycling, which leads to additional carbon dioxide emissions, shipping containers can be directly reused in construction. Owing to their steel construction, high load capacity, resistance to weather conditions and standardized dimensions, shipping containers represent suitable modular units for the construction of various types of buildings. Particularly interesting is their application in multi-storey buildings, where the modular principle enables quick construction, flexibility of design and reduction of the construction waste [3, 5].

The aim of this paper is to consider the possibilities of using old shipping containers as a resource for sustainable and circular construction of multi-storey buildings. A special focus is placed on the contribution of this concept to the reduction of negative impacts of building construction on the environment, as well as on its compliance with the principles of the Green Building approach.

2. THE CONSTRUCTION INDUSTRY AND PRINCIPLES OF CIRCULAR ECONOMY

The construction industry is one of the most important economic branches of modern society, but at the same time one of the largest consumers of natural resources. Also, the construction sector contributes to the creation of large amounts of waste and emissions of harmful gases that affect climate changes. The traditional model of development based on the linear principle of "take-make-waste", proved to be unsustainable in the long term, due to limited natural resources and the increasing burden on the environment. In response to these challenges, the concept of circular

economy has been developed. The main goal of the circular economy is to extend the life of products and materials through their reuse, renewal, repurposing and recycling [6], which would result in minimizing waste and maximizing the use of existing resources. In civil engineering, the application of the circular economy implies the use of recycled and renewable materials, the design of buildings with the possibility of disassembly and reuse of elements, the reduction of construction waste and the extension of the life of existing structures. A particularly important place is occupied by the adaptive repurposing of existing products and structural systems, which avoids the need for the production of new materials and additional energy consumption. Furthermore, including waste management in the planning process is essential for a holistic approach to enable the potential for reuse and creation of high-quality products and implement waste management systems [7]. The modern concept of sustainable construction is based on these principles. Sustainable buildings are not only viewed through energy efficiency during service, but also through the entire life cycle of the materials and constructions incorporated in them. In this context, materials and systems that enable the reduction of embodied energy, carbon dioxide emissions and the amount of waste during the construction and use of buildings are becoming increasingly important.

The reuse of shipping containers is one of the examples of successful application of circular economy principles in construction. Instead of becoming waste or raw material for recycling at the end of their transport life, containers can be used as ready-made modular building units with significant constructive potential [3, 5].

3. SHIPPING CONTAINERS AS A RESOURCE FOR CIRCULAR CONSTRUCTION

Shipping containers are designed for long-term use in the demanding conditions of international transport. During their service life, they are exposed to heavy loads, aggressive climatic conditions, sea water and frequent manipulations. Despite this, their steel structure allows a high degree of resistance and a long service life. After approximately ten to fifteen years of use in the transport industry, a large number of containers become economically unprofitable for further use. As a consequence large amounts of unused containers are formed in many ports around the world, which is a potential waste [3, 5]. From the perspective of sustainable development, these containers can be seen as a valuable resource for circular construction and sustainable building practice. Their basic structure already has a significant load capacity, resistance to external actions and the possibility of connection into larger structural assemblies. Thanks to the standardized dimensions, it is possible to design modular systems of different sizes and purposes. The basic ISO dimensions of the containers allow them to be easily combined in the horizontal and vertical direction. Container walls can be partially removed to form larger spatial units, while multiple containers can be connected into unique functional modules. In this way, it is possible to design residential, business, educational, tourist and public buildings [3]. A special advantage is that the containers are already manufactured industrial elements. Their reuse eliminates the need for the production of new structural components, thus reducing

the consumption of raw materials, energy and emissions associated with the production process. In addition, the modular nature of the containers allows a high degree of prefabrication. Most of the construction works, including the installation of installations, thermal insulation, finishing coatings and equipment, can be carried out in the controlled conditions off-site [3]. This increases the quality of the works performed, shortens the construction time and reduces the amount of waste on the construction site. The possibility of disassembly and reuse is an additional advantage compared to conventional buildings. At the end of the building lifetime, individual modules can be moved, reconfigured or reused in another location, further extending their life cycle.

4. CONTRIBUTION OF SHIPPING CONTAINER REUSE TO SUSTAINABLE CONSTRUCTION

The use of old shipping containers in the construction of multi-storey buildings brings a number of ecological benefits that are in line with modern principles of sustainable construction and circular economy. One of the most important advantages is reducing the amount of waste. Instead of disposing of or recycling a large number of containers, their repurposing enables the direct extension of the life cycle of the existing product. Another important aspect is related to the reduction of consumption of natural resources, since the containers are already made structural elements. In particular, the need for the production of new steel elements is reduced, which contributes to the preservation of natural resources. An important contribution is reflected in the reduction of carbon dioxide emissions. Steel production is an energy-intensive process with significant CO_2 emissions. Reuse of existing steel structures avoids part of the emissions that would occur during the production of new building materials. This approach contributes to reducing the overall carbon footprint of the construction sector. In addition, steel recycling is also a process with CO_2 emissions. For example, when recycling 100 kg of steel, the emission of CO_2 is about 35 to 70 kg, depending on the source of electrical energy [8]. An additional advantage comes from a shorter construction time. Shorter construction time means less energy consumption, less use of construction machinery and less negative impact on the environment of the construction site.

Table 1 shows a qualitative comparison of the basic characteristics of conventional and container construction from the sustainability aspect based on the reviewed literature and previous knowledge. The purpose of this comparison is not to provide a quantitative environmental assessment but to synthesize the main characteristics discussed across previous studies. The comparison indicates that container construction demonstrates advantages particularly regarding material reuse, modularity and compatibility with circular construction principles. However, environmental performance remains dependent on project-specific factors, technical adaptation measures and compliance with regulatory requirements.

From the aspect of sustainable urban development, container buildings can represent an effective solution for various housing needs, including social housing, student housing and affordable urban residential units. Given the growing number of

implemented container-based projects worldwide, two selected examples are presented in this paper to illustrate the application of reused shipping containers in multi-storey buildings. These are the student housing projects "Keetwonen" in Amsterdam, Netherlands (Fig. 1) [9] and "Cité A Docks" in Le Havre, France (Fig. 2) [10]. Container-based buildings may also provide temporary accommodation solutions following natural disasters. Their flexibility enables adaptation to different user needs and changing conditions over time.

Table 1. Comparison of sustainable characteristics of conventional and container construction

Sustainability aspect	Conventional Construction	Container Construction
Consumption of virgin materials	Higher	Reduced through reuse
Construction waste generation	Higher	Lower
Embodied environmental impact	Higher	Potentially reduced
Construction speed	Standard	Very high
Prefabrication level	Limited	High
Adaptability and reuse potential	Limited	High
Circular economy compatibility	Moderate	High
Potential for modular expansion and adaptation	Limited	Very high
Compatibility with green building strategies	Applicable	Highly compatible
Resource efficiency	Moderate	Increased



Figure 1. Keetwonen, [9]



Figure 2. Cité A Docks, [10]

5. INTEGRATION OF CONTAINER BUILDINGS WITH GREEN BUILDING PRINCIPLES

The concept of Green Building implies the design, construction and use of buildings in a way that minimizes negative impacts on the environment during the entire life cycle of the building. In addition to the rational use of energy and water, special importance is attached to the choice of materials, the reduction of harmful gas emissions and the improvement of the quality of the indoor environment [1]. Thanks to their characteristics, buildings built from old shipping containers can successfully meet a large number of requirements of modern sustainable construction. Their main

advantage is reflected in the fact that they represent an example of direct reuse of an existing product, thus realizing one of the basic principles of the circular economy. However, the sustainability of these buildings does not only result from the reuse of containers. Additional design measures can significantly improve their energy and environmental performance. One of the most important measures is the application of quality thermal insulation. The steel container walls have high thermal conductivity, which is why it is necessary to provide adequate protection against heat loss during the winter and overheating during the summer period. Modern insulation materials enable achieving a high level of energy efficiency and creating a pleasant interior environment. The authors of the paper [11] have evaluated case studies of existing shipping container buildings incorporating net-zero strategies. The study reveals that residential buildings have remained the focal point of net-zero energy buildings, while commercial buildings receive insufficient attention despite their high energy consumption. Renewable energy sources play a particularly important role. The flat roof surfaces of container buildings are suitable for installing photovoltaic panels and solar collectors. In this way, part of the required energy can be produced at the building itself, which reduces dependence on conventional energy sources and carbon dioxide emissions. Green roofs represent another measure that can contribute to the sustainability of container buildings. Green roofs are generally built to enhance the energy efficiency of their buildings, but many other benefits exist [12]. In addition to improving thermal insulation characteristics, the vegetation layer contributes to retaining storm water, reducing the effect of urban heat islands and improving the biodiversity of urban environments. An important aspect of sustainability also relates to the management of water resources. By integrating the system for collecting and using rainwater on the roof top of container buildings, it is possible to reduce the consumption of drinking water for irrigation of green areas, technical water and other secondary purposes. Rainwater Harvesting (RWH) is probably the most ancient practice in use in the world to cope with water supply needs. In urban areas, RWH consists of the concentration, collection, storage and treatment of rainwater from rooftops, terraces, courtyards, and other impervious building surfaces for on-site use [13]. Natural ventilation and optimal orientation of the building can also contribute to reducing energy consumption. By designing suitable openings, shades and ventilation systems, it is possible to improve the quality of the indoor environment and reduce the need for mechanical cooling and ventilation. By combining the above measures, container buildings can achieve a high level of sustainability and represent a competitive alternative to traditional building systems within the modern Green Building approach. In order to better understand ecological benefits and challenges of container construction, a comparative analysis was carried out between the pioneering and world's largest student’s container settlement Keetwonen, Fig. 1 and the more aesthetically advanced Cité à Docks project, Fig. 2. The analysis results are given in the Table 2, as well as the short interpretation about each parameter. The comparison also includes an indicative estimation of avoided CO_2 emissions associated with container reuse instead of recycling. Estimated avoided CO_2 emissions are based on a simplified calculation using the number of reused shipping containers and average emissions associated with container recycling [8]. This simplified calculation is intended solely to

illustrate one of the potential environmental benefit of container reuse and does not represent LCA. Although both projects use the same basic module, their green building philosophies and technical solutions differ drastically. While Cite a Docks successfully addresses the issues of aesthetics, natural light, and microclimate through its open form, Keetvonen wins in fundamental Green Building disciplines: ecological water management, construction speed that minimizes site pollution, and ability to be completely disassembled and relocated without creating construction waste. This comparative overview indicates that the reuse of shipping containers can support sustainable construction through different mechanisms depending on the project context and intended function.

Table 2. Comparative analysis of the selected container buildings from the sustainability perspective

Parameter	Keetwonen	Cité à Docks	Interpretation
Construction year	2005.	2010.	Keetwonen - one of the pioneers of container construction
Place	Amsterdam, Netherlands	Le Havre, France	Cité à Docks - a short way of transporting old containers
Purpose	Student housing	Student housing	The same
Container type	ISO Standard 40’	ISO Standard 40’	The same
Number of storeys	5	4	Keetwonen 1 storey higher
Project scale	1034 modules (Biggest in the world)	100 modules (Smaller scale)	Scale vs architectural refinement
Structural system	Containers stacked on top of each other	Containers supported by the steel structure	Cité à Docks needs new steel
Net module area	28 m^2	25 m^2	Keetwonen offers slightly higher spatial comfort
Construction speed	Extremely fast (150 apartments per month)	Slower construction due to complex on-site assembly and insulation	Keetwonen reduced on-site construction activities
Estimation of avoided CO_2 emissions resulting from container reuse instead of recycling	~ 2000 kg x 1034= 2068 t of CO_2	~ 2000 kg x 100= 200 t of CO_2	Greater estimated potential for avoided recycling-related CO_2 emissions
Management of water	Integrated system for rainwater drainage on the roof	Standard city drainage network	Keetwonen has more advanced ecological water management
Module mobility	High - the complex was disassembled and the modules were relocated	Low - building is fixed to a location	Keetwonen better supports circular construction principles

6. LIMITATIONS AND CHALLENGES

Despite numerous advantages, the application of old shipping containers in the construction of multi-storey buildings faces certain technical, functional and regulatory challenges. One of the most important problems is related to the thermal characteristics of the steel structure. The structure of the container, should be considered in achieving indoor thermal comfort [14]. Steel conducts heat very quickly, which can lead to large temperature fluctuations in the interior if adequate thermal insulation is not provided. That is why the quality of the building envelope design plays a key role in achieving energy efficiency. An additional challenge is the occurrence of corrosion. Although the containers are designed to work in demanding transport conditions, long-term service and eventual mechanical damage can lead to the onset of corrosion processes. Therefore, it is necessary to carry out a detailed assessment of the condition of each container before its conversion. From a structural point of view, the removal of parts of the walls to create larger rooms can affect the load-bearing capacity of the structure. In such cases, additional structural reinforcements are necessary to ensure the safety and stability of the building. Fire protection is another important issue. Although steel is a non-flammable material, at high temperatures its mechanical characteristics decrease. Therefore, it is necessary to provide appropriate fire protection measures in accordance with current regulations. In addition to technical aspects, certain obstacles also exist at the social level. A part of the professionals and general public still associates container buildings with temporary or low-quality solutions [5]. Such prejudices often represent an obstacle to their wider application, despite the fact that modern projects show a high level of architectural and functional value. Finally, in most countries there are not sufficiently developed legal regulations that would precisely define the design and construction of buildings made of shipping containers. The lack of specific standards can complicate the process of designing, obtaining construction permits and realizing such projects. The American IBC standard is currently the only example in the world where the state consciously created a special legal apparatus just for this type of buildings, while in the rest of the world (like in the EU) general standards on steel structures, such as EN 1993 and technical material standards apply. While the USA offers ready-made type solutions and clear amendments for container architecture, in the rest of the world the principle of individual engineering calculation and adaptation to general regulations for traditional steel buildings is applied. The American International Building Code (IBC) is one of the most developed regulatory approaches for repurposed intermodal shipping containers which are recognized within the Section 3115 [15]. Since the 2021 edition, Section 3115 includes specific provisions related to documentation, structural verification, fire safety, foundations and design requirements for shipping containers used as permanent buildings. In practice, containers must demonstrate compliance with applicable structural, thermal and safety requirements after modification. Additionally, reused containers generally rely on international container standards such as ISO 668 [16] for dimensions and load ratings, ISO 1496-1 [17] for structural durability testing and ISO 6346 [18] for identification and traceability of shipping containers. All of the above indicates that the wider implementation of container-based construction may require

further adaptation of existing regulatory frameworks and the development of more specific guidelines to support the sustainable reuse of shipping containers in the construction sector.

7. CONCLUSION

Contemporary challenges of sustainable development require finding new approaches to the design and construction of civil engineering structures that will enable a more efficient use of natural resources and reduction of negative impacts on the environment. The analysis presented in this paper shows that shipping containers have numerous characteristics that make them suitable for use in the construction of multi-storey buildings. Their modularity, load capacity, standardized dimensions and the possibility of prefabrication enable more efficient construction compared to many conventional construction systems. The special value of this approach is reflected in extending the life cycle of existing industrial products, reducing the amount of waste, more rational use of material resources and reducing the need for the production of new building elements. The comparative overview of conventional and container construction (Table 1), together with the comparative analysis of representative container buildings (Table 2), further confirms the sustainability potential of container buildings while highlighting their practical opportunities and limitations. In addition, the overview of the existing regulatory framework indicates that wider implementation of this construction approach will require further adaptation of regulations and the development of more specific technical guidelines. Additional integration of renewable energy sources, green roofs and rainwater harvesting systems can further improve environmental performance; however, it is still necessary to address thermal insulation, corrosion protection and fire resistance. The sustainability of container buildings does not result solely from the reuse of containers, but also depends on the quality of design solutions, the choice of materials and the way the building is used during its lifetime. Based on the presented review, it can be concluded that old shipping containers represent a valuable secondary construction resource with significant potential for application in sustainable and circular construction of multi-storey buildings. Their wider application can contribute to reducing the negative impacts of the construction industry on the environment and represent one of the possible directions for the development of future green cities.

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Research paper

RUBBERIZED CONCRETE AS A SUSTAINABLE AND GREEN BUILDING MATERIAL

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Abstract

The global environmental problems facing the world today largely stem from the excessive exploitation of natural resources. An increasing number of world studies aim to find ways to replace natural resources, introducing new building materials that utilize plants, polymers, and industrial or municipal waste. On the other hand, approximately 90% of waste tyres end up in landfills, meaning there is no designated plan for their further utilization. One of the various solutions for reducing tyres waste and protecting the environment involves using waste tyres in green building materials. This study investigates the properties of concrete mixtures in which a portion of the fine aggregate is replaced by waste rubber particles, with the aim of reducing existing waste and the need for natural aggregate. For the purposes of this paper, 4 different mixtures were tested that differ in the percentage of rubber: replacements of 0, 15%, 30% and 50% of the aggregate with waste tyre by volume. Consistency of the fresh concrete decreased as the percentage of waste rubber increases, as well as the bulk density of hardened concrete, resulting in lightweight building materials. The strength properties and water resistance of the tested samples also decreased with the increase of the rubber waste percentage. The results indicate that increasing the waste rubber in concrete mixtures has a significantly more adverse effect on compressive strength and water impermeability than on flexural strength. However, despite the reduction in strength caused by the use of rubber in the concrete, concrete with a high content of rubber particles (50%) would be suitable for non-load-bearing elements, whereas lower contents (15% and 30%) remain viable for structural applications. The positive properties of concrete with waste rubber are highlighted, their application is suggested.

Key words: *Rubberized Concrete, Waste Rubber, Green Building Materials, Sustainability*

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1. INTRODUCTION

The global environmental problems facing the world today largely stem from the excessive exploitation of natural resources by humans. An increasing number of studies aim to find ways to replace natural resources, introducing new construction materials that utilize plants, polymers, and industrial or municipal waste [1]. The goal is achieving lower bulk density and a more favourable thermal conductivity, while simultaneously maintaining strength properties comparable to those of traditional building materials.

Since vehicles have become an essential means of transport, there is a proportional increase in the number of tyres that have reached the end of their service life, i.e. that are no longer functional. This type of waste has been a prominent subject of research in recent years because is difficult to reuse or recycle. Approximately 90% of waste tyres end up in landfills, meaning there is no designated plan for their further utilization. One of the various solutions for reducing tyres waste and protecting the environment involves using waste tyres in sustainable building materials. In recent years, there has been significant scientific research focused on using waste tyres as a raw material in cement-based composites—specifically, concrete and mortar.

Ahmad et al. [2], Adwan & Alzubi [3], Bu et al. [4], Marinelli et al. [5], Motloq et al. [6], and others have investigated the potential of using specific quantities of waste rubber and its effect on concrete properties. Due to their exceptional strength, flexibility, and stress-control attributes, rubber granules are commonly used in cementitious composites as a replacement for fine (≤ 4.75 mm) and coarse (≤ 20 mm) aggregates. The literature confirms that the inclusion of rubber effectively improves concrete workability, [5]. Due to the poor bond between the cement matrix and the rubber, many researchers choose to treat rubber particles with 10% NaOH before incorporating them into the concrete [7]. Furthermore, when smaller rubber particle sizes are used, the concrete exhibits a lower wear depth. Compared to gravel particles, the compact and dense rubber-concrete matrix is more advantageous because the addition of rubber creates fewer voids than in conventional concrete, thereby reducing the depth of carbonation. Recycling rubber waste eliminates the need for tyre disposal, which is one of the major environmental challenges of the future [4].

Around 3.5 million tonnes of waste tyres are generated annually in Europe. Although Europe boasts the highest rate of waste tyres collection (approximately 95%), changes in environmental legislation and inadequate waste management capacity are creating a major problem [2]. Data regarding municipal waste for the period from 2020 to 2024 in Macedonia, obtained from the national State Statistical Office [8], is given in Table 1.

Table 1. Municipal waste in Macedonia 2020–2024, [8]

Municipal waste in Macedonia 2020 - 2024					
	2020	2021	2022	2023	2024
Total quantity of collected waste	630 086 t	632 087 t	605 638 t	621 686 t	627 471 t
Tyre waste	1005 t	1598 t	1478 t	1301 t	1136 t
Waste deposited at landfill	99,80 %	99,80 %	99,80 %	99,80 %	99,80 %

Although the volume of tyre waste appears insignificant compared to Europe, we frequently witness piles of untreated, stockpiled tyres as well as numerous illegal landfills across the country. There is no doubt that greater emphasis needs to be placed on this issue in the future.

Given the relevance of the topic and the aforementioned reasons, the aim of this study is to evaluate the potential use of waste vehicle tyres while simultaneously reducing the consumption of natural aggregates in concrete. Several concrete mixture formulations were prepared, incorporating waste rubber aggregate at levels of 0%, 15%, 30%, and 50%. The properties of the concrete mixtures (fresh concrete consistency) and the properties of the hardened concrete (bulk density, compressive strength, flexural strength, and water impermeability) were evaluated.

2. MATERIALS AND METHODS

2.1. Materials

Several types of mix designs were prepared for the concrete mixtures, incorporating waste rubber aggregate at levels of 0%, 15%, 30%, and 50% of the fine aggregate. Table 2 shows the quantity of material required to produce 1 m³ of concrete.

Table 2. Mix design for C30/37 with CEM II/A-LL 42.5 R (1 m³)

Aggregate fraction [kg]				cement [kg]	water [kg]	admixture [kg]	rubber [kg]
0/4mm	4/8mm	8/16mm	16/32mm				
740	220	480	340	380	190	2.5	/

The concrete mixture was prepared in accordance with MKS EN 12350-1 [9]. A total of nine concrete cubes (15/15/15 cm) and two concrete prisms (10/10/50 cm and 15/15/60 cm) were produced for each mixture. Consequently, a volume of 0.0709 m³ of concrete was required for each mixture to produce the necessary number of specimens. To replace 15%, 30%, and 50% of the fine aggregate in the tested specimens, quantities of 2.11 kg, 4.23 kg, and 7.04 kg were used, respectively.

Portland cement CEM II/A-LL 42.5 R was used to prepare the mix designs presented in this paper. Its composition consists of 80–94% clinker, 6–20% limestone, and 0–5% other constituents. It has a strength class of 42.5 MPa and exhibits high early strength. Two different types of aggregate were used: river aggregate (0/4 mm) from the Aradiko Kop Skopje processing plant. In accordance with the MKS EN 1097-3 [10] standard, with bulk density of 1590 kg/m³, and crushed limestone aggregate (4/8, 8/16, and 16/32 mm) from the In Mak Kumanovo quarry. Water from the Skopje municipal water supply system was used to prepare the concrete mixtures.

Ading's SUPERFLUID 21M1M was used in the preparation of the concrete mixtures. It enables a high degree of water reduction in the concrete and the production of concrete with high consistency classes. The admixture was 0.65% of the cement mass.

A waste tyre is defined as a tyre that has reached the end of its useful life and is discarded—or intended or required to be discarded—by the end user. For this research,

the raw material was supplied by the company "Uni-Royal Kompani" from Prilep, Fig.1. In accordance with the MKS EN 1097-3 [10], the bulk density of the waste tyre material was determined to be 395 kg/m³.



Figure 1. Finely chopped waste rubber



Figure 2. Determination of consistency (Source: Authors)

2.2. Methods

The consistency of fresh concrete is determined in accordance with MKS EN 12350-2 [11], as presented in Fig.2. The tested samples were taken in accordance with MKS EN 12350-1 [9].

The density of hardened concrete is determined in accordance with MKS EN 12390-7 [12]. The standard offers two methods for calculating the specimen volume: by water displacement and by calculation based on measured dimensions, taking into account prescribed tolerances. In this test, the volume of the concrete specimens was determined by calculation; specifically, the specimen dimensions were measured, and the volume V was recorded in m³. The specimens are weighed on a scale with an accuracy of 0.1 g, and their mass is recorded in kg.

The compressive strength of the specimens was determined in accordance with the EN 12390-3 standard [13]. The specimen was tested in a machine that meets the requirements specified in EN 12390-4 [14]. The maximum load sustained by the test specimen is recorded, and the stress is then calculated. Figure 3 shows the measurement equipment. The test specimens shall be cubes, prisms or cores that meet the requirements set out in the standards [15]. After removing the specimens from the curing tank, they must be tested within 10 hours. The loading rate is in the range of 0.6 ± 0.2 MPa/s. After applying an initial load not exceeding 30% of the failure load, the load is applied to the specimen without impact, increasing continuously at the selected constant rate (±10%) until the specimen can no longer sustain the load.

The flexural strength test was conducted in accordance with MKS EN 12390-5 [16]. The testing equipment must comply with MKS EN 12390-4 [14]. The load-application equipment consist of two lower rotating supports and two upper ones designed to distribute the load into two equal parts, Fig. 4. Both the upper and lower supports must be made of steel and have a diameter of 20 to 40 mm. Their length must be at least 10 mm greater than the width of the specimen to be tested. Before being placed in the testing press, the specimen must be dry; specifically, if it has been cured in a water bath, it must be allowed to stand or have excess water wiped off. The load is applied normally to the side of the mould where it was filled, at a constant rate ranging from 0.04 MPa/s to 0.06 MPa/s.





Figure 3. Compressive strength testing equipment *Figure 4. Flexural strength test (Source: Authors)*

The depth of penetration of water under pressure is determined in accordance with MKS EN 12390-8 [17]. The specimen may be a cube, prism, or cylinder, with minimum dimensions of 150 mm for the surface to be tested and no other dimension less than 100 mm, Fig.5. Testing began when the specimen was 28 days old. The surface subjected to pressure must be roughened using a steel wire brush. The specimen was placed in the testing apparatus and subjected to a pressure of 500 ± 50 kPa for a duration of 72 ± 2 hours. After the pressure had been applied for the specified duration, the specimen was removed from the testing apparatus. Excess water is removed from the side subjected to the pressure. The specimen was split into two parts, perpendicular to the face subjected to the pressure. After splitting, the specimen was allowed to dry so that the depth of water penetration is clearly visible. The water penetration was measured from the surface subjected to the pressure to the tip of the penetration and was expressed in millimetres (mm).





Figure 5. Impermeability testing equipment *Figure 6. Water penetration depth (Source: Authors)*

Compressive strength testing was performed on six concrete cubes for each mix design (two each at 7, 14, and 28 days). Water impermeability testing was conducted on three concrete cubes, and flexural strength testing was performed on two concrete prisms.

3. RESULTS

Testing of the fresh concrete consistency was performed in accordance with the MKS EN 12350-2 standard [11]. The results are presented in Figure 7. The density of hardened concrete, obtained according to [12] is presented in the Figure 8.

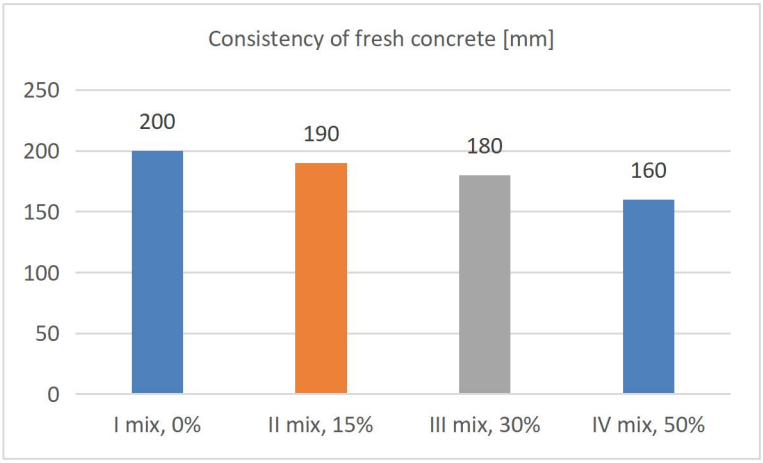


Figure 7. Consistency depending on the percentage replacement of fine aggregate with waste rubber

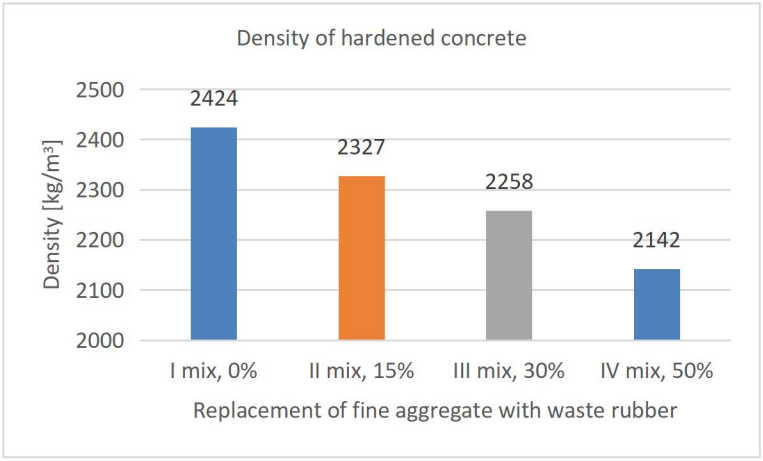


Figure 8. Relationship between density and percentage replacement of fine aggregate with rubber

Compressive strength was tested in accordance with MKS EN 12390-3 [13]. A testing machine compliant with MKS EN 12390-4 [14] was used for this purpose. Flexural strength was determined in accordance with the MKS EN 12390-5 standard [16]. The results for compressive strength at 7, 14, and 28 days and for the flexural strength for all the tested specimens are presented in Table 3.

The relationship between the flexural strength and percentage replacement of fine aggregate with waste rubber is presented in Fig. 10.

The depth of water penetration under pressure is determined in accordance with MKS EN 12390-8 [17], as presented in Figure 6. The results measured at 28 day are presented in Table 4 and Figure 11.

Table 3. Compressive strength at 7, 14 and 28 days and flexural strength of different mixtures

Property	Specimen	I mix, 0% waste rubber	II mix, 15% waste rubber	III mix, 30% waste rubber	IV mix, 50% waste rubber
Compressive strength 7 days [MPa]	1	49.9	28.9	23.9	17.3
	2	49.4	29.4	24.7	16.8
	Average	49.65	29.15	24.3	17.05
	± SD	0.354	0.354	0.566	0.354
Compressive strength 14 days [MPa]	1	51.5	32.6	26.4	18.8
	2	55.2	33.1	27.2	18.2
	Average	53.35	32.85	26.8	18.5
	± SD	2.616	0.354	0.566	0.424
Compressive strength 28 days [MPa]	1	56.1	34.7	28.4	20.7
	2	59	35	28.9	20.3
	Average	57.55	34.85	28.65	20.5
	± SD	2.051	0.212	0.354	0.283
Flexural strength 28 days [MPa]	1	5.030	4.540	3.980	2.120
	2	5.640	4.210	3.620	2.370
	Average	5.335	4.375	3.8	2.245
	± SD	0.431	0.233	0.255	0.177

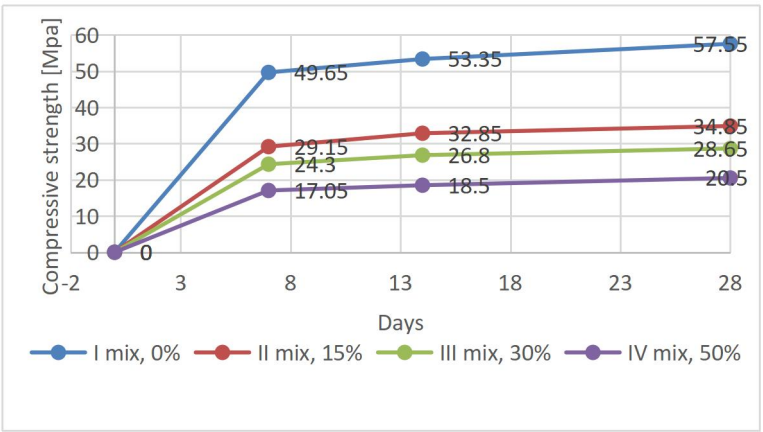


Figure 9. Increase in compressive strength at 7, 14 and 28 days for different mixtures

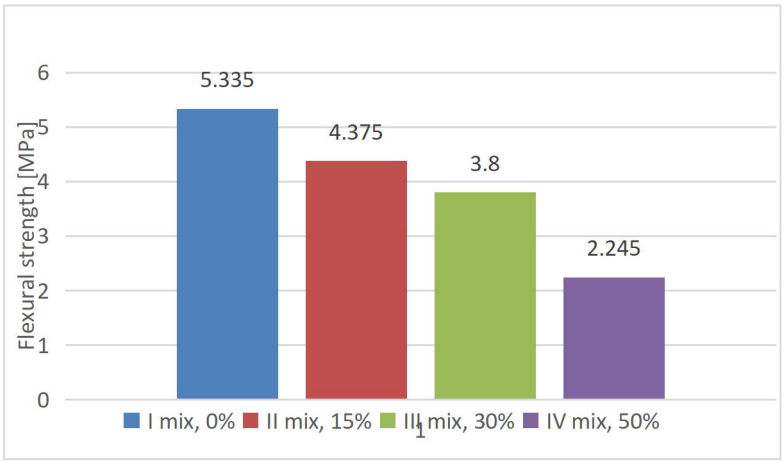


Figure 10. Flexural strength versus percentage replacement of fine aggregate with waste rubber

Table 4. Water penetration at 28 days for samples of different mixtures

Property	Specimen	I mix, 0% waste rubber	II mix, 15% waste rubber	III mix, 30% waste rubber	IV mix, 50% waste rubber
water penetration [mm]	1	19	32	40	47
	2	20	39	46	52
	3	21	37	44	54
	Average	20	36	43.33	51
	± SD	1.000	3.606	3.055	3.606

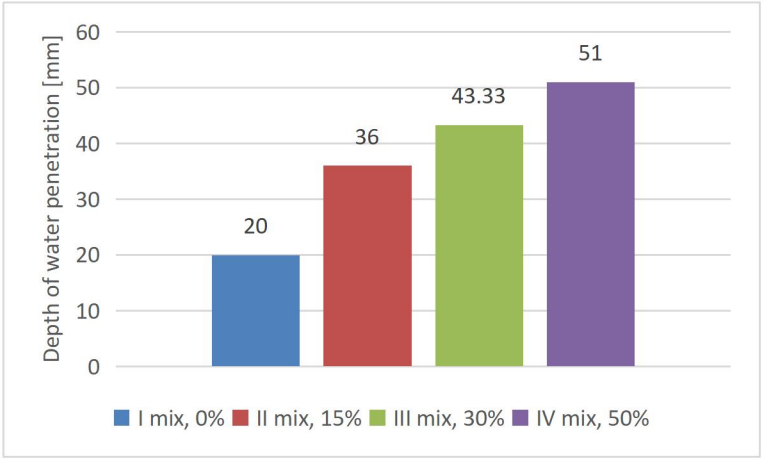


Figure 11. Depth of water penetration at 28 days, depending on the percentage replacement of fine aggregate with waste rubber

4. DISCUSSION

An analysis of the fresh concrete results leads to the conclusion that the consistency decreases for a constant water-cement ratio and varying amounts of waste rubber particles (samples with 0%, 15%, 30%, and 50% replacement). The control mix exhibits the highest consistency value (200), whereas consistency decreases as the rubber content in the concrete composition increases (Fig.7). Although the samples containing 50% waste rubber show a 20% reduction in consistency compared to the reference sample, all mixtures fall within consistency class S4. Therefore, the concrete possesses sufficient workability to be used as pumped concrete.

Due to the low density of the rubber, increasing its content results in concrete that is lighter than the reference mix. A 4% reduction in density is observed in concrete with a 15% rubber addition compared to the reference, while a 6.8% reduction is noted with a 30% addition; an 11.6% reduction in density is observed with a 50% rubber compared to the reference of 2424 kg/m^3 (Fig.8). Based on the presented mechanical properties of the corresponding cubes and prisms, it can be immediately concluded that increasing the percentage of waste rubber replacing fine aggregate reduces strength characteristics and increases water penetration, as presented in Table 3 and Figures 9 and 10. Compared to the control specimen with 0% rubber (57.55 MPa), the compressive strength of concrete decreased by 39.4% at 15% replacement, by 50.2% at 30% replacement, and by 64.4% at 50% replacement. Regarding the flexural strength of tested prisms, it decreased by 18% at 15% replacement, by 28.8% at 30% replacement, and by 57.9% at 50% replacement, compared to the control specimen with 0% rubber (5.335 MPa). Water penetration through concrete cubes increased by 80% at 15% replacement, by 116.5% at 30% replacement, and by 155% at 50% replacement, compared to the reference sample with 20 mm, Fig. 11 and Table 4.

The tests conducted indicate that increasing the percentage of waste rubber in concrete mixtures has a significantly more adverse effect on compressive strength and water impermeability than on flexural strength. The results show that, despite the reduction in strength caused by the use of rubber in the concrete, concrete with a high content of rubber particles would be suitable for non-structural applications.

5. CONCLUSION

This paper investigates the properties of concrete mixtures and hardened concrete in which a portion of the fine aggregate is replaced by waste rubber particles. Several different concrete mix designs were prepared with waste rubber aggregate contents of 0%, 15%, 30%, and 50%. The consistency of fresh concrete and bulk density, compressive strength, flexural strength and water impermeability of hardened concrete were tested. Given the lack of prior research in this field in Macedonia, any conclusion from this study highlighting the beneficial properties of concrete incorporating waste rubber represents a potential opportunity to reduce rubber waste, mitigate environmental impacts associated with rubber incineration and the excessive extraction of stone aggregates, lower concrete costs, and advance circular economy

goals within the construction industry. The research contributes in the field of green concrete with rubber. The possibility of shredding waste vehicle tyres and reusing them as a partial replacement for concrete aggregates offers a range of benefits for ecosystem preservation: it is a sustainable practice for managing vast quantities of waste tyres, given their low cost and availability, and it reduces the consumption of natural sand used in concrete. The research on rubberized concrete confirm its practical applicability in construction projects and serve as an incentive for engineers to pursue more sustainable solutions. The use of rubberized concrete could offer additional benefits, such as reduced CO_2 emissions, savings in resources and energy, and lighter structures, which need to be confirmed through a life-cycle assessment.

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Review paper

CO_2 CARBONATION OF FLY ASH AND THE FORMATION OF GRANULATED CARBONATED PRODUCTS FOR CONCRETE APPLICATIONS

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Abstract

Mineral carbonation of fly ash is a controlled physicochemical route in which reactive Ca- and Mg-bearing phases bind CO_2 as stable carbonates. This critical review evaluates reaction mechanisms, carbonation-assisted granulation and the use of carbonated fly ash in concrete, with particular attention to high-calcium and fluidized-bed-combustion ashes. Recent studies confirm that performance is strongly feedstock- and process-specific: reported results range from approximately 94 kg CO_2/t for wet-carbonated high-calcium fly ash to carbonation efficiencies of 78–95% in selected aqueous systems, while fly-ash-rich artificial aggregates have achieved pellet strengths close to 10 MPa after combined air and CO_2 curing. Carbonation can reduce residual free CaO, improve volume stability and modify porosity, but excessive surface precipitation, soluble salts, high absorption and non-uniform core conversion remain important limitations. Carbonated pellets are therefore treated as multiphase artificial aggregates rather than pure $CaCO_3$ granules. The most defensible near-term applications are controlled precast and non-reinforced products; reinforced-concrete use additionally requires verification of alkalinity, cover carbonation, chloride transport and corrosion protection. The review concludes that CO_2 uptake must be reported together with mineralogical conversion, pellet properties, concrete performance and a transparent net-CO_2 balance.

Key words: *fly ash, mineral carbonation, CO_2 utilization, granulation, concrete*

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1. INTRODUCTION

Fly ash is a fine particulate residue generated during the combustion of coal, lignite, biomass and other solid fuels. Its established use in construction is mainly associated with pozzolanic or latent hydraulic activity, filler effects and the partial replacement of Portland cement. However, not all fly ashes comply with the chemical, mineralogical and environmental requirements for use as a conventional supplementary cementitious material. Their properties vary with fuel type, combustion technology, flue-gas treatment, collection point and storage history [1,2]. This variability has stimulated research into alternative valorisation pathways in which fly ash is treated as a reactive mineral feedstock rather than used directly as an unmodified cement replacement.

Mineral carbonation is one such pathway. Calcium- and magnesium-bearing phases react with CO_2 and are converted, wholly or partly, into carbonate phases that are stable over long time scales [3–5]. In reinforced concrete, natural carbonation of hardened cement paste is generally a durability concern because it lowers pore-solution pH and may depassivate embedded steel. Controlled pre-carbonation of fly ash has a different purpose: recent high-calcium-fly-ash studies show that it can consume residual free CaO, increase volume stability and store measurable CO_2 before the material is incorporated into a cementitious product [6]. The distinction between pre-carbonation of the ash and carbonation of the cover concrete is therefore fundamental.

The aim of the paper is to critically systematize current knowledge on the carbonation of fly ash with CO_2, explain the governing chemical and transport mechanisms, evaluate carbonation-assisted granulation, and define the conditions under which the resulting material may be used in concrete. The paper is a critical narrative review and does not present original experimental results. Its contribution is the integration of reaction chemistry, processing parameters, environmental safety, aggregate performance, concrete durability and net CO_2 accounting into a single decision framework for subsequent laboratory and pilot-scale research.

2. REVIEW METHODOLOGY AND SCIENTIFIC SCOPE

A structured critical narrative review was conducted using peer-reviewed literature available through ScienceDirect, SpringerLink, Google Scholar and Crossref. The search covered publications from 2000 to August 2026, with recent experimental evidence from 2022–2026 used to establish the current state of the art and earlier studies retained where they define reaction mechanisms or durability concepts. Search combinations linked “fly ash” with “mineral carbonation”, “CO_2 uptake”, “accelerated carbonation”, “high-calcium fly ash”, “fluidized-bed combustion ash”, “artificial aggregate”, “pelletization”, “granulation”, “carbonation curing”, “leaching”, “durability” and “concrete”.

Studies were included when the investigated ash or residue was clearly identified and when carbonation conditions and/or quantitative or phase-based evidence relevant to CO_2 binding, free-CaO stabilization, granule properties, environmental

behaviour or concrete performance were reported. Studies without sufficient material identification or without evidence transferable to fly-ash carbonation and concrete applications were excluded. Search results were screened against these criteria, and 20 unique sources were retained for the final critical synthesis.

Critical comparison was performed at four linked levels: feedstock chemistry and mineralogy; carbonation conditions and measured CO_2 uptake; granule or aggregate physical-mechanical performance; and concrete or environmental response. Because the studies differ in ash origin, free-CaO content, liquid-to-solid ratio, CO_2 concentration, temperature, pressure, particle size and reactor configuration, reported optima are interpreted as study-specific rather than universal. Quantitative values are therefore compared together with their experimental context and used to define screening ranges rather than general design limits.

3. FLY ASH AS A REACTIVE CARBONATION FEEDSTOCK

3.1. Chemical and mineralogical variability

Low-calcium coal fly ash is commonly dominated by aluminosilicate glass, quartz and mullite, whereas high-calcium ash may additionally contain free CaO, portlandite, calcium silicates, aluminates and sulfates. Fluidized-bed-combustion ash frequently contains higher proportions of free lime and anhydrite because of lower combustion temperature and in-furnace desulfurization [1,2,7]. Theoretical carbonation capacity increases with reactive Ca and Mg content; practical capacity is lower because not all Ca and Mg are accessible or reactive within the selected process time.

A reliable feedstock assessment should combine X-ray fluorescence (XRF), X-ray diffraction (XRD), thermogravimetry and derivative thermogravimetry (TG/DTG), scanning electron microscopy with energy-dispersive spectroscopy (SEM/EDS), particle-size distribution, specific surface area, loss on ignition, moisture, free CaO, pH and electrical conductivity. XRF alone cannot determine carbonation capacity because it does not distinguish reactive free lime from calcium bound in relatively inert silicate or sulfate phases. XRD identifies crystalline phases, whereas TG/DTG supports quantification of portlandite and carbonate decomposition. Quantitative XRD with an internal standard or Rietveld analysis is preferable when the amorphous fraction must be estimated.

3.2. Environmental compatibility and volume stability

Fly ash may contain trace elements such as As, Cr, Pb, Zn, Cu, Ni, Mo and Se, and their mobility can change as carbonation lowers alkalinity. For fluidized-bed-combustion fly ashes containing 1.7–6.8% free CaO, a reported CO_2-binding potential of 9.7–15.7% was accompanied by a pH decrease from about 12 to about 9 and reduced leachability of several contaminants, including Zn, Cu, Pb, Ni, As, Hg, Cd and Cr; sulfate behaviour was ash-dependent and did not show a uniform reduction [7]. Because industrial residues differ markedly in phase composition and contaminant inventory, these environmental effects cannot be generalized across ash sources [8].

Environmental compatibility should therefore be verified by standardized leaching tests on the raw ash, carbonated powder or granule and, where relevant, the crushed final concrete product.

Free CaO and reactive MgO govern both carbonation potential and dimensional stability. Delayed hydration may cause expansion, while a dense carbonate rim may leave an unreacted core. Verification should therefore include residual free lime, expansion or soundness, cross-sectional microscopy and sulfate control.

4. CHEMICAL AND TRANSPORT MECHANISMS OF CO_2 CARBONATION

Carbonation requires the simultaneous availability of gaseous or dissolved CO_2, water and reactive alkaline-earth phases. CO_2 first diffuses through the gas-filled pore space and dissolves in a thin water film. Depending on pH, dissolved inorganic carbon is present mainly as $CO_2(aq)$, HCO_3^- and CO_3^{2-}. At the same time, dissolution or hydration of CaO, $Ca(OH)_2$ and other Ca-bearing phases supplies Ca^{2+} to the pore solution. Once supersaturation is reached, $CaCO_3$ nucleates and precipitates [3,4]. The simplified reactions are:

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (2)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3(s) \quad (3)$$

These equations describe the global stoichiometry but not the rate-controlling steps. Under very dry conditions, dissolution and ionic transport are insufficient. Under water-saturated conditions, gas diffusion is strongly restricted. The fastest reaction is therefore commonly observed at an intermediate moisture content, although the optimum depends on particle size, pore structure, mixing intensity and reactor design [3,4]. Pre-hydration may increase the availability of portlandite but can also cause agglomeration and reduce gas permeability.

Calcite, aragonite and vaterite may form, with calcite being thermodynamically stable and vaterite metastable. Polymorph, crystal morphology and spatial distribution influence porosity, pellet strength, water absorption and interfacial behaviour; total carbonate content alone is insufficient.

A dense carbonate shell may make the reaction diffusion-controlled and conceal an unreacted core. Cross-sectional SEM/EDS, phase analysis after controlled grinding and residual free-CaO measurement are therefore needed to demonstrate uniform conversion.

5. CARBONATION-ASSISTED GRANULATION

5.1. Process routes

Four principal process routes can be distinguished: carbonation of loose ash prior to granulation; simultaneous wetting, pelletization and carbonation; pelletization followed by carbonation curing; and repeated wetting-carbonation cycles. For producing artificial

aggregate, pelletization followed by controlled carbonation is technically attractive because pellet geometry and gas exposure can be regulated separately. Simultaneous carbonation may accelerate early stiffening, but premature surface precipitation can restrict further growth or cause non-uniform pellets.

Disc pelletizers and rotating drums produce cold-bonded agglomerates by nucleation, coalescence and layering. Liquid content has a narrow optimum: too little water produces dusty weak pellets, while excess water causes sticking, deformation and poor gas transport. Any supplementary binder must be included in the carbon balance.

5.2. CO_2 source and curing conditions

Pure CO_2 supports controlled laboratory work, whereas conditioned process gas is more industrially relevant. Because flue gas may contain water vapour, SOx, NOx, oxygen and particulates, results obtained with pure CO_2 cannot be transferred directly; gas composition, flow, pressure, humidity and temperature must be reported.

Higher CO_2 concentration can accelerate early reaction, but final conversion may be limited by reactant depletion or surface passivation. Temperature and curing time must be optimized against CO_2 uptake, residual free CaO, pellet strength, absorption, leaching and energy demand.

Recent experiments show that carbonation performance cannot be ranked by a single uptake value without considering feedstock and reactor conditions. Ding et al. obtained 94.8% carbonation efficiency from low-CaO fly ash (7.272 wt% CaO) in seawater at ambient temperature and pressure using 99% CO_2; the high efficiency was associated with a pH window of 8.2–10.4 that favoured Ca release and carbonate precipitation [9]. Miao et al. reported a maximum uptake of 0.128 g CO_2/g circulating-fluidized-bed fly ash and 78.17% efficiency in direct aqueous carbonation [10]. For high-calcium Class C fly ash, Ge et al. measured 94 kg CO_2/t and 57.21% efficiency after wet carbonation; the treatment significantly reduced free CaO and improved volume stability, while cement paste containing carbonated fly ash showed 98.97% and 113.41% higher compressive strength than the corresponding untreated-fly-ash paste at 1 and 3 d, respectively [6]. At aggregate scale, Zhang et al. used 70% fly ash, 15% Portland cement and 15% slag; after 3 d air curing plus 12 h carbonation curing, pellet strength reached 9.98 MPa, water absorption 10.35% and CO_2 content 4.33%, and concrete containing the aggregate reached 37.94 MPa compressive strength [11]. Using cold-bonded fly-ash lightweight aggregate, Yao et al. reported that 4 h carbonation with simulated coal-fired flue gas containing 15% CO_2 and 1000 ppm SO_2 increased CO_2 uptake by 25.8% and reduced porosity and water absorption; however, the effect of SO_2 on leaching was element-dependent and requires separate environmental verification [12]. The comparison demonstrates that ash chemistry, liquid phase, gas concentration, curing sequence and the performance metric must be reported together; a high carbonation efficiency does not by itself establish a suitable concrete aggregate.

6. CHARACTERIZATION AND PERFORMANCE VERIFICATION

Successful carbonation must be demonstrated by complementary methods. XRD identifies the appearance or increase of carbonate peaks and the reduction of portlandite or other crystalline reactants. TG/DTG is commonly used to estimate carbonate-bound CO_2 from mass loss in the de-carbonation range, but overlapping decomposition of different carbonate, hydrate and sulfate phases can bias the result. Baseline correction using untreated ash and confirmation by total inorganic carbon analysis improve reliability. SEM/EDS provides morphological and spatial evidence but is semi-quantitative and should not be used alone to calculate bulk conversion.

For granulated products, chemical evidence must be linked to engineering performance. Minimum characterization should include particle-size distribution, loose and compacted bulk density, apparent particle density, water absorption, open porosity, resistance to crushing, abrasion or attrition, fines generation and dimensional stability. Water absorption is particularly important because highly porous pellets may remove mixing water, reduce workability and change the effective water-to-binder ratio. Pre-wetting may control this effect, but it introduces additional water and must be standardized.

Standard selection also requires care. Carbonated pellets are commonly lightweight and porous, so methods developed for normal-weight natural aggregate are not automatically interchangeable. EN 1097-6:2022 explicitly provides reference methods for particle density and water absorption of both normal-weight and lightweight aggregates [13], whereas EN 13055:2016 provides the product framework for lightweight aggregates, including manufactured aggregates from industrial by-products and end-use-dependent performance requirements [14]. Fragmentation or abrasion methods developed for dense natural aggregate may still provide comparative information for sufficiently robust fractions, but their results should be interpreted together with particle density, friability and the intended application.

The ITZ requires direct study because a rough carbonate-rich surface may enhance mechanical interlocking, while a porous shell or high absorption may create a locally weak zone. Backscattered-electron imaging, elemental mapping and fracture analysis can distinguish pellet failure from ITZ debonding.

7. POTENTIAL USE IN CONCRETE

7.1. Microfiller and partial binder replacement

Finely ground carbonated ash can act as a microfiller by improving particle packing and providing nucleation surfaces. Calcium carbonate can also modify aluminate reactions in Portland-cement systems and promote carbonate-bearing hydrate assemblages [15]. However, pre-carbonation may consume phases that would otherwise contribute to pozzolanic or hydraulic reactions. The net result is therefore a balance among filler and nucleation effects, dilution, residual reactivity and changes in

water demand; a fixed replacement level cannot be recommended independently of ash chemistry and fineness.

Replacement levels such as 5%, 10% and 20% may be used for screening, but they are not general application limits. Strength at several ages must be interpreted with calorimetry, phase assemblage, porosity and durability because similar 28-day strength does not prove equivalent service performance.

7.2. Artificial aggregate and precast products

Carbonated pellets may partially replace natural fine or lightweight aggregate. Their suitability depends on grading, density, crushing and abrasion resistance, water absorption, freeze–thaw stability and compatibility with the intended concrete. Low-density porous pellets may reduce unit weight but commonly increase absorption and may reduce elastic modulus. Conversely, internal water stored in pre-wetted pellets can contribute to internal curing, provided that desorption kinetics and the effective mixture water are quantified.

Controlled precast and non-reinforced products are the most realistic near-term applications. Structural reinforced concrete requires additional evidence on cover carbonation and chloride transport [16–18], together with electrical resistivity and corrosion-related electrochemical indicators where reinforcement is present.

8. CRITICAL DISCUSSION AND RESEARCH GAPS

The principal value of fly-ash carbonation is the possibility of combining waste valorisation with CO_2 utilization, but laboratory efficiency cannot be equated directly with industrial performance. Process configuration is particularly important: recent seawater-carbonation work showed that, under otherwise comparable ambient conditions, carbonation efficiency decreased from 94.8% in an open system to 26.5% in a sealed system as elevated CO_2 partial pressure altered dissolution and precipitation behaviour. This illustrates the risk of transferring optimum laboratory conditions directly to dust-contained or gas-recycling industrial reactors [19]. Likewise, gross carbonate formation may be offset by electricity for grinding and pelletization, heat for drying, CO_2 conditioning, transport and additional binder, while service-life effects also influence the environmental balance. A carbon-negative claim therefore requires a transparent system boundary and inventory rather than uptake data alone [5,8,20].

Compositional variability is a major barrier to standardization. Industrial implementation requires feedstock acceptance limits, rapid incoming control and batch-to-batch statistics; blending may reduce variability but can dilute the reactive fraction.

Research must couple CO_2 uptake with service-life performance. Increased compressive strength may coexist with greater shrinkage, lower modulus, higher absorption or deeper cover carbonation; a balanced performance matrix is therefore essential.

Terminology must reflect demonstrated material identity. “Carbonated fly ash”, “artificial aggregate” and “$CaCO_3$ granule” are not interchangeable, and claims of $CaCO_3$

production require quantitative phase evidence and disclosure of the residual non-carbonate fraction.

Five priorities emerge for future research: standardized feedstock classification based on reactive rather than total Ca/Mg; coupled carbonation–granulation kinetics; quantitative links between carbonation degree, pellet pore structure and concrete performance; long-term durability, leaching and reinforcement protection; and net CO_2 benefit under realistic industrial boundaries. These gaps define the logic of the validation programme proposed in Section 9.

9. PROPOSED LABORATORY VALIDATION PROGRAMME

Based on the identified evidence gaps, a six-stage validation framework is proposed as an authors' synthesis of established characterization and performance methods. Stage 1 characterizes the feedstock by XRF, quantitative XRD, TG/DTG, SEM/EDS, particle size, specific surface area, loss on ignition, free CaO, moisture, pH, conductivity, soluble salts and leaching. Stage 2 screens moisture content, CO_2 concentration, temperature and time, with gas consumption/outlet concentration for mass balance and TG/DTG or total inorganic carbon for bound CO_2.

Stages 3 and 4 comprise granulation and carbonation curing. Disc angle, speed, feed rate, liquid addition, residence time and target grading should be reported. Green-pellet yield and strength are followed by residual free CaO, carbonate content, cross-sectional conversion, density, absorption, crushing, attrition and leaching tests.

Stage 5 evaluates reference concrete, powder additions and at least two pellet replacement levels. Fresh-state tests include consistency, density and air content; hardened-state tests include strength, modulus, shrinkage, absorption, water penetration, resistivity, chloride transport, freeze–thaw resistance and carbonation depth. Reinforced-concrete use additionally requires corrosion indicators.

Stage 6 quantifies net CO_2 benefit from measured uptake and process inventory, with sensitivity to electricity mix, CO_2 source, transport, drying, pellet yield and service life. Pilot production is justified only after chemical, mechanical, durability and environmental criteria are met.

10. CONCLUSIONS

Controlled carbonation of fly ash can convert reactive Ca- and Mg-bearing phases into stable carbonates while modifying particle surfaces and, for suitable high-calcium ashes, reducing residual free CaO. High-calcium and fluidized-bed-combustion ashes generally offer the greatest direct carbonation potential, whereas low-calcium Class F ash may require activation or an external Ca source. Carbonation-assisted granulation can produce multiphase pellets for investigation as artificial aggregate, but these products should not be described as pure $CaCO_3$ unless phase composition and purity are quantitatively demonstrated.

Potential applications include microfiller use, partial binder replacement and partial aggregate substitution. Controlled precast or non-reinforced products remain the most

defensible initial route; reinforced concrete additionally requires evidence on alkalinity, cover carbonation, chloride resistance, dimensional stability and corrosion protection. Environmental value should be reported as net rather than gross CO_2 benefit, combining measured uptake with process energy, material and transport inputs and verified service performance.

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Sustainable Development Goals: Industry, Innovation and Infrastructure

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Review paper

INNOVATIVE NANOMATERIALS AND BUILDING ENERGY EFFICIENCY

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Abstract

This paper examines how selected nano-related technologies can be used in energy-efficient new buildings and retrofit, with emphasis on the point at which material-scale performance becomes relevant to architectural and engineering design. The review distinguishes regulatory nanomaterials from nano-enabled composites/products and from advanced functional systems, and groups the selected technologies by four building functions: (1) thermal resistance, (2) thermal storage, (3) optical and surface control, and (4) structural/durability enhancement. Reported performance values are retained only where they can be linked to identifiable evidence and are interpreted in relation to the complete building assembly. Silica aerogel and VIPs are most convincing where available thickness is limited; nano-enhanced PCMs depend on an appropriate phase-change range and verified cycling behaviour; nano-coatings and smart glazing depend strongly on exposure and control conditions; and nano-modified cementitious materials contribute mainly through durability and added functionality. The paper also considers EU-aligned governance, occupational exposure, life-cycle assessment, product transparency, public procurement and the need for testing under Western Balkan conditions. The resulting design-and-verification framework supports selective use of these technologies where their specific function can be demonstrated at building scale.

Key words: *nanomaterials, nano-enabled systems, building envelope, energy efficiency, life-cycle assessment*

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1. INTRODUCTION

durability of the built stock. Buildings account for about 30% of global final energy demand, while the wider buildings and construction sector remains a major source of energy-related emissions and material consumption [1,2]. However, the term "nanomaterial" must not be used as a blanket label: under the European Commission recommendation, regulatory classification depends on the number-based particle-size distribution and specified particle dimensions [3]. Across the reviewed technologies, nanoscale pores, particles and interfaces can alter heat transfer, radiation, latent storage, surface chemistry and cementitious microstructure [4-13]. A building product may therefore contain a nanomaterial without the complete product itself meeting the regulatory definition.

The purpose of the review is to translate the available material evidence into criteria that can be used in architectural and engineering decisions. Three questions guide the assessment: what function is expected from the technology; which measurable indicator demonstrates that function; and which conditions at component or building scale may reduce the laboratory or catalogue performance. Organising the discussion by function, rather than by product label, also makes it possible to compare technologies against the same design constraints: heat and solar transfer, moisture and fire compatibility, durability, installation, safety and life-cycle consequences.

2. METHODOLOGICAL FRAMEWORK AND CLASSIFICATION BOUNDARY

The paper uses a targeted narrative review combined with comparative analysis. Peer-reviewed reviews and representative studies with a clear building application were considered together with relevant EU institutional documents. Preference was given to evidence that connects a nanoscale mechanism with a measurable property of a product, component or assembly. Because the reviewed studies differ in materials, test conditions and reporting units, the analysis is not treated as a statistical meta-analysis. Numerical values are used as source-specific indicative ranges; they should not replace product declarations, project-specific testing or the applicable harmonised test methods in design practice.

Four functional groups are adopted: (I) thermal-resistance systems; (II) thermal-storage systems; (III) optical and surface-control systems; and (IV) structural/durability-enhancement systems. The classification boundary is deliberately separated from function. Silica aerogel is a nanoporous/nanostructured insulating material, but regulatory nanomaterial status must be demonstrated for the specific material against the particle criteria in the European Commission definition [3-5]. A VIP is an evacuated product whose high performance commonly relies on a nanostructured fumed-silica core and a gas-barrier envelope [6]. A conventional PCM is not a nanomaterial, whereas a nanoparticle-enhanced PCM is a nano-enabled composite [7,8]. TiO2 nano-coatings contain nanoscale constituents when nano-TiO2 is used [9,10]; smart glazing is an advanced functional system whose electrochromic layers may be nanostructured [11]; and nano-modified cementitious composites contain deliberately introduced nanoscale additions [12,13].

3. FUNCTION-BASED ASSESSMENT OF SELECTED TECHNOLOGIES

3.1. Group I - Thermal resistance: aerogel and VIP

Silica aerogels suppress solid and gaseous heat transfer through a highly porous nanoscale network. Reviews report thermal conductivity of approximately 0.010-0.020 W/(m K), with values around 0.013-0.014 W/(m K) frequently reported for silica aerogels [4,5]. Their main architectural advantage is high resistance at low thickness, especially where envelope geometry constrains conventional insulation [4,5]. Transparent or translucent aerogel glazing can also preserve a substantial fraction of daylight; reported visible-light transmittance reaches approximately 0.75 in reviewed systems, although haze, moisture compatibility, mechanical protection and cost remain design constraints [5].

VIPs provide even lower centre-of-panel conductivity but are more dependent on factory integrity and detailing. A state-of-the-art review reports approximately 0.002-0.004 W/(m K) at delivery, with typical performance around 0.008 W/(m K) after 25 years of ageing [6]. The panel cannot normally be cut on site, and perforation, edge effects and vacuum degradation can dominate the realised U-value. VIPs are therefore best treated as dimensionally coordinated components for roofs, terraces, prefabricated panels and other space-constrained details, not as a direct like-for-like substitute for conventional insulation.

3.2. Group II - Thermal storage: nano-enhanced PCM

PCMs buffer temperature by storing and releasing latent heat; the base PCM itself is not necessarily nanoscale. Nano-enhancement uses graphene, graphite, carbon nanotubes, metal oxides or other nanoscale phases to improve heat transfer or shape stability [7,8]. For building-oriented organic PCMs, literature reports phase-change temperatures commonly within about 19-29 degrees C and heats of fusion around 120-280 kJ/kg, illustrating why transition range and latent capacity must be specified together rather than by material name alone [7]. Nano-addition can increase conductivity but may reduce latent heat per unit mass or increase viscosity; dosage and cycling stability must therefore be experimentally verified [8]. In buildings, the useful indicator is not only conductivity but the matched melting range, enthalpy, number of stable cycles and reduction of peak temperature or load under the relevant climate and operating schedule.

3.3. Group III - Optical and surface control: nano-coatings and smart glazing

TiO2 nano-coatings can provide photocatalytic activity and photo-induced changes in surface wettability [9,10]. Building-scale performance is exposure- and substrate-dependent: irradiance, pollutant type, TiO2 dispersion, binder/substrate characteristics, abrasion, washing and ageing influence retained activity [10]. Therefore, specifications should report the relevant test metric - for example pollutant-removal efficiency, contact-angle/wetting response or optical properties - together with the exposure

protocol and post-ageing retention, rather than relying on a generic "self-cleaning" claim [10].

Smart glazing should likewise be classified as an advanced functional building system, not automatically as a nanomaterial. Electrochromic technologies use thin functional layers to vary the transmission of visible light and solar energy under an applied electrical potential [11]. For building design, U-value, solar factor/g-value, visible transmittance, switching range, switching time and cycle durability are more meaningful than the term "smart" alone. Annual performance also depends on orientation, shading, control logic and occupancy, so dynamic glazing requires whole-building simulation and commissioning rather than assessment from an isolated material property [11].

3.4. Group IV - Structural and durability enhancement: nano-modified cementitious materials

Nano-SiO2, TiO2 and carbon-based nanoscale additions can influence hydration, nucleation, pore structure, cracking, durability and, in selected systems, conductivity or sensing [12,13]. These materials usually do not reduce wall U-value directly; their energy relevance is principally indirect through durability, maintenance reduction, moisture resistance or thinner high-performance components. For nano-SiO2, review evidence indicates that beneficial mechanical and durability effects are often reported at additions of about 2-3% in the studied cementitious systems, but the optimum is mixture-specific and cannot be treated as a universal dosage [13]. Because agglomeration and poor dispersion can negate benefits, every quantitative claim should identify nanoparticle dosage, particle form, dispersion protocol, reference mixture, curing regime and statistically reported comparison [12,13].

Table 1. Functional classification, status and evidence-traceable performance indicators

Function	Technology	Classification	Quantitative indicator / evidence source
I Thermal resistance	Silica aerogel	Nanoporous/nanostructured material; regulatory status product-specific [3]	λ ≈ 0.010–0.020 W/(m K); glazing τv up to ≈ 0.75 [4,5]
I Thermal resistance	VIP	Advanced evacuated product; commonly nano-enabled by fumed-silica core	λ ≈ 0.002–0.004 W/(m K) initial; service-life ageing must be declared [6]
II Thermal storage	Nano-enhanced PCM	Nano-enabled composite	Report Tm and ΔH; organic building PCMs ≈ 19–29 °C; 120–280 kJ/kg [7,8]
III Optical/surface	TiO2 nano-coating	Nanomaterial-containing functional layer [9]	Repor catalytic/wetting/optical metric before and after defined ageing/exposure [9,10]

III Optical/surface	Smart glazing	Advanced functional system; may use nanostructured layers [11]	Report U, g, τv, switching range/time and cycle durability [11]
IV Structure/durability	Nano-cementitious composite	Nano-enabled composite [12,13]	Report dosage/dispersion and change vs reference; nSiO2 often beneficial ≈ 2–3% in reviewed systems [12,13]

4. BUILDING-SCALE INTEGRATION AND SELECTION

Material properties become useful to the designer only after they are translated to the assembly in which the product will operate. For aerogel and VIP systems, joints, edge losses, moisture, ageing and workmanship may substantially reduce the advantage suggested by centre-of-product values [4-6]. We therefore consider selective, hybrid use more defensible than blanket substitution: aerogel or VIP at thickness-critical details [4-6]; PCM where the expected daily temperature cycle activates the selected transition range [7,8]; photocatalytic or electrochromic systems where exposure and control conditions are known [9-11]; and nano-modified cementitious materials only against a defined reference mixture and durability target [12,13]. In heritage retrofit the decision is narrower still, because reversibility, vapour/capillary compatibility, facade geometry and daylight must be preserved. Thin high-performance materials are consequently most useful at carefully diagnosed details rather than as automatically preferable envelope solutions [4,5].

Table 2. Building-scale decision and verification matrix

Design problem	Candidate technology	Required performance evidence	Principal risk	Verification route
Thickness-limited detail	Aerogel / VIP	U-value and ψ-value, including edge effects; hygrothermal check	Perforation; condensation; ageing	Full-scale detail / validated simulation
Summer overheating	NePCM; smart glazing	Peak operative T; cooling peak; g; switching schedule	Inactive PCM; glare; control failure	Climate-specific annual simulation + monitored pilot
Polluted/exposed facade	TiO2 nano-coating	Aged optical / wetting / catalytic response	Wash-off; abrasion; uneven ageing	Weathering + release/leaching assessment
Durability-critical element	Nano-modified cementitious composite	Reference-normalized strength/durability; service life	Agglomeration; worker exposure	Documented mix/dispersion + standard tests

5. EU-ALIGNED GOVERNANCE, SAFETY, LIFE CYCLE AND WESTERN BALKANS

For nano-related construction products, traceability is not only a matter of citation; it also affects regulatory and occupational-safety decisions. REACH and CLP apply within

the existing substance framework, while registered nanoforms are subject to explicit information requirements for nanoform characterisation and chemical safety [14]. Exposure is especially relevant when handling, spraying, cutting, grinding, maintenance or demolition can release airborne particles. EU-OSHA recommends a precautionary approach and a hierarchy of controls where hazard information remains incomplete [15]. In specification practice, the physical form and the life-cycle stage should therefore be stated: a constituent bound in a finished product does not present the same exposure situation as a dry powder or an abraded coating. The technical file should accordingly include safety information, engineering and organisational controls, PPE for residual risk, maintenance procedures and end-of-life handling [14,15].

The same caution is required in environmental assessment. Operational energy savings alone are not sufficient for comparing technologies with different production routes, service lives or replacement needs. Building-level LCA should use a consistent functional equivalent, system boundary, service-life assumptions and life-cycle model, following the principles formalised in EN 15978:2026 [16]. Product transparency is also becoming more explicit in EU construction-product policy. Regulation (EU) 2024/3110 establishes the framework for a construction digital product passport and requires the passport information to be accurate, complete and up to date [17]. Directive 2014/24/EU also allows life-cycle costing in public procurement to include acquisition, use, maintenance, end-of-life and verifiable environmental externalities [18]. For a nano-related product, a technically credible procurement file should therefore request declared performance, information on nanoform/content where applicable, safety documentation, durability evidence, assumed service life and end-of-life information, rather than treating the word "nano" as evidence of superior performance.

For the Western Balkans, the immediate policy context is the continuing alignment of the green transition with EU legislation and policy. The Revised Green Agenda Action Plan (2025-2030) strengthens alignment with the European Green Deal and the EU acquis [19], but it does not create a separate regional regulatory regime for nanomaterials in construction. In our view, this makes local performance evidence more, not less, important. Validation programmes should reproduce representative summer solar exposure, winter operation, humidity and driving rain, as well as realistic construction tolerances, maintenance capacity and product availability. Pilot applications should report material properties together with assembly-level U-values and linear thermal transmittance ψ-values or optical indicators where relevant, hygrothermal response, ageing or cycling, installation deviations, occupational controls and monitored in-use behaviour. These items are proposed here as a regional research and verification agenda; they should not be read as an assumption that results obtained in other climates transfer unchanged to Balkan buildings.

6. PROPOSED DESIGN AND VERIFICATION MODEL

On the basis of the review, we propose a six-step design sequence. First, identify the dominant energy, comfort, moisture or durability problem. Second, establish whether the candidate is an intrinsic nanomaterial, a nano-enabled composite/product or an

advanced functional system. Third, select the relevant functional group and the quantitative indicators listed in Table 1. Fourth, test whether those indicators remain meaningful in the complete assembly through thermal-bridge, hygrothermal or annual energy analysis, as appropriate. Fifth, examine occupational exposure, life-cycle impacts, repairability, procurement documentation and end-of-life. Finally, verify the installed result through commissioning and monitoring. If the claimed benefit cannot be linked to an appropriate test, declaration or peer-reviewed evidence source, it should not be used as the basis for specification.

7. CONCLUSION

The technologies considered in this review should not be treated as a single material class. Silica aerogel is a nanoporous/nanostructured insulation technology whose regulatory status must be established for the specific material against the relevant particle criteria [3-5]. A VIP is an evacuated product that may use a nanostructured fumed-silica core [6]. Nanoparticle-enhanced PCMs and nano-modified cementitious materials are nano-enabled composites [8,12,13], while TiO2 coatings contain nanomaterials when nanoscale TiO2 is deliberately incorporated [9,10]. Smart glazing is better described as an advanced functional system that may include nanostructured electrochromic layers [11]. Keeping these categories separate is important because their mechanisms, exposure pathways and verification requirements are not interchangeable.

From an architectural-engineering standpoint, the evidence favours targeted use. Aerogel and VIPs have their clearest role where high thermal resistance must be achieved within limited thickness [4-6]. NePCMs are credible only when the transition temperature is matched to the climate and operation and cycling performance is documented [7,8]. Coatings and smart glazing require verification under the relevant exposure and control conditions [9-11], while nano-modified cementitious materials should be judged against a reference mixture with documented dispersion and durability [12,13]. EU-aligned practice adds traceability of nanoforms under REACH, precautionary occupational-safety management, building-level LCA, construction-product transparency and life-cycle-based procurement [14-18]. For the Western Balkans, closer alignment with the European Green Deal and acquis should be accompanied by locally validated evidence under regional climatic, construction and maintenance conditions [19].

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Review paper

CIGARETTE-BUTT-DERIVED FIRED CLAY BRICKS: PERFORMANCE, ENVIRONMENTAL SAFETY AND ARCHITECTURAL APPLICATIONS

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Abstract

Cigarette butts (CBs), composed mainly of slowly degradable cellulose acetate, are a persistent and contaminated urban waste stream. Their incorporation into fired clay bricks offers a route for waste valorization and controlled pore formation. This review examines manufacturing, microstructure, engineering performance, environmental safety and architectural applicability of CB-derived fired clay bricks. Evidence from laboratory studies shows that low CB additions, commonly around 0.5-2.0 wt.%, reduce density and thermal conductivity, but increasing porosity also lowers compressive strength and raises water absorption. High-temperature firing destroys most organic constituents, while reported leachate concentrations from properly fired specimens remain below the regulatory thresholds used in the cited studies. The material is therefore most promising where mixture composition and firing conditions are optimized for the required masonry performance. Industrial-scale validation, long-term field monitoring and comparative life-cycle assessment remain necessary before broad specification in buildings.

Key words: *cigarette butts; fired clay bricks; cellulose acetate; circular economy; thermal insulation*

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1. INTRODUCTION

The construction sector is facing increasing pressure to reduce its environmental impact through the adoption of sustainable materials and circular economy principles. Simultaneously, the generation of persistent solid waste continues to grow, creating significant challenges for waste management systems worldwide. Among the most widespread forms of urban litter are discarded cigarette butts, which represent the most frequently collected anthropogenic waste item in streets, parks, beaches and public spaces. It is estimated that approximately 5.7 trillion cigarettes are consumed annually, with the majority of filters being improperly discarded into the environment rather than collected through organized waste management systems [1,2].

Conventional cigarette filters are manufactured predominantly from cellulose acetate, a thermoplastic polymer characterized by high chemical stability and extremely slow biodegradation. Depending on environmental conditions, complete degradation may require several years or even decades. During this period, cigarette butts gradually release numerous hazardous substances, including nicotine, heavy metals, polycyclic aromatic hydrocarbons and other toxic organic compounds accumulated during tobacco combustion. Consequently, discarded cigarette filters represent not only an aesthetic problem but also a potential source of soil and water contamination, negatively affecting terrestrial and aquatic ecosystems [2-4].

The incorporation of cigarette butts into fired clay bricks offers several technological advantages. During firing, cellulose acetate undergoes thermal decomposition, producing uniformly distributed pores throughout the ceramic body. This controlled increase in porosity decreases bulk density and significantly improves thermal insulation, thereby enhancing the energy efficiency of masonry walls. At carefully optimized replacement levels, the reduction in compressive strength remains within the ranges reported as potentially suitable for selected load-bearing or non-load-bearing masonry applications [1,5,6].

The objective of this review is to provide a comprehensive evaluation of cigarette-butt-derived fired clay bricks by critically examining manufacturing technologies, microstructural evolution, engineering performance, environmental safety and potential architectural applications. Particular emphasis is placed on understanding the relationships between processing parameters, pore development and final material properties, thereby providing an integrated assessment of the feasibility of this innovative ceramic material for sustainable building construction.

2. CIGARETTE BUTTS AS A SUSTAINABLE ADDITIVE IN FIRED CLAY BRICKS

2.1. Chemical Composition and Physicochemical Characteristics of Cigarette Filters

Cigarette filters are primarily manufactured from cellulose acetate, a thermoplastic derivative of cellulose obtained through the acetylation of natural cellulose fibers. Cellulose acetate typically accounts for more than 95 wt.% of the filter composition,

while the remaining fraction consists of plasticizers, predominantly triacetin, paper wrapping materials and trace additives introduced during industrial production. The fibrous structure of cellulose acetate provides the filtration efficiency required during cigarette consumption but also contributes to its remarkable persistence in the environment after disposal [2,4].

Experimental studies consistently report that only relatively small quantities of cigarette butts are necessary to modify brick properties. Replacement levels between 0.5 and 2.0 wt.% have generally produced the most favorable balance between reduced density, improved thermal insulation and acceptable mechanical performance. At higher concentrations, excessive pore formation may significantly reduce compressive strength and increase water absorption, thereby limiting practical applications for structural masonry units [1,5,6].

2.2. Behaviour of Cigarette Butts during Brick Manufacturing

The incorporation of cigarette butts into clay bricks modifies the manufacturing process primarily through the thermal decomposition of cellulose acetate during firing. Unlike conventional mineral additives, cigarette filters do not participate directly in ceramic sintering but function as sacrificial pore-forming agents. As the firing temperature increases, the organic component decomposes and volatilizes, generating a controlled porous network that significantly influences the physical and thermal characteristics of the final ceramic product [1,3].

During firing, several temperature-dependent transformations occur simultaneously. Initially, physically bound water evaporates, followed by the dehydroxylation of clay minerals. At temperatures above approximately 250-300 °C, cellulose acetate begins to thermally degrade, releasing volatile gaseous products that gradually escape through the ceramic body. As firing progresses toward temperatures between 900 and 1050 °C, ceramic sintering densifies the mineral matrix while preserving the pores created by polymer decomposition. The resulting microstructure consists of a dense ceramic skeleton containing numerous fine, uniformly distributed pores that contribute to lower density and reduced thermal conductivity [1,5].

2.3. Manufacturing Technology of Cigarette-Butt-Derived Fired Clay Bricks

The manufacturing process consists of five principal stages: raw material preparation, mixing, shaping, drying and firing. Natural clay is first processed to obtain a homogeneous particle-size distribution suitable for extrusion or molding. In parallel, collected cigarette butts undergo pretreatment involving separation of residual tobacco, washing, drying and mechanical shredding. The treated fibers are then incorporated into the clay mixture at predetermined replacement levels, typically ranging between 0.5 and 2.0 wt.%, depending on the targeted engineering performance of the final product [3,5].

The firing stage governs the final microstructure and performance of cigarette-butt-derived bricks. Depending on the clay composition, maximum firing temperatures typically range between 900 and 1050 °C. During heating, the organic components of

cigarette filters decompose completely, generating gases that escape from the ceramic matrix and leave behind a finely distributed pore network. Simultaneously, clay minerals undergo sintering and partial vitrification, producing a dense ceramic framework that surrounds the newly formed pores. The balance between pore generation and ceramic densification ultimately determines density, compressive strength, thermal conductivity and water absorption of the finished bricks [1,5,7].

Careful optimization of processing parameters is essential for achieving satisfactory engineering performance. Experimental studies demonstrate that firing temperature, heating rate, soaking time and cigarette-butt content collectively control pore morphology and ceramic densification. Higher firing temperatures generally improve sintering and mechanical strength but may also reduce total porosity through enhanced vitrification. Conversely, excessive waste incorporation increases pore connectivity, leading to higher water absorption and lower compressive strength. Therefore, manufacturing parameters should be optimized simultaneously rather than independently to obtain the most favorable balance between structural integrity and thermal insulation [1,3,6].

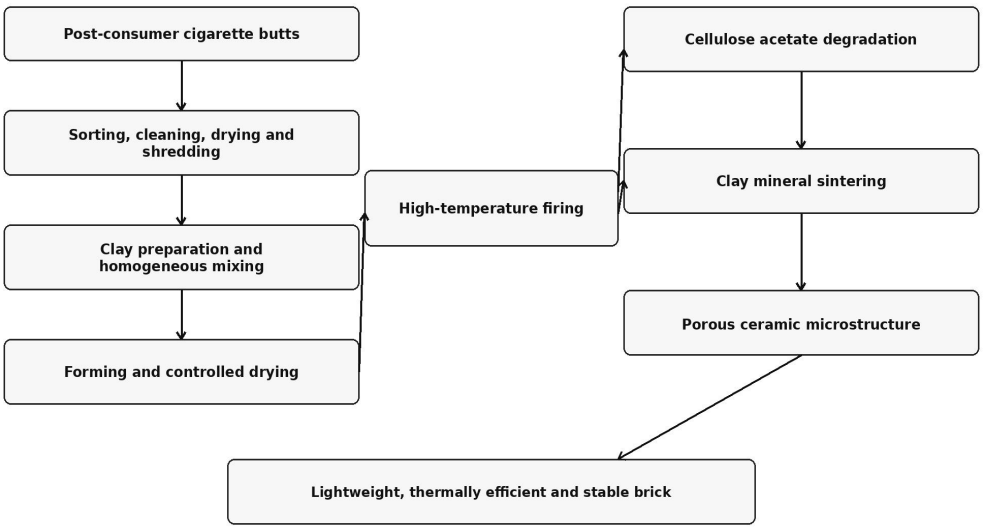


Figure 1. Technological and physicochemical pathway for manufacturing cigarette-butt-derived fired clay bricks (authors' illustration).

Table 1. Comparison of conventional and cigarette-butt-derived fired clay bricks.

Aspect	Conventional fired clay brick	CB-derived fired clay brick
Raw materials	Natural clay and standard additives	Natural clay with 0.5-2.0 wt.% pre-treated CB waste
Firing mechanism	Clay sintering and vitrification	Sintering plus cellulose-acetate decomposition and pore formation
Bulk density	Reference density	Generally reduced because of additional pores
Thermal conductivity	Higher for denser ceramic body	Lower when fine air-filled pores are uniformly distributed
Main limitation	Energy-intensive firing	Strength and water absorption must be controlled by dosage and firing

3. STRUCTURE-PROPERTY RELATIONSHIPS IN CIGARETTE-BUTT-DERIVED FIRED CLAY BRICKS

3.1. Microstructural Evolution

The engineering performance of fired clay bricks containing cigarette butts is governed primarily by the evolution of their microstructure during thermal processing. Unlike conventional dense ceramic materials, the incorporation of cellulose acetate fibers intentionally modifies the internal pore system, producing lightweight ceramic products with improved thermal insulation characteristics. The final microstructure results from the combined effects of clay mineral transformations, sintering mechanisms and the thermal degradation of cigarette filters during firing [1,3].

Scanning electron microscopy reported in numerous experimental investigations demonstrates that low cigarette-butt contents produce a relatively uniform distribution of fine, isolated pores surrounded by a dense ceramic matrix. These closed pores reduce thermal conductivity by limiting heat transfer through the material while only slightly affecting its mechanical resistance. As the waste content increases, both pore diameter and pore connectivity become progressively larger, producing a more heterogeneous internal structure characterized by interconnected voids and thinner ceramic walls [5,6].

Microstructural observations further indicate that the pores generated by cellulose acetate decomposition are generally rounded and uniformly distributed when the waste content remains within the recommended range. Rounded pores are less detrimental to compressive strength than elongated or irregular voids because they produce lower stress concentrations under mechanical loading. Consequently, optimizing both pore size distribution and pore geometry is essential for achieving an appropriate balance between thermal insulation and structural performance [3,6].

3.2. Bulk Density

During firing, cellulose acetate fibers are almost completely decomposed, leaving numerous microscopic voids distributed throughout the ceramic matrix. These pores reduce the volume fraction occupied by solid material, thereby decreasing the overall density of the fired brick. Experimental investigations consistently demonstrate that density reduction is approximately proportional to the amount of incorporated cigarette-butt waste, although the exact relationship depends on clay composition, firing temperature and the degree of ceramic vitrification achieved during sintering [1,5].

However, density should not be minimized without considering its influence on other engineering properties. Very low densities generally indicate excessive pore connectivity and reduced ceramic skeleton continuity, which may adversely affect compressive strength, durability and water resistance. Therefore, the optimum manufacturing strategy aims to achieve moderate density reduction while preserving sufficient structural integrity for long-term service under mechanical and environmental loading [3,7].

3.3. Compressive Strength

The reduction in compressive strength is primarily associated with the increase in total porosity generated during the thermal decomposition of cellulose acetate. As the organic fibers volatilize during firing, they leave behind pores that reduce the effective load-bearing cross-sectional area of the ceramic matrix. Under compressive loading, stresses become concentrated around these pores, facilitating crack initiation and propagation. Consequently, compressive strength generally decreases with increasing cigarette-butt content [1,5].

Despite this reduction, the relationship between porosity and strength is not purely linear. When cigarette-butt additions remain relatively low, typically between 0.5 and 2.0 wt.%, the pores are generally small, rounded and uniformly distributed throughout the ceramic body. This microstructure limits stress concentration and allows the surrounding vitrified ceramic matrix to maintain sufficient structural continuity. As a result, the decrease in compressive strength is moderate and remains within ranges reported as potentially suitable for selected masonry applications [5,6].

3.4. Water Absorption

The increase in water absorption is directly associated with the formation of additional pores following the thermal decomposition of cellulose acetate. As the organic fibers volatilize during firing, they generate a porous network capable of storing and transporting water. The extent of water uptake depends not only on total porosity but also on pore size distribution, pore connectivity and the degree of ceramic vitrification achieved during sintering [1,5].

Experimental studies consistently demonstrate that water absorption increases with increasing cigarette-butt content. Bricks containing low replacement levels, generally up to approximately 1 wt.%, exhibit only moderate increases in water absorption because the newly formed pores remain predominantly isolated or only weakly interconnected. Under these conditions, the ceramic matrix maintains sufficient continuity to limit capillary water transport while simultaneously providing improved thermal insulation through the presence of entrapped air [5,6].

3.5. Thermal Conductivity

The reduction in thermal conductivity results primarily from the low thermal conductivity of air contained within the pores generated during the thermal decomposition of cellulose acetate. Since air is a much poorer heat conductor than the ceramic matrix, increasing the volume of uniformly distributed closed pores effectively interrupts heat flow through the brick. This mechanism explains the consistent decrease in thermal conductivity reported by experimental investigations as cigarette-butt content increases [1,5].

Several studies have demonstrated that relatively small additions of cigarette butts produce measurable improvements in thermal insulation without causing unacceptable reductions in mechanical performance. Bricks containing approximately 1 wt.% cigarette butts typically exhibit a significant decrease in thermal conductivity while

maintaining compressive strength within the limits required for structural masonry applications. This balance between mechanical resistance and thermal efficiency represents one of the principal advantages of cigarette-butt-derived fired clay bricks over conventional dense ceramic products [5,6].

3.6. Durability

The long-term performance of fired clay bricks is strongly influenced by their pore system. Uniformly distributed, predominantly closed pores generated by the thermal decomposition of cellulose acetate reduce density and improve thermal insulation without significantly compromising structural stability. In contrast, excessive pore connectivity facilitates moisture penetration, increasing the susceptibility of the material to weathering processes such as freeze-thaw deterioration, salt crystallization and repeated wetting-drying cycles. Consequently, maintaining a controlled pore structure is essential for achieving satisfactory durability [1,5].

Freeze-thaw resistance is particularly important in temperate climates because water retained in connected pores can generate hydraulic pressure and initiate microcracking. The available evidence establishes the importance of controlling open porosity, but does not yet provide a sufficient basis for a general long-term freeze-thaw rating of CB-derived bricks. Durability should therefore be verified for the intended exposure class and manufacturing formulation [5,6].

4. ENVIRONMENTAL SAFETY OF CIGARETTE-BUTT-DERIVED FIRED CLAY BRICKS

4.1. Thermal Degradation and Immobilization of Contaminants

During the production of fired clay bricks, cigarette butts are exposed to temperatures typically ranging from 900 to 1050 °C. At these temperatures, cellulose acetate undergoes complete thermal decomposition, while the majority of organic pollutants are oxidized into gaseous products that are removed during firing. Thermogravimetric and chemical analyses reported in recent studies demonstrate that the organic fraction of cigarette filters is almost entirely destroyed before the completion of the firing cycle, preventing its persistence within the final ceramic product [1,5].

Simultaneously, mineral transformations occurring within the clay matrix promote the stabilization of inorganic contaminants. As sintering progresses, clay particles undergo partial vitrification, producing a dense ceramic framework capable of physically encapsulating trace metallic elements. Some contaminants also become chemically incorporated into newly formed crystalline or amorphous ceramic phases, further reducing their mobility. Consequently, the final fired brick functions as a stable ceramic matrix in which potentially hazardous inorganic constituents remain immobilized throughout the service life of the material [3,6].

4.2. Heavy Metal Leaching Behaviour

Experimental leaching studies consistently demonstrate that properly fired cigarette-butt-derived bricks release only negligible quantities of heavy metals when subjected to standardized leaching procedures. The extremely low concentrations measured in aqueous extracts indicate that the ceramic matrix effectively limits contaminant mobility through a combination of physical encapsulation and chemical immobilization. As a result, the concentrations of released metals generally remain well below internationally accepted regulatory limits for construction materials and inert waste products [3,6].

4.3. Life-Cycle Considerations and Sustainability Assessment

The replacement of a small fraction of natural clay with cigarette-butt waste also contributes to the conservation of non-renewable mineral resources. Although the replacement levels are relatively low, widespread industrial implementation could substantially decrease the cumulative demand for virgin clay extraction over time. Reduced extraction activities may lessen land degradation, habitat disturbance and the environmental impacts associated with quarrying operations, thereby improving the overall sustainability profile of ceramic manufacturing [5,6].

From the perspective of circular economy principles, cigarette-butt-derived fired clay bricks represent an example of industrial symbiosis in which problematic municipal waste is transformed into a durable construction product with long service life. Rather than following the traditional linear model of extraction, consumption and disposal, this approach promotes resource circulation by maintaining material value within the production cycle. Such strategies are increasingly encouraged by international sustainability policies seeking to reduce waste generation, improve resource efficiency and decrease greenhouse gas emissions throughout the construction industry [2,8].

5. ARCHITECTURAL APPLICATIONS OF CIGARETTE-BUTT-DERIVED FIRED CLAY BRICKS

One of the principal architectural advantages of cigarette-butt-derived bricks is their contribution to energy-efficient building envelopes. Because the incorporation of cigarette butts reduces thermal conductivity through controlled pore formation, masonry walls constructed with these bricks exhibit improved thermal resistance compared with conventional fired clay products. Improved insulation decreases heat transmission through external walls, thereby reducing heating demand during winter and cooling demand during summer. These characteristics contribute directly to lower operational energy consumption and reduced greenhouse gas emissions throughout the building life cycle [1,5].

The lower bulk density of cigarette-butt-derived bricks also offers important structural and architectural benefits. Lightweight masonry units reduce permanent loads acting on foundations and supporting structural systems, facilitating more efficient structural design while simplifying transportation and on-site construction.

Reduced material weight improves handling during installation and may contribute to shorter construction times, particularly in low-rise and medium-rise residential buildings where masonry remains one of the dominant wall construction systems [3,6].

From an architectural perspective, CB-derived units could be integrated into conventional masonry systems if their dimensions, strength class, moisture behaviour and compatibility with mortars are demonstrated under the applicable product and design standards. Their use should therefore be specified by performance class rather than assumed to be interchangeable with every conventional fired clay unit [5,7].

Despite these advantages, practical implementation should remain based on optimized manufacturing conditions that ensure consistent engineering performance. Appropriate control of cigarette-butt content, firing temperature and quality assurance procedures is essential to maintain the balance between structural capacity, durability and thermal efficiency required for long-term architectural applications. When these requirements are satisfied, cigarette-butt-derived fired clay bricks represent a technically feasible and environmentally responsible alternative to conventional ceramic masonry materials.

6. CONCLUSIONS

The thermal decomposition of cellulose acetate during firing produces a controlled porous microstructure that significantly influences the engineering performance of the final material. Properly optimized cigarette-butt contents, generally around 1 wt.%, reduce bulk density and thermal conductivity while maintaining compressive strength, water absorption and durability within the limits required for fired clay masonry applications. The resulting lightweight ceramic products offer improved thermal insulation, contributing to enhanced building energy efficiency and reduced operational energy consumption.

High-temperature ceramic processing also provides an effective mechanism for environmental protection. Organic contaminants present in cigarette filters are almost completely decomposed during firing, whereas residual inorganic constituents become immobilized within the vitrified ceramic matrix. Experimental investigations report low heavy metal leaching from properly manufactured bricks, supporting environmental acceptability under the leaching conditions evaluated in the cited studies.

Although the available scientific evidence confirms the technical feasibility of this recycling approach, successful industrial implementation requires careful optimization of manufacturing parameters, including waste content, pretreatment procedures and firing conditions. Future research should focus on large-scale industrial production, long-term field performance and comprehensive life-cycle assessment to facilitate broader commercial adoption.

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TOPIC 04

ADAPTIVE REUSE & BUILT HERITAGE

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

A COMPARATIVE CODING FRAMEWORK FOR ADAPTIVE REUSE OF HISTORIC HOSPITAL BUILDINGS AND COMPLEXES

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Abstract

Historic hospital buildings and complexes represent a specific category of built heritage whose obsolescence is related not only to medical function, but also to inherited spatial organisation, layout form, technical requirements and urban position. Although many no longer meet contemporary healthcare standards, they often retain significant architectural, urban and heritage value.

The objective of this paper is to develop a comparative coding framework for analysing adaptive reuse of historic hospital buildings and complexes. The research is based on 43 international examples of former healthcare buildings and complexes converted predominantly to non-medical functions. Each case is coded according to current use, original healthcare function, hospital layout form, urban position, construction period, architectural style, heritage status and data reliability. The database is analysed through descriptive statistics, cross-tabulation, exploratory association testing and interpretative pattern analysis.

The results show that cultural, hotel and residential functions are the most frequent reuse directions. Older and highly valuable hospital buildings are more often associated with cultural or museum reuse, while later, larger and more spatially adaptable complexes tend to support hotel, residential or mixed-use transformation. The framework provides a structured basis for comparing inherited hospital characteristics and contemporary programme selection.

Key words: *adaptive reuse, hospital heritage, coding framework, hospital layout form, built heritage*

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1. INTRODUCTION

Historic hospital buildings and complexes represent a distinctive category of built heritage whose adaptive reuse cannot be understood solely as functional replacement. Their transformation is shaped by inherited spatial organisation, urban position, architectural character, heritage significance and the capacity of existing layouts to accommodate contemporary programmes.

Unlike many other historic building types, hospitals were designed according to specific medical, institutional and organisational principles. Wards, pavilions, courtyards, circulation systems, service zones and plot structures reflected healthcare regimes rather than generic architectural requirements. When medical use becomes obsolete, these inherited spatial characteristics may either facilitate or constrain future reuse, influencing the suitability of cultural, residential, hotel, educational or mixed-use programmes.

Consequently, adaptive reuse of historic hospital buildings and complexes should be analysed not only through heritage conservation and sustainability, but also through the relationship between inherited spatial configuration and future functional compatibility.

General studies of adaptive reuse emphasise extending building life cycles, reducing demolition, preserving embodied resources and maintaining cultural continuity [1–6]. In healthcare architecture, the reuse of obsolete facilities is linked to changing medical standards and regulatory requirements [7,8], while heritage conservation frames reuse as a way to keep historic buildings active while preserving authenticity and social value [9–12]. However, a compact comparative coding tool that relates inherited hospital layout form to new programme selection is still lacking.

The objective of this paper is to develop a comparative coding framework for investigating the relationship between inherited hospital layout form, heritage characteristics and contemporary reuse outcomes. Rather than serving only as a descriptive classification, the framework establishes a transferable analytical structure for comparing otherwise diverse hospital reuse cases.

2. ADAPTIVE REUSE OF HOSPITAL HERITAGE

Within built heritage, adaptive reuse extends building life and maintains cultural continuity while keeping historically significant buildings active through compatible new functions [1–12, 18]. In former hospitals, reuse is specifically conditioned by ward structures, circulation systems, courtyards, service areas and relationships between functional units. These inherited arrangements often differ from contemporary non-medical requirements, making spatial configuration a key factor in reuse potential.

Previous studies have examined adaptive reuse primarily through sustainability, conservation and economic feasibility [1–12], while healthcare-related research has focused on changing medical standards, hospital planning and patient environments [7,8,13]. Studies dealing with hospital morphology show that layout characteristics, spatial hierarchy, complexity and relationships between functional units provide a

useful basis for comparing healthcare buildings across different historical periods [15–17].

Urban position also affects reuse potential. Earlier hospitals were often established on generous peripheral sites that later became integrated into expanding urban areas, while more recent healthcare planning increasingly considered landscape quality, orientation and therapeutic environmental conditions [14]. Together with layout form, these contextual characteristics influence the range of functions that can be accommodated after medical use has ceased.

These observations provide the conceptual foundation for the comparative coding framework developed in this study. The framework treats layout form, urban context and inherited organisational structure as key analytical variables for interpreting the relationship between historic hospital characteristics and contemporary reuse outcomes.

3. RESEARCH DESIGN AND CODING METHODOLOGY

This study adopts an exploratory comparative design to investigate adaptive reuse in historic hospital buildings and complexes. It uses a structured corpus of 43 international examples of former healthcare buildings or complexes converted to predominantly non-medical uses. Rather than seeking statistical representativeness, the study aims to identify recurring relationships between inherited spatial characteristics and reuse outcomes through systematic comparison.

The unit of analysis is a historic hospital building or complex, understood as a former healthcare building, group of buildings, hospital estate or urban block with discontinued or transformed medical function and architectural, urban, typological, social or heritage significance. The term is not limited to legally protected monuments; later twentieth-century complexes are included when their scale, morphology or urban role is relevant for adaptive reuse analysis.

The analysed examples were selected according to five criteria: identifiable original healthcare function; completed adaptive reuse or defined non-medical function; sufficient information on current use, layout form, urban position and heritage status; contribution to layout-form diversity; and illustration of a relevant reuse direction. The corpus was assembled from academic literature, institutional sources and documented redevelopment projects. It is a purposive comparative sample designed to maximise analytical diversity rather than a systematic global inventory.

The research methodology follows three sequential stages: (1) case selection and data collection, (2) coding using predefined analytical categories and (3) comparative analysis of the coded dataset. During database development, academic literature, institutional reports, architectural documentation, site plans and floor plans were examined to identify the inherited spatial organisation of each hospital building or complex. Particular attention was devoted to hospital layout form, the principal analytical variable of the proposed framework (Figure 1). Each case was then transformed into a standardised analytical record covering current use, original

healthcare function, hospital layout form, urban position, construction period, architectural style, heritage status and data reliability.

The coded database was analysed using descriptive statistics, cross-tabulation and interpretative pattern analysis. Frequency distributions and percentages were used to describe the structure of the sample, while cross-tabulations examined relationships between current use, hospital layout form and construction period. Because of the limited and purposively selected sample, inferential statistics were used only in an exploratory manner. An exploratory chi-square test and Cramer's V were applied to the full HLF × CU table, while Fisher exact tests were used for selected planned comparisons with small expected frequencies. The aim was not to establish statistically representative global models, but to identify recurring tendencies within the selected comparative corpus.

4. CODING CATEGORIES

The proposed coding framework transforms heterogeneous hospital reuse projects into a standardised analytical dataset suitable for systematic comparison. Each case was coded using eight categories: current use, original healthcare function, hospital layout form, urban position, construction period, architectural style, heritage status and data reliability.

Current use (CU) records the dominant post-medical function, while original healthcare function (OHF) identifies the principal historical medical purpose. Hospital layout form (HLF), the central analytical variable, records the dominant inherited spatial configuration relevant to adaptive reuse. Four aggregated layout forms were identified: hospital village, pavilion, block and campus (Figure 1). Hospital village denotes a layered ensemble of interconnected buildings, courtyards and functional units; pavilion refers to separate or semi-separated ward buildings in open or landscaped sites; block describes compact buildings organised as wings, courtyards or urban blocks; and campus refers to larger hospital estates with multiple buildings and open spaces. These categories describe spatial organisation rather than historical medical planning concepts.

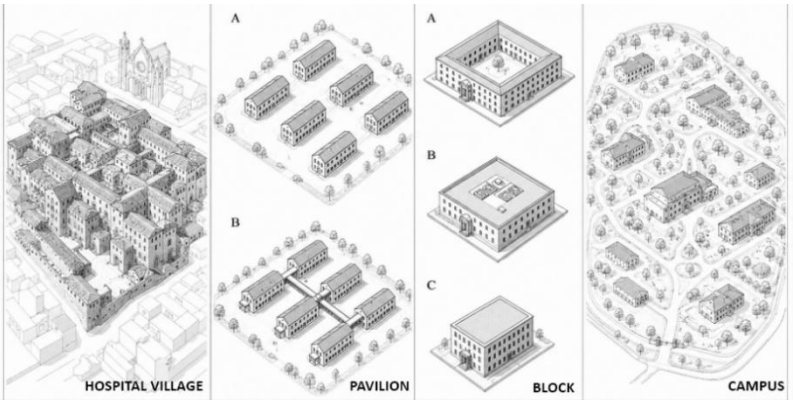


Figure 1. Schematic interpretation of hospital layout forms used in coding. Source: authors

Urban position (UP) records the relationship between the hospital and its surrounding context, while construction period, architectural style and heritage status describe historical and conservation characteristics. Data reliability (DR) indicates the quality and consistency of available comparative information.

Table 1. Coding categories used in the comparative analysis

Code group	Codes	Meaning
Current use (CU)	CU1–CU6	CU1 culture/museum; CU2 hotel/tourism; CU3 housing; CU4 mixed use; CU5 office/public administration; CU6 university/education
Original healthcare function (OHF)	OHF1–OHF7	OHF1 general hospital; OHF2 sanatorium; OHF3 military hospital; OHF4 psychiatric hospital; OHF5 children's hospital; OHF6 specialised hospital; OHF7 other healthcare use
Hospital layout form (HLF)	HLF1–HLF4	HLF1 hospital village; HLF2 pavilion; HLF3 block; HLF4 campus
Urban position (UP)	UP1–UP5	UP1 central urban; UP2 inner urban; UP3 peripheral/suburban; UP4 parkland/landscape; UP5 isolated/specific
Construction period (CP)	CP1–CP5	CP1 pre-1800; CP2 1800-1899; CP3 1900-1945; CP4 post-1945; CP5 unknown
Architectural style (AS)	AS1–AS13	AS1 Medieval/Gothic; AS2 Renaissance; AS3 Baroque; AS4 Classical; AS5 Historicist; AS6 Romanesque; AS7 Beaux-Arts; AS8 Arts and Crafts; AS9 Art Deco; AS10 Modernist; AS11 Regional Revival; AS12 Mixed/layered; AS13 Other
Heritage status (HS)	HS1–HS5	HS1 confirmed protection; HS2 partial protection; HS3 contextual protection; HS4 no confirmed protection; HS5 unknown/insufficient data
Data reliability (DR)	DR1–DR3	DR1 high; DR2 medium; DR3 low reliability of available comparative data

Table 1 summarises the coding categories and their associated codes, while Table 2 illustrates their application to selected examples from the comparative database. The database consists of 43 coded cases; due to the page limit, only selected examples are presented here, while the complete coded database is available from the authors upon request.

Table 2. Example of coded cases from the comparative database

Case	Country	Constr. period	Current function	CU	OHF	HLF	UP	HS	AS	DR
Santa Maria della Scala, Siena	Italy	pre-1800	cultural / museum use	CU1	OHF1	HLF1	UP1	HS1	AS12	DR1
Hôtel-Dieu de Marseille	France	1800–1899	hotel / tourism	CU2	OHF1	HLF3	UP1	HS1	AS4	DR1
Bristol General Hospital	United Kingdom	1800–1899	residential reuse	CU3	OHF1	HLF3	UP2	HS1	AS5	DR1
Sant Pau, Barcelona	Spain	1900–1945	cultural / museum use	CU1	OHF1	HLF2	UP2	HS1	AS5	DR1
Genesee Hospital	USA	1900–1945	mixed use	CU4	OHF1	HLF4	UP3	HS4	AS5	DR2

Note: The table shows selected coded cases only; code meanings are defined in Table 1.

5. COMPARATIVE RESULTS

The coded database enables comparison between cases through shared analytical variables and reveals recurring relationships between inherited spatial characteristics and contemporary reuse outcomes. The analysis identifies three dominant adaptive reuse directions within the selected corpus: cultural and museum functions, hotel and tourism development, and residential conversion. Together, these categories account for more than 85% of the analysed cases, indicating that historic hospital buildings are most frequently transformed into programmes capable of accommodating existing spatial structures while preserving their architectural identity (Table 3).

Table 3. Distribution of analysed cases by current use

Current use category	Number of cases	Share
Culture / museum / cultural function	14	32.6%
Hotel / tourism	12	27.9%
Housing / residential	11	25.6%
Mixed use	3	7.0%
Office / public administration	2	4.7%
University / education	1	2.3%

Table 4 summarises both the distribution of hospital layout forms and their relationship with current use. Block configurations constitute the largest group within the dataset, followed by hospital villages, campuses and pavilion systems. This distribution reflects the diversity of historic hospital development and the different levels of spatial complexity present in the analysed corpus. More importantly, the cross-tabulation indicates that reuse outcomes are not evenly distributed across layout forms. Although these relationships should not be interpreted as deterministic, they reveal recurring tendencies and suggest that hospital layout form is an important analytical variable for evaluating adaptive reuse potential.

Table 4. Relationship between hospital layout form and current use

Layout form	Culture	Hotel	Housing	Mixed	Office	Univ.	Total
Hospital village	7	1	0	0	0	0	8 (18.6%)
Pavilion	2	1	2	0	1	0	6 (14.0%)
Block	4	8	7	2	1	0	22 (51.2%)
Campus	1	2	2	1	0	1	7 (16.3%)

An exploratory chi-square test of the full HLF × CU table suggested a possible moderate association, $\chi^2(15, N = 43) = 22.95$, $p = 0.085$, Cramer's $V = 0.42$. Since several expected frequencies were small, two planned Fisher exact tests were applied. Hospital village forms were associated with cultural/museum reuse (7/8 vs. 7/35; $p = 0.0007$), while block forms were associated with hotel, residential and mixed-use redevelopment (17/22 vs. 9/21; $p = 0.031$). These exploratory results support the interpretation that inherited layout form is related to reuse direction.

5.1. Cultural and museum reuse

Cultural and museum reuse is the most frequent category in the analysed sample. It is often associated with buildings that have strong architectural, historical or symbolic value, where the former hospital history and spatial organisation become part of the cultural narrative. Courtyards, chapels, wards and historic interiors can support museum, gallery, archive or public cultural functions. Examples include Santa Maria della Scala in Siena and the Recinte Modernista Sant Pau in Barcelona.

5.2. Hotel and tourism reuse

Hotel and tourism reuse is another frequent direction. Former hospitals in central urban areas, historic districts or visually prominent locations can become attractive for hospitality because their architectural identity contributes to the experience of place [19]. This pattern is illustrated by the Hôtel-Dieu de Marseille and St. Vincent's Hospital in Santa Fe, both converted into hotels while retaining a recognisable historical identity.

The coding suggests that hotel reuse is often connected with location value and recognisable architectural character. Compact historic hospitals can be adapted for hospitality when room organisation, service circulation and public areas can be inserted without excessive loss of heritage character.

5.3. Residential reuse

Residential reuse is strongly connected with the capacity of the building or site to support subdivision into dwelling units. Former hospitals with repeated spatial modules, large floor areas, separate wings or significant open space may be suitable for housing. Examples include Bristol General Hospital, converted into The General as a heritage-led residential scheme with mixed-use elements.

Residential reuse is often linked to broader site transformation, including new open spaces, additional buildings or phased development. In larger former hospital complexes, this process may also contribute to the transformation of the surrounding urban area by introducing new housing, public space, commercial uses and improved connectivity. Smaller urban hospitals, by contrast, depend more on the internal adaptability of the existing structure.

5.4. Mixed, institutional and educational reuse

Mixed-use reuse appears in fewer cases, but it demonstrates the capacity of hospital complexes to become part of broader urban regeneration. Large hospital sites or urban blocks may not be adequately reused through a single programme; combinations of housing, hotel, cultural, commercial and public functions may better respond to their spatial complexity. Mixed-use reuse is illustrated by Cook County Hospital in Chicago, while educational reuse is represented by the former hospital in Lecco, transformed into a university campus.

Institutional reuse, including public administration and education, shows another form of continuity: although the medical function is lost, the building remains part of civic or institutional infrastructure. Former wards, administrative zones and service areas may be adapted into offices, classrooms or public service spaces.

5.5. Secondary patterns in the coded corpus

Geographical variation was also observed. In the selected corpus, examples from the United States are more often linked to hotel, residential and mixed-use redevelopment, the United Kingdom to residential conversion, Italy to cultural reuse, Spain to cultural and public functions, and France to hotel and cultural programmes. These are indicative tendencies within the analysed sample rather than representative national models.

Table 5. Relationship between construction period and current use (count; row %)

Period	Culture	Hotel	Housing	Mixed	Office	Univ.	Total
Pre-1800	11 (73.3%)	3 (20.0%)	0 (0.0%)	0 (0.0%)	1 (6.7%)	0 (0.0%)	15
1800–1899	1 (8.3%)	5 (41.7%)	4 (33.3%)	1 (8.3%)	0 (0.0%)	1 (8.3%)	12
1900–1945	2 (14.3%)	3 (21.4%)	6 (42.9%)	2 (14.3%)	1 (7.1%)	0 (0.0%)	14
Post-1945	0 (0.0%)	1 (50.0%)	1 (50.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	2
Total	14 (32.6%)	12 (27.9%)	11 (25.6%)	3 (7.0%)	2 (4.7%)	1 (2.3%)	43

The second pattern concerns construction period (Table 5). Earlier hospital buildings, especially those constructed before 1800, are strongly associated with cultural and museum reuse, reflecting exceptional heritage significance and symbolic value. Nineteenth-century hospitals demonstrate a more balanced distribution between hotel and residential conversion, whereas twentieth-century examples more often accommodate residential, hotel and mixed-use redevelopment. Construction period does not determine adaptive reuse outcomes, but it contributes to understanding relationships between historical development, inherited spatial organisation and programme selection.

6. DISCUSSION

The comparative coding framework demonstrates that systematic coding can provide insights that remain less evident in descriptive case-based studies. By transforming diverse hospital buildings and complexes into a common analytical structure, the framework enables comparison of adaptive reuse projects according to consistent spatial, historical and contextual variables rather than through isolated examples.

The findings suggest that adaptive reuse outcomes are influenced by the interaction of multiple inherited characteristics rather than by any single determinant. The original healthcare function alone does not sufficiently explain later reuse outcomes. Instead, hospital layout form, urban position, construction period, architectural character and heritage status appear to shape the range of programmes that can be accommodated.

Among the analysed variables, hospital layout form emerges as a particularly informative comparative parameter. Rather than representing a historical typological classification, it functions as an organisational descriptor of inherited spatial structure that links architectural morphology with functional adaptability. The observed relationships between layout form and reuse direction indicate that spatial configuration should be considered during the earliest stages of adaptive reuse

evaluation. The geographical and chronological patterns identified within the corpus should be interpreted cautiously. They do not represent statistically representative national or historical models, but they nevertheless suggest that adaptive reuse reflects broader cultural, planning, economic and conservation contexts.

The principal limitation of the research lies in the simplification required by comparative coding. Complex hospital sites frequently comprise multiple construction phases, layered heritage values and mixed redevelopment programmes that cannot be fully represented through categorical variables alone. Nevertheless, such abstraction is necessary to enable systematic comparison across a heterogeneous international corpus.

7. CONCLUSION

This paper has presented a comparative coding framework for analysing adaptive reuse of historic hospital buildings and complexes. By integrating information on original healthcare function, current use, hospital layout form, urban position, construction period, architectural style, heritage status and data reliability into a common analytical structure, the framework enables systematic comparison between otherwise heterogeneous international case studies.

The application of the framework to a corpus of 43 adaptive reuse projects demonstrates that cultural and museum functions, hotel and tourism development, and residential conversion represent the dominant reuse strategies within the analysed sample. The results further indicate that adaptive reuse outcomes are associated not only with heritage significance or former medical function, but also with inherited spatial organisation and contextual characteristics. In particular, hospital layout form appears to be a valuable comparative variable for interpreting recurring reuse tendencies across different geographical and historical contexts.

The principal contribution of this research is a transferable comparative framework that organises complex architectural information into a consistent coding structure. In the early design stages, it can support preliminary evaluation of adaptive reuse potential and help identify programme and intervention strategies compatible with inherited spatial organisation, heritage constraints and urban context. It does not replace detailed architectural, conservation, technical or economic assessment, but structures the initial screening and prioritisation of alternatives. Future research may translate selected categories into indexed indicators of spatial flexibility, heritage significance, urban integration and functional compatibility.

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Research paper

ADAPTIVE REUSE OF TRADITIONAL ARCHITECTURE: A CASE STUDY OF AN OLD HOUSE IN THE RURAL SETTLEMENT OF MUŽINAC

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Abstract *Old houses in rural areas preserve the spirit of past times, materializing tradition, local customs, and construction skills that shape the identity of a place. This paper addresses the issue of adaptive reuse of traditional vernacular architecture through the case study of an old house in the rural settlement of Mužinac, in Municipality of Sokobanja, southeastern Serbia. The aim of the research is to define a sustainable approach to the restoration, reconstruction and revitalization of a vernacular building by proposing structural interventions and identifying an appropriate new function. Field analysis, precise measurements, and documentation were used to assess the existing condition and define appropriate intervention strategies based on the principle of minimal intervention. The results demonstrate that a traditional house can be brought back to life in a relatively simple manner, thereby promoting a sustainable approach to the preservation of rural architectural heritage and the safeguarding of local traditions.*

Key words: *adaptive reuse, restoration, reconstruction, revitalization, traditional rural architecture, Rtanj Tea House*

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1. INTRODUCTION

Old houses in rural settlements, as examples of vernacular traditional architecture, represent valuable heritage that preserves the spirit of past times, embodies tradition and building craftsmanship, and connects new generations with their ancestors [1] [2]. Despite their significant cultural, historical, and ecological value, only a small number of well-preserved old houses remain in Serbia [3] [4]. Most of them are deteriorating due to long-term exposure to harsh weather conditions and careless human interventions [5] [6]. Rural vernacular architecture not only reflects the rich history and traditions of rural communities but also achieves harmony with the natural, cultural, and social context through the use of local natural materials and traditional construction techniques [7] [8].

This paper focuses on the analysis and proposed adaptive reuse of an old house in the rural settlement of Mužinac, Municipality of Sokobanja, southeastern Serbia, examined from architectural, structural, and functional perspectives. Although the building is not designated as a cultural heritage asset [9], it possesses characteristics of vernacular architecture that contribute to the local identity and should therefore be preserved [10]. Accordingly, this study addresses the following research question: "How can adaptive reuse ensure the long-term preservation and sustainable use of vernacular rural architecture?" In order to answer the research question, adaptive reuse was analyzed through three complementary aspects: restoration, reconstruction, and revitalization, applied to the subject building. The aim of this study is to explore the possible solutions that would simultaneously preserve the building's original characteristics and enable its contemporary use in accordance with the modern needs of people. The study also demonstrates the benefits of applying the principle of minimal intervention [11], emphasizing the preservation of existing materials, authenticity, and the avoidance of unnecessary alterations [12] [13].

2. RESEARCH METHODOLOGY

Adaptive reuse is examined through restoration, reconstruction, and revitalization. Restoration is applied to preserved elements requiring repair; reconstruction to missing or severely deteriorated elements; and revitalization to the compatible new function needed for long-term use. Each proposal follows the condition assessment.

Methods included field inspection, precise measurement, technical documentation, and identification of damage to architectural and structural elements. The adaptive-reuse proposal was then developed according to the principle of minimal intervention.

2.1. Existing condition analysis

The house is located in the village of Mužinac (Figure 1a), within the Municipality of Sokobanja in southeastern Serbia. The cadastral area of Mužinac includes part of the Special Nature Reserve Rtanj, which gives the area ecological significance and potential for the development of tourism-related activities.



Figure 1. Location of the house a) in relation to the village of Mužinac b) in relation to immediate surroundings (GeoSrbija, Google Earth, author's processing)

Located in the central part of a rural household in the southern section of the village settlement, the old house opens on its western side toward Dušanke Spajić Street, while within the household there are four additional structures: newer house, old granary and two barns (Figure 1b). The house was built before World War II and was originally used for residential purposes, while today it is used as a storage space. The main reason for the underutilization of the house's potential is the current condition of its architectural elements, which are partially damaged.

The building (Figure 2) is a traditional timber-framed (bondruk) [14] house characterized by a stone masonry basement, timber structural elements, earthen infill walls, wooden floor and roof structures, and largely preserved original joinery. Despite a prolonged period of inadequate maintenance and exposure to external factors, the overall structural condition remains stable. The condition assessment was carried out through an in situ visual inspection and an authorial assessment, based on observable deterioration, material condition, structural stability, and the preservation of individual building elements.

The stone basement walls and primary timber load-bearing elements are well preserved, while the most significant deterioration is visible in the roof covering, where damaged clay tiles and deteriorated battens have led to water infiltration. Additional deterioration is evident in the external wall finishes, where the loss of protective plaster layers has exposed parts of the earthen infill to weathering. Original windows and doors have been retained to a large extent, exhibiting only localized damage and material loss. Overall, the building retains a high degree of authenticity, with most architectural elements remaining intact and requiring primarily conservation, repair, and localized restoration interventions rather than extensive reconstruction.



Figure 2. The old house in Mužinac (author)

The house has a rectangular floor plan, with a ground floor and a basement, both levels having separate entrances on the southern facade. Due to the slope of the terrain, the basement is partially underground and smaller in size than the ground floor. The ground floor consists of four rooms, whose layout is characteristic of the Morava house. On the western side, there is a canopy, later added along the edge of the plot next to the road, which disrupts the harmony of the house's original appearance (Figure 3).

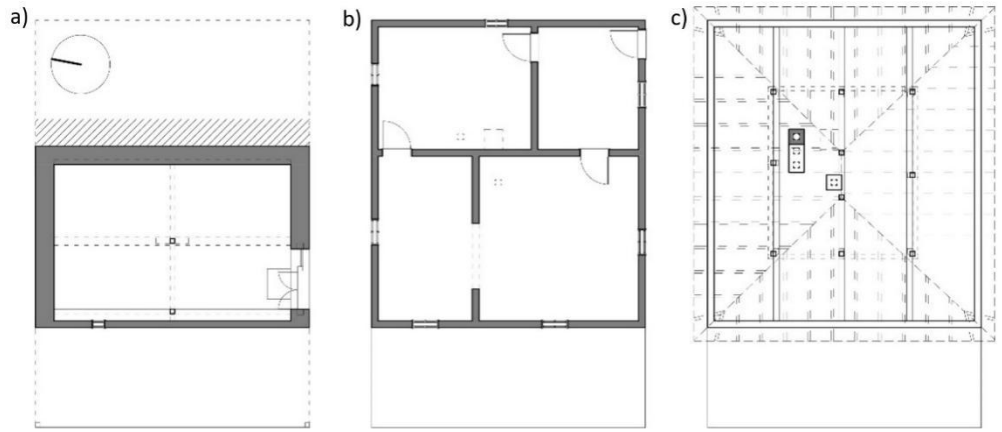


Figure 3. Plans of the old house: a) basement plan, b) ground floor plan, c) roof structure plan (author)

2.2. Restoration aspect of adaptive reuse

Restoration refers to the process of returning the existing fabric of a place to a known earlier state by removing accretions or by reassembling existing elements without introducing new materials [11]. In the case of the subject building, restoration involves the repair and conservation of existing architectural elements rather than their replacement with new ones, while preserving as much original material as possible [15].

Regarding the walls, damaged infill should be restored using traditional techniques such as 'čatma' and 'plet' [14], followed by a traditionally applied lime-plaster finish.

Basement walls require only localized repointing to improve durability and weather protection.

The intermediate wooden floor structure is generally sound; damaged boards should be replaced, after which the floor should be sanded and protected.

The rammed-earth floor requires leveling and consolidation. Although a wooden finish could align it with the other rooms, retaining rammed earth in at least one room would preserve this traditional construction technique.

The attic structure requires removal and repair of deteriorated infill with traditional materials (mud, straw, and twigs), followed by lime whitewashing.

Windows and interior doors should be conserved by reinstating missing glazing, repairing or replacing individual fittings, filling and sanding the timber, and applying protective finishes.

Both chimneys should be returned to use. On the three-flue chimney, the functional flue should be repaired and the two unused sections dismantled.

2.3. Reconstruction aspect of adaptive reuse

Reconstruction refers to the process of returning a place to a known earlier state but it is distinguished from restoration by introducing new materials into the fabric [11]. Reconstruction is applied where restoration is no longer feasible; in the case of the subject building, it is required for the rebuilding and/or replacement of certain architectural elements in order to restore the building to its original functional condition.

Based on visible damage (Figure 4), it can be concluded that the two exterior walls of the entrance room originally contained arches, indicating that the house belongs to the Moravian architectural style [16]. The arches were later infilled, thereby transforming the porch into an enclosed entrance room.

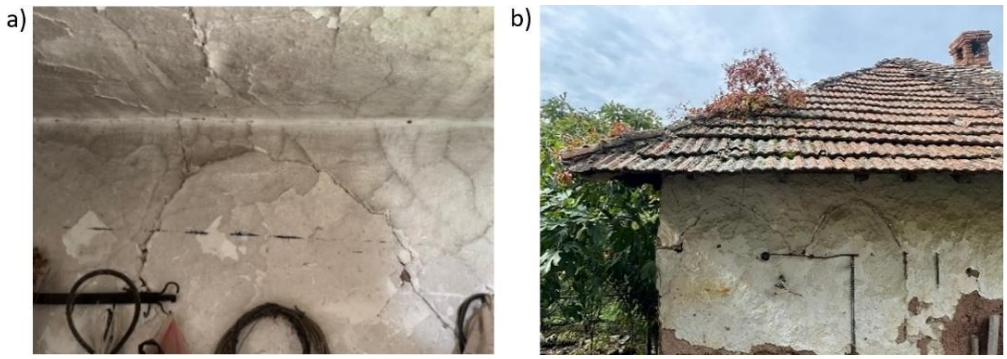


Figure 4. Visible damage within the entrance area indicating the former existence of arches: a) interior view, b) exterior view (author)

One of the elements to be reconstructed is the entrance area, which originally functioned as a porch (trem). It is proposed that this space be restored in accordance with its original form and construction principles, using traditional building techniques. Given that the structural system of the building is preserved, the porch can be re-established by removing the existing infill and reopening the original arched openings. Three arches are planned on the southern side and two more on the eastern side. The

exact positions of these arches correspond to their original locations and can be identified based on semicircular traces and damage patterns preserved on the walls. This reconstruction would reintroduce two entrances through the porch instead of the existing single entrance, thereby restoring the characteristic features of Moravian-style vernacular architecture (Figure 5). The existing entrance doors, which are in poor condition and do not belong to the original architectural concept, should be removed, as the reintroduction of arches in accordance with the original facade design is planned at this location.

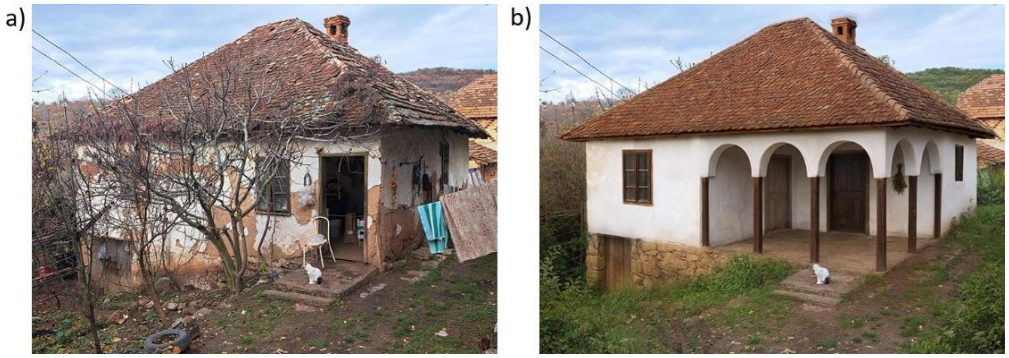


Figure 5. Reconstruction aspect of adaptive reuse: southeastern view: a) existing condition, b) proposed reconstruction (author, author's intervention on the photograph, use of AI and Photoshop)

The canopy located on the western part of the building, which was intrusively added at the end of the last century as a garage space, should be dismantled. This addition significantly alters the original appearance and identity of the house. In order to bring back the building's former architectural expression and achieve a more coherent facade composition, the canopy is to be removed, ensuring that the remaining structure of the building is not affected.

The roof requires reconstruction, which includes carefully removing and storing the roof tiles, followed by partial dismantling of the roof structure in order to repair damaged elements. Sound columns and beams should be preserved, while only those elements that are in poor condition and structurally compromised should be replaced. Since the rafters are in a deteriorated condition, they need to be largely replaced with new ones. For certain parts of the structure, it is possible to reuse preserved timber from the dismantled canopy. After the roof structure has been restored, the roof should be re-covered with the preserved original clay tiles, while missing quantities should be supplemented with reclaimed tiles of the same type, sourced from dismantled buildings of the same period in the surrounding area, in order to ensure material and visual consistency of the roofing. As for one of the chimneys, the removed section should be rebuilt and aesthetically integrated with the existing structure.

2.4. Revitalization aspect of adaptive reuse

Revitalization refers to the process of introducing new uses for buildings while minimizing the impact on their original values and characteristics, with the primary objective of extending their lifespan and ensuring their continued use [17].

In order for the building to be revitalized, it is necessary to redefine its function. Several adaptive reuse options were considered, including residential reuse, an ethnographic museum, and tourist accommodation. Considering that a residential building already exists on the plot, it is not advisable to revitalize the old house as another living space. Even with full rehabilitation, the use of original furniture, and the preservation of the traditional spatial organization, such a building would not be able to fully meet the needs of a contemporary user. Tourist accommodation would require extensive alterations and modern sanitary facilities that would compromise authenticity. A conventional ethnographic museum would preserve the building but would provide limited economic sustainability.

Therefore, it is necessary to establish a new function, while the house would retain its authentic appearance, restored and reconstructed through the previously defined interventions that return its original character. Accordingly, the most appropriate and sustainable use of the building is its transformation into an unconventional museum, the "Rtanj Tea House." This concept preserves the architectural heritage while integrating the local identity of the area through the traditional practice of medicinal herb collection, which has long been part of the inhabitants' everyday life, including the owner's household. By presenting this intangible cultural heritage alongside traditional architecture, crafts, and other local values, the proposed function creates tourism potential and supports long-term economic sustainability.

In addition to its museum function, the building would also have the potential to partially function as a small commercial space, a showroom for local products, as well as an environment for rest, tasting, and tourist visits. In this way, the new function would significantly contribute to the sustainability of the entire household.

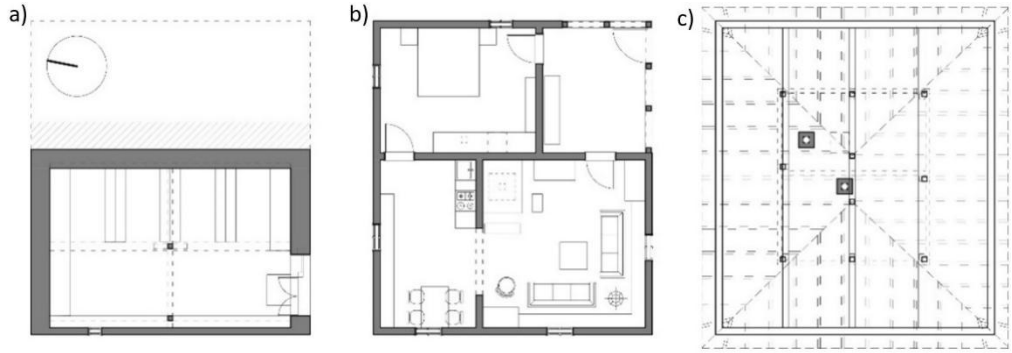


Figure 6. Plans of the revitalized old house: a) basement plan, b) ground floor plan, c) roof structure plan (author)

The ground floor is designed in such a way as to preserve the existing circular flow of rooms. The porch in the southeast becomes a visitor information space, from which one enters the southwestern room arranged as a living area with displayed products and items of cultural value. The chimney is used to form a hearth, "ognjište", assumed to be an original element of the house, where visitors can learn about tea preparation and taste the products. In the northwest, there are displayed products and a small auxiliary kitchen for tea preparation. The northeastern room offers an experience of

sleeping on a straw mattress accompanied by the scents of indigenous medicinal herbs and has access to the porch. No bathroom or toilet is planned within the house, in accordance with the preservation of its original character, as these facilities were traditionally located outside the house. If required, such facilities could be provided in an existing auxiliary building within the household or through a new discreet secondary structure designed according to conservation principles. The basement is arranged to serve as a storage area for products (Figure 6).

3. RESEARCH RESULTS

Table 1 summarizes the condition of the main building elements, the proposed measures, and intervention intensity established by in situ visual inspection and authorial assessment. Low, medium, and high intensity correspond respectively to damage affecting up to 20%, 20–50%, and more than 50% of an element. Low- and medium-intensity interventions are treated as restoration; high-intensity interventions require reconstruction because they introduce new material or structural components.

Restoration is proposed for basement and ground-floor walls, floors, doors, intermediate and attic structures, windows, and one chimney. Reconstruction is required for the severely deteriorated roof, porch, and partly collapsed chimney, while the intrusive canopy is removed.

Table 1. Comparative overview of architectural elements, proposed restoration and reconstruction measures, and intensity of required interventions

Building element	Existing condition	Intervention type	Intensity
Ground floor walls	Structurally sound and stable, with local infill damage	Restoration: repair of masonry infill and lime mortar finishing	Medium
Basement walls	Stable, partially washed-out joints	Restoration: repointing of joints	Low
Intermediate floor structure	Functional, with partial deformations and infill damage	Restoration: replacement of damaged floor sections, impregnation of timber	Medium
Attic structure	Main wooden elements stable, infill damaged	Restoration: repair of damaged infill sections, lime mortar finishing	Medium
Floor	Uneven, partially damaged	Restoration: repair, leveling and consolidation of rammed earth	Low
Windows	Partially damaged but functional	Restoration: repair, sanding, and protective coating application	Medium
Doors	Minor damage	Restoration: improvement of current condition, sanding and protective coating	Low

Roof structure	Roof covering and some structural elements damaged	Reconstruction: repair of individual structural elements and reinstallation of roof tiles	High
Chimney 1	Stable and partially damaged	Restoration: repair of the damaged sections	Medium
Chimney 2	Partially collapsed	Reconstruction: replacement of the collapsed section	High
Porch	Traces of a former porch on the walls	Reconstruction: full reconstruction of the porch	High
Canopy	In conflict with the rest of the building	Removal and dismantling of a later intrusive addition	High

Revitalization introduces the sustainable 'Rtanj Tea House' within the preserved Moravian-house framework, combining tourism, local products, heritage presentation, and education about medicinal plants. The proposal thus restores the original architectural character while assigning a viable contemporary use.

Adaptive reuse supports long-term preservation by combining minimal intervention, traditional techniques, and compatible local, reused, and natural materials with a viable new function. Limiting work to necessary repairs or replacements preserves the house's form, spatial organization, authenticity, and heritage values, while locally available resources reduce costs and the 'Rtanj Tea House' concept ensures continued use.

4. CONCLUSION

This study highlights that adaptive reuse can ensure the long-term preservation and sustainable use of vernacular rural architecture by balancing heritage conservation, material authenticity, and the integration of appropriate contemporary functions. It emphasizes the importance of preserving rural houses as part of both tangible and intangible cultural heritage, with particular attention to the use of traditional, locally sourced, and environmentally sustainable materials. The proposed model can serve as a guideline for the restoration of similar vernacular houses in southeastern Serbia and beyond, encouraging further research into traditional techniques, the involvement of local communities, and the development of sustainable usage programs.

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Research paper

ADAPTIVE REUSE OF ABANDONED BUILDINGS FOR RURAL REVITALIZATION: PRIJEDOR CASE STUDY

Malina Čvoro[1], Andrej Simićević[2]

Abstract

Rural depopulation is one of the most significant socio-spatial challenges in Southeast Europe, leading to building abandonment, the deterioration of cultural landscapes, and declining economic opportunities. This paper presents the results of research conducted within the RurALL project, which aimed to explore the potential of adaptively reusing deteriorating buildings as a tool for the sustainable revitalization of rural areas. The study was carried out in the rural territory of the City of Prijedor, Bosnia and Herzegovina, through a participatory and collaborative planning process inspired by the principles of the New European Bauhaus initiative. The research combined field surveys, the mapping of deteriorating buildings, stakeholder engagement workshops, spatial analysis, and architectural design development. Twenty buildings in villages surrounding Prijedor were analysed and assigned potential new functions in accordance with local needs and development priorities. Based on the analysis, three adaptive reuse pilot projects were developed, representing different categories: public, commercial, and community-oriented functions. The research findings indicate that adaptive reuse can make a substantial contribution to environmental sustainability by preserving embodied resources and reducing construction waste, while simultaneously supporting social inclusion, local entrepreneurship, and the preservation of rural identity. The study proposes a methodological framework for rural revitalization that integrates community participation and architectural design guided by the principles of sustainable development.

Key words: *adaptive reuse, rural revitalization, community participation, sustainable architecture, New European Bauhaus*

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1. INTRODUCTION

Villages in our country, some of which are almost on the verge of disappearing, possess rich cultural and architectural heritage. Their authentic architecture makes them a suitable basis for cultural, economic, and research projects that highlight the value and importance of heritage and its preservation, while also offering local communities a sustainable model for village survival. [1] [2] The objective is clear: to prevent further deterioration and devastation through care and attention to the significance of heritage. Introducing carefully selected new functions and activities would bring renewed vitality to the community. The reconstruction of existing architecturally valuable buildings and the construction of new facilities would protect villages from further decline and preserve the architectural and cultural heritage of the region. [3]

Rural depopulation is an urgent territorial challenge across Europe, characterised by population decline, ageing, economic stagnation, and the abandonment of buildings and infrastructure. These trends are particularly visible in Bosnia and Herzegovina, where many villages face continuous out-migration and declining economic activity.

The City of Prijedor faces similar challenges. Population decline in rural areas, insufficient employment opportunities, underdeveloped infrastructure, and limited access to public services have contributed to the abandonment of numerous residential and public buildings. At the same time, these structures represent a significant spatial resource with the potential to support future development if used appropriately.

Contemporary European policies increasingly promote adaptive reuse as an alternative to demolition and new construction. In this context, the New European Bauhaus initiative advocates solutions that combine sustainability, aesthetics, and social inclusion. The European RurALL project [4] was implemented within this framework, based on the idea of approaching the development and revitalization of deteriorating rural settlements by strengthening the capacities of local communities and local government. The aim of this paper is to analyse the methodological framework developed within the project and assess its potential to support sustainable rural revitalization through the adaptive reuse of abandoned buildings.

2. THEORETICAL FRAMEWORK

Buildings have always been reused for both pragmatic and symbolic reasons. However, out of the turbulent twentieth century, stimulated by reactions against modern “clean” planning, a new field of policy and practice emerged in the 1970s in response to the growing conservation movement and increasing environmental awareness. This field came to be known as “adaptive reuse.” [8]

The last decade in particular has seen a surge of interest in adaptive reuse, both in practice and in academic writing. Today, the practice can be observed across the architectural spectrum, from large-scale, professionally led projects to the most modest community-generated initiatives. Adaptive reuse is ideologically supported through

heritage preservation and carbon-reduction campaigns and is increasingly evident in policy and education.

2.1. Adaptive Reuse of Buildings

Adaptive reuse is the process of converting existing buildings to new functions while preserving their architectural, structural, cultural, and historical values. Unlike demolition and new construction, this approach is based on the principles of sustainable development, as it extends the service life of buildings, reduces the consumption of natural resources, and minimises construction waste [5]. At the same time, adaptive reuse contributes to the preservation of embodied energy, namely the energy already invested in material production, transport, and building construction, thereby significantly reducing the overall carbon footprint compared with new construction [6].

In contemporary architectural theory, adaptive reuse is increasingly recognised as one of the key strategies of the circular economy in construction because it enables the reuse of the existing building stock instead of consuming new material and energy resources. In addition to its environmental benefits, this approach has an important social and cultural dimension, as it helps preserve place identity, the continuity of urban and rural landscapes, and the collective memory of local communities [7]. Particularly in rural and mountainous environments, where traditional architecture is an important carrier of local identity, adaptive reuse makes it possible to reconcile contemporary spatial requirements with the preservation of heritage and natural values.

Adaptive reuse is therefore understood today not only as a conservation practice but also as an integral strategy of sustainable architectural design that connects the environmental, economic, social, and cultural dimensions of development.

2.2. Principles of the New European Bauhaus

The New European Bauhaus (NEB), launched by the European Commission in 2021 as part of the European Green Deal, is an interdisciplinary initiative that connects architecture, urban planning, design, culture, art, science, and technology with the aim of shaping a sustainable, inclusive, and aesthetically high-quality built environment. Unlike traditional approaches that view sustainability primarily through technical and energy-related aspects, the NEB promotes a holistic approach in which environmental responsibility, spatial quality, and social inclusion are inseparable [1].

The New European Bauhaus concept is based on three core values: sustainability, which includes carbon-emission reduction, the circular economy, energy efficiency, the use of renewable and local materials, and biodiversity conservation; beauty, which goes beyond visual appearance to encompass spatial quality, the experience of place, cultural identity, and users' emotional connection with their environment; and togetherness, which includes inclusiveness, accessibility, equality, participatory planning, and the active involvement of local communities in shaping space. These three values provide the foundation for transforming the built environment towards climate neutrality and a higher quality of life.

3. METHODOLOGY

The research was conducted within the RurALL project in the rural settlements of the City of Prijedor. The methodology translated the theoretical principles outlined above into a framework for preserving the existing building stock and local identity while improving the energy, functional, and social qualities of space. It emphasised local and natural materials, circular resource use, community involvement, and preservation of the cultural landscape.

The methodological framework can be presented through five clearly defined research phases:

Phase 1 - Identification and mapping of neglected buildings. Existing rural buildings were identified through field surveys, GIS analysis, and databases from previous projects. Their physical condition, ownership status, accessibility, and development potential were assessed.

Phase 2 - Community involvement. Participatory workshops were organised with local residents, community representatives, entrepreneurs, and public institutions. The workshops explored local needs, development priorities, and possible future uses of abandoned buildings.

Phase 3 - Functional classification. Based on community input and expert assessment, potential new functions were categorised into three groups: public and community-support functions, commercial functions, and residential functions.

Phase 4 - Development of adaptive reuse concepts. Twenty conceptual proposals were prepared for the adaptive reuse of abandoned or underused buildings. These concepts represented different approaches to revitalizing rural settlements and served as the basis for selecting pilot interventions.

Phase 5 - Detailed architectural design. The final step involved selecting three pilot projects. They were developed in detail and evaluated in terms of spatial feasibility, sustainability, and implementation potential.

The diagram summarises the participatory process and its sustainability outcomes.

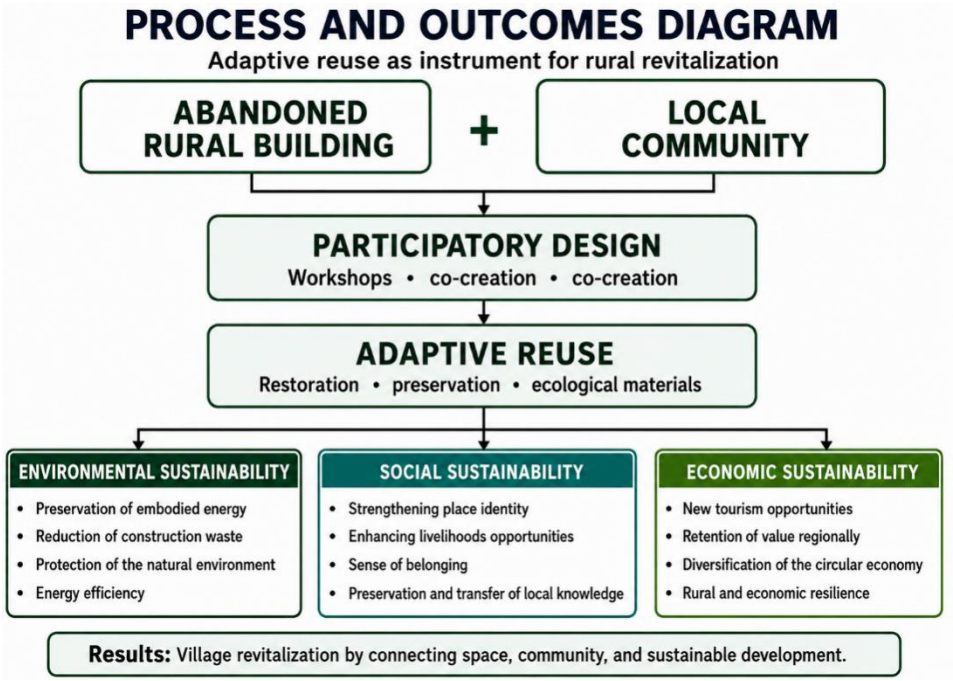


Figure 1. Process and outcomes of the participatory adaptive reuse methodology. Source: Authors' documentation.

4. RESULTS

4.1. Functional Transformation of Rural Buildings

The research showed that abandoned and underused rural buildings in the Prijedor area have considerable potential for new, multifunctional programmes. Through field surveys, community workshops, and expert analysis, twenty buildings were selected and broad adaptive reuse guidelines proposed. The functions were conceived as a network of activities supporting everyday life, local resources, and the distinctiveness of the rural landscape. Most proposals focused on rural tourism, community services, local entrepreneurship, cultural and educational programmes, with additional residential, business, and service functions, including hybrid work-residence models. This demonstrates that rural adaptive reuse must address residents' needs, economic feasibility, and long-term management, not only physical rehabilitation.

The process resulted in three detailed pilot designs: a wine-tasting house in Knežica, a community centre in the former school in Jelovac, and a co-working/start-up hub in Jelićka. These examples represent three different intervention models: commercial-tourism, public-community, and entrepreneurial-educational. This diversity demonstrates the flexibility of the methodological framework and its applicability to different building types, ownership situations, and local-community development priorities.

4.2. Twenty Conceptual Ideas for Adaptive Reuse

In addition to the three detailed pilot projects, twenty conceptual ideas were prepared for mapped buildings in rural Prijedor. Each included broad recommendations for programme transformation, future use, and improvement of physical condition. Rather than complete technical documentation, they form a catalogue of possibilities that local government and communities can use for further planning, funding applications, and phased implementation.

The proposals combined ideas gathered through community workshops and fieldwork with expert architectural analysis. Priority was given to buildings with strong local potential, preservation of cultural, historical, and ambient values, and functions suited to local needs. Proposed uses range from residential, business, tourism, educational, and social programmes to hybrid work-residence models.

Together, the twenty ideas extend the research from individual pilots to a broader rural network. They frame abandoned buildings as dispersed spatial resources that can be systematically activated into new local functions, giving adaptive reuse a strategic role in long-term rural revitalization while preserving identity, supporting the local economy, and strengthening social cohesion.



Figure 2. Example of an existing rural building and an adaptive reuse concept. Source: Authors' documentation.

4.3. Pilot Project 1 - Wine-Tasting House, Knežica

The first pilot project concerns the conversion of an existing barn structure in Knežica into a wine-tasting and storage house. The project is linked to the idea of an experimental vineyard in Knežica, where agricultural innovation is regarded as a driver of local-community development. The new programme includes spaces for tasting, wine storage, educational activities, and the presentation of local products, transforming a neglected rural building into a meeting point for agriculture, tourism, and culture.

The intervention preserves the recognisable volume, structural logic, material expression, and rural character of the building while introducing a new internal layout and contemporary access, service, and terrace areas. It thus combines traditional architectural elements with the principles of the "smart village," energy efficiency, and the local economy.

This pilot project has strong potential for the development of rural and wine tourism because it introduces a programme capable of attracting visitors, supporting local producers, and creating new forms of education in agriculture, processing, and product presentation. The preliminary financial estimate for the project is BAM 115,020.50, positioning it as a moderate-scale intervention with clear economic and promotional benefits for the local community.





Figure 3 (left). Existing condition of the Wine-Tasting House, Knežica. Source: Authors' documentation.
Figure 4 (right). Architectural visualization of the proposed wine-tasting house in Knežica. Source: Authors' documentation.

4.4. Pilot Project 2 - Community Centre, Jelovac

The second pilot project was developed for the former school building in the village of Jelovac. The building, which already holds a strong symbolic role in the collective memory of the local community, was proposed for transformation into a community centre. This conversion preserves the building's public character and continues its role as a gathering place while adapting it to the contemporary needs of residents.

The new programme includes a community gathering space, facilities for children, educational and recreational activities, and the possibility of occasional accommodation for hikers or children from urban areas participating in outdoor-school programmes and similar activities. This combination of functions allows the building to operate not only occasionally, but as a flexible space for different user groups and seasonal scenarios.

The design adapts the existing school typology into a more open and flexible public space, improving accessibility, comfort, and capacity for uses ranging from workshops and meetings to children's stays and organised visits. The project shows how reusing rural public buildings can strengthen belonging, intergenerational exchange, and rural-urban connections. The preliminary value of the intervention is BAM 121,353.00.





Figure 5 (left). Existing condition of the former school in Jelovac. Source: Authors' documentation.
Figure 6 (right). Architectural visualization of the proposed community centre in Jelovac. Source: Authors' documentation.

4.5. Pilot Project 3 - Co-working Hub, Jelićka

The third pilot project concerns an unused part of the local community building in Jelićka, proposed for conversion into a co-working space and start-up hub for young people. Unlike the first two examples, this intervention is directly oriented towards contemporary working models, local entrepreneurship, and retaining young people in the village. Adaptive reuse thus becomes an instrument of demographic and economic renewal, rather than merely a method of rehabilitating physical structures.

The programme includes shared workspaces, meeting rooms, education, presentations, training, and support for small local initiatives. With the increasing digitalisation of work, it can help young people develop business ideas locally while providing a networking platform for producers, organisations, entrepreneurs, and public institutions.

The architectural significance of this project lies in the capacity of an existing public building to accommodate a new hybrid function without losing its primary community role. Converting unused space reduces the need for new construction, activates an existing resource, and creates an environment that connects work, learning, and social interaction. The preliminary financial estimate is BAM 107,694.41, making this pilot project the most affordable of the three detailed designs, while offering strong potential for long-term social and economic effects.



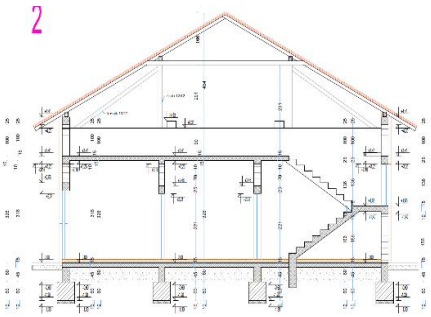


Figure 7 (left). Existing condition of the local community building in Jelićka
Figure 8 (right). Section of the local community building in Jelićka. Source: Authors' documentation.

5. DISCUSSION

The findings show that adaptive reuse of abandoned rural buildings extends beyond individual architectural intervention, functioning as a spatial-development mechanism that connects heritage protection, environmental responsibility, the local economy, and social cohesion. Buildings that became symbols of depopulation can thus become resources for a new cycle of village life. [11]

Environmentally, reusing existing structures reduces new construction, material consumption, and waste while preserving embodied energy. In rural environments, this is particularly relevant because interventions are closely connected to natural landscapes, agricultural land, and local material resources.

Socially, the involvement of residents, institutions, entrepreneurs, and experts was essential to the relevance of the proposals. Workshops, field visits, and stakeholder communication incorporated community needs and expectations into the designs, increasing local ownership and the prospects for long-term use, maintenance, and management. [12]

Economically, the three pilots demonstrate different models for activating local resources: rural tourism and local products in Knežica, community services and education in Jelovac, and entrepreneurship and youth retention in Jelićka. Their differences show that village revitalization requires context-specific combinations of functions rather than a universal model.

Overall, the Prijedor case study confirms that abandoned rural buildings are not merely a problem of spatial deterioration, but potential infrastructure for new forms of social, economic, and cultural life. When based on local needs, expert knowledge, and the principles of sustainable development, adaptive reuse can become one of the key instruments of rural revitalization.

6. CONCLUSION

The RurALL research demonstrates that adaptive reuse of abandoned and underused buildings can be a significant instrument for rural revitalization. In villages within the City of Prijedor, neglected building stock represents not only a spatial problem but also a development resource that, through careful analysis, preservation, and conversion, can accommodate new public, commercial, educational, and social programmes responding to local needs.

The significance of the research lies in a methodology connecting field mapping, existing-condition analysis, stakeholder involvement, twenty conceptual ideas, and three detailed pilot projects. The process shows that rural architectural design must address not only physical renewal but also social sustainability, the local economy, cultural identity, and long-term management. Adaptive reuse is therefore understood as a process connecting space, community, and village development potential.

The results should be understood as a starting point for further development rather than as completed implementation. Realisation depends on resolved property and legal relations, the technical condition of the buildings, detailed technical documentation,

more precise bills of quantities and cost estimates, defined management models, and secured financial resources through local, national, and European programmes. Continued participation, institutional support, and long-term maintenance are equally important, since sustainability ultimately depends on whether renewed spaces are accepted, used, and maintained by the community itself. Adaptive reuse must therefore be understood as a continuous process rather than a one-off design or construction activity.

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Research paper

ADAPTIVE SPATIAL POTENTIAL OF STARA PLANINA VERNACULAR HOUSING: PRINCIPLES FOR SUSTAINABLE RURAL REVITALIZATION

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Abstract

The adaptive reuse of vernacular housing has become an important strategy for preserving architectural heritage while responding to contemporary residential needs and supporting the sustainable revitalization of rural settlements. Within this context, the vernacular house of the Stara Planina region represents a valuable example for examining how inherited spatial organization can accommodate future transformation without compromising its architectural identity. This paper investigates the adaptive potential of the Stara Planina vernacular house through a qualitative comparative analysis of five representative house types. The evaluation is based on five criteria: functional adaptability, spatial transformability, polyvalency, neutrality, and spatial redundancy. The analysis focuses on the relationship between floor plan organization, circulation patterns, room geometry, and the role of auxiliary and semi-open spaces in enabling future adaptation. The results indicate that adaptive spatial potential is shaped by the interaction of spatial organization, building size, and typological characteristics. Compact, symmetrical, and modular layouts, characterized by balanced relationships between living and circulation spaces and limited spatial hierarchy, demonstrate the greatest capacity to accommodate contemporary requirements. Auxiliary spaces, including the ćiler, porch, and doksat (divanhana), further enhance adaptability by providing spatial reserves that enable extension and transformation with minimal intervention. The identified spatial principles provide a basis for the adaptive reuse of Stara Planina vernacular housing, supporting its continued use while preserving its architectural and heritage values and contributing to sustainable rural revitalization.

Key words: *vernacular housing, Stara Planina, spatial adaptability, adaptive reuse, rural revitalization*

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1. INTRODUCTION

Adaptability has been recognized as an important principle of sustainable housing, enabling buildings to accommodate changing patterns of use, extend their functional lifespan, and reduce the need for extensive reconstruction or replacement [1–4]. In this context, vernacular architecture provides valuable insights for adaptive reuse, as its spatial organization evolved through long-term adaptation to local environmental, socio-economic, and cultural conditions [5, 6]. Recent studies emphasize that its value lies not in reproducing traditional forms but in understanding the spatial principles and adaptive strategies embedded within them [6–8]. Vernacular buildings embody accumulated spatial knowledge shaped by environmental conditions, available resources, and cultural practices, supporting transformation while preserving architectural identity [7, 9]. Adaptive reuse therefore provides a framework for extending the functional life of existing buildings while maintaining their architectural and cultural values [10, 11].

In the Stara Planina region, previous studies have highlighted the architectural and cultural significance of traditional dwellings and their spatial organization for preservation, transformation, and sustainable rural regeneration [12–15]. Developed through gradual adaptation to local conditions, the Stara Planina vernacular house integrates the *iža*, enclosed rooms, auxiliary spaces, and transitional areas into a spatial structure reflecting traditional rural life. This spatial structure provides a basis for examining how existing vernacular houses can accommodate new or changing uses, extending their functional life while preserving their architectural and cultural values.

This paper evaluates the adaptive spatial potential of the Stara Planina vernacular house through a comparative analysis of five representative house types. The research asks how differences in spatial organization among these house types affect their potential for future adaptation, considering five criteria: functional adaptability, spatial transformability, polyvalency, neutrality, and spatial redundancy. The comparative analysis aims to identify spatial principles that can inform adaptive reuse strategies and contribute to sustainable rural revitalization through the continued use and adaptation of existing vernacular housing.

2. CONCEPTUAL FRAMEWORK AND METHODOLOGY

2.1. Adaptive Reuse of Vernacular Housing

Adaptive reuse provides a framework for the continued use of existing building stock by balancing the preservation of architectural values with new functions and contemporary requirements. Rather than focusing solely on conservation, it considers buildings as evolving spatial resources whose viability depends on their ability to accommodate functional changes and shifting patterns of use [10, 11]. The potential for adaptive reuse depends not only on new functions but also on the spatial qualities of existing buildings. Research on adaptable and flexible housing has shown that spatial organization and the relationship between spaces influence future transformations. Adaptive potential is therefore related to spatial configuration, circulation, functional hierarchy, and auxiliary or transitional spaces [1, 2].

This approach is particularly relevant in rural contexts affected by demographic decline, migration, and socio-economic changes. In mountain regions, the decline of rural settlements threatens the continuity of vernacular architectural traditions. Studies of Stara Planina villages have shown that migration and socio-economic transformations have contributed to the deterioration of traditional architectural practices and the loss of valuable housing heritage [12]. In this context, adaptive reuse can support sustainable rural revitalization by extending the functional life of existing vernacular houses, enabling their continued use and adaptation, and preserving their architectural and cultural values [7, 9]. Within the Stara Planina region, adaptive reuse provides a framework for integrating traditional housing into rural renewal processes. The concept of an architectural reserve has been proposed as a model for protecting and reinterpreting built heritage through its connection with broader territorial and cultural values [16], while other studies demonstrate that the spatial organization of traditional houses in the region provides a basis for contemporary adaptation while maintaining regional identity [14, 15]. Accordingly, this research examines adaptive spatial potential as the capacity of vernacular housing to accommodate contemporary residential requirements through the reinterpretation of existing spatial structures. This potential depends not only on building size or the complexity of spatial organization, but on the ability of spatial structures to accommodate change, providing the basis for the comparative evaluation of five representative types of the Stara Planina vernacular house.

2.2. Research Methodology and Evaluation Framework

The research is based on a qualitative comparative analysis of the Stara Planina vernacular house, focusing on the relationship between spatial organization and adaptive spatial potential within the context of adaptive reuse. The study does not aim to predict specific transformation scenarios, but to identify the inherent spatial capacities embedded in vernacular house types and their potential for future adaptation.

The study examines five representative house types selected from the broader range of traditional rural housing in the Stara Planina region to capture its main typological variations. The selection is based on previous studies of traditional architecture, rural settlements, and built heritage in this region, particularly the research of Gorica Ljubenov on architectural characteristics, regional variations, and heritage values of traditional rural housing [13, 17]. The five types are therefore treated as broader typological groups rather than individual case studies, with each type reflecting recurring spatial and organizational characteristics. They cover the main spatial variations identified in regional typological studies, from compact plans centred on the *iža* to more complex arrangements with auxiliary and semi-open spaces. This range enables comparison of their adaptive potential. Additional studies on the transformation and preservation of traditional architecture, renovation potential of vernacular houses, and sustainable rural development provide the basis for analysing adaptive reuse and village renewal processes [12, 14–16, 18].

The adaptive spatial potential of the selected house types is evaluated through five criteria derived from previous research on adaptable and flexible housing and applied to the characteristics of the Stara Planina vernacular house: functional adaptability, spatial transformability, polyvalency, neutrality, and spatial redundancy [1, 2, 15, 19, 20]. These criteria were selected to capture different aspects of spatial capacity for change, including the ability to accommodate changing uses, modify spatial arrangements, support multiple uses, and make use of existing spatial reserves for future adaptation.

Functional adaptability refers to the capacity to accommodate changing uses with minimal intervention. *Spatial transformability* describes the potential to modify layouts through reconfiguration, connections, extensions, or integration of semi-open spaces. *Polyvalency* refers to the ability of rooms to support different uses according to their geometry and spatial relationships. *Neutrality* indicates the extent to which spaces remain free from fixed functions, allowing different patterns of occupation. *Spatial redundancy* refers to auxiliary, transitional, and semi-open spaces that provide reserves for future adaptation.

The analysis considers spatial configuration, spatial hierarchy, circulation patterns, room geometry, accessibility, and the role of auxiliary, transitional, and semi-open spaces as indicators of the defined evaluation criteria. Each criterion was assessed at three qualitative levels: low, moderate, and high, reflecting the degree to which the spatial characteristics of each house type support adaptive change. Low indicates limited capacity and dependence on the existing arrangement; moderate indicates adaptation under certain spatial conditions or with limited intervention; and high indicates greater capacity supported by favourable spatial organization, geometry, accessibility, or spatial reserves. The assessment was based on the typological analysis and applied consistently across all five house types.

3. CASE STUDY

3.1. Vernacular Housing of Stara Planina

The vernacular houses of Stara Planina represent a distinctive regional housing tradition shaped by the environmental, economic, and social conditions of southeastern Serbia. Developed mainly during the late nineteenth and early twentieth centuries, they reflect accumulated building knowledge and the gradual adaptation of residential space to rural household needs [13, 21]. The predominant type is the timber-frame (bondruk) house, with a timber structure filled with wattle and daub or adobe and supported by stone foundations adapted to sloping terrain. Its spatial organization developed incrementally, with rooms and auxiliary spaces gradually added while preserving the logic of the traditional dwelling. Centred on the *iža* (main living room), the spatial organization incorporates enclosed rooms, the *ćiler* (storage room), and transitional spaces such as the porch and *doksat (divanhana)*. The integration of residential and agricultural functions, together with auxiliary spaces within the household compound, defines the functional and spatial character of traditional rural housing.

3.2. Selection of Representative House Typologies

This study examines the adaptive spatial potential of the Stara Planina vernacular house through a qualitative comparative analysis of five representative house types. The selected examples represent different stages in the development of the regional dwelling tradition and are based on previous research, including architectural surveys and typological studies of vernacular housing [13, 22]. The analysed types range from compact layouts centred around the *iža* to more complex arrangements with additional rooms and spatial reserves, reflecting different levels of spatial complexity. Each house type was analysed according to the evaluation framework presented in Chapter 2, applying the same criteria to enable qualitative comparison of their spatial characteristics and adaptive potential. Table 1 presents the selected typologies, including their main characteristics, location, period of development, and a representative example of each house type. Figure 1 provides a comparative overview of their floor plans and façades.

Table 1. Representative examples of Stara Planina vernacular house typologies

Type	House type name	Period	Representative house	Village
01	House with arcaded porches integrated into the façade	Late 19th–early 20th c.	House of Mita Angelov	Visočki Odorovci, Serbia
02	House with a porch extending beyond the façade	Late 19th–early 20th c.	House of Petko Metodijev	Petrlaš, Serbia
03	Two-storey house with a *doksat* porch	Early 20th c.	House of Božidar Panajotović	Šugrin, Serbia
04	House with a porch and a *doksat* (divanhana)	Early 20th c.	House of Blagoje Penčić	Cerova, Serbia
05	L-shaped house	First half of the 20th c.	House of Bogosav Mančić	Dojkinci, Serbia

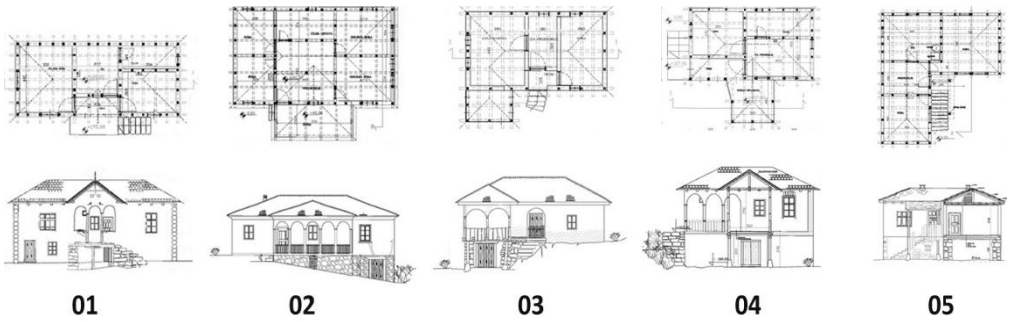


Figure 1. Selected house types: plans and façades [22]

3.3. Typological Analysis

3.3.1. Type 01: Houses with arcaded porches integrated into the façade plane

Type 01 represents an early and compact stage in the development of the Stara Planina vernacular house, dating from the end of the 19th century. It is characterized by a porch integrated into the façade plane, forming an entrance zone and transition between interior and exterior. The spatial composition is based on a symmetrical and

modular layout, with the *iža* as the central living space and surrounding rooms arranged around it. Despite its modest scale, this type demonstrates adaptive potential through the neutrality and polyvalency of its spatial structure, while the porch provides limited spatial reserve for forming an entrance hall. The regular room proportions, flexible spatial relationships, and possibility of modifying internal connections or enclosing the porch enable future adaptation while preserving the architectural identity (Figure 2, a).

3.3.2. Type 02: Houses with a porch extending beyond the façade plane

Type 02 represents a developed stage in the evolution of the Stara Planina vernacular house, characterized by a more articulated spatial organization with six rooms. The plan is structured around a central entrance hall providing access to all spaces, with the *ćiler* positioned on the main axis and the rooms symmetrically arranged along a perpendicular axis. The regular geometry, modular composition, and balanced spatial structure significantly contribute to its adaptive potential. Similar room proportions and flexible relationships between spaces enable diverse configurations, while the *ćiler* is well suited to contemporary service functions and the porch provides additional spatial reserve for future adaptation. These characteristics support a wide range of functional arrangements and spatial transformations while allowing adaptation with minimal changes to the existing structure (Figure 2, b).

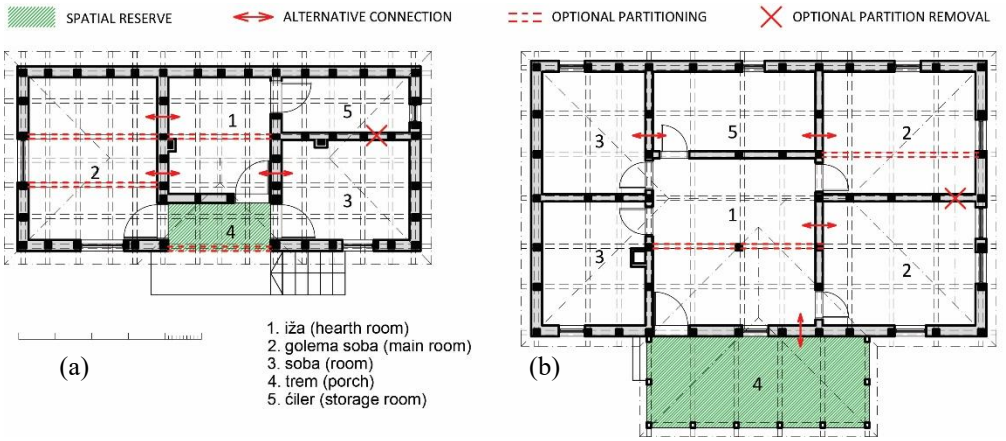


Figure 2. Analysed house plans: (a) Type 01, (b) Type 02 (drawn by the authors)

3.3.3. Type 03: Two-storey houses with a doksat

Type 03 represents a stage in the development of the two-storey Stara Planina vernacular house, characterized by the addition of a corner *doksat (ćoška)* that transforms the rectangular plan into an L-shaped composition. The *iža* remains the central living and circulation space, while the added *doksat* extends the spatial organization. The regular geometry of the main rooms supports functional adaptability, while their defined proportions limit the degree of neutrality and polyvalency. The *ćiler* remains suitable for contemporary service functions. The potential enclosure of the *doksat* provides additional spatial reserve for future adaptation, while the porch can be transformed into an entrance space (Figure 3, a).

3.3.4. Type 04: Houses with a porch and a doksat (divanhana)

Type 04 represents a mature stage in the evolution of the Stara Planina vernacular house, characterized by a two-storey organization of residential, semi-open, and auxiliary spaces. The ground floor is mainly used for storage, while the upper floor contains the living area organized around the *iža*, which functions as the main living and circulation space despite its peripheral position within the plan. The porch and *doksat (divanhana)* enrich the spatial structure, while the *ćiler* provides a suitable location for contemporary service functions. These auxiliary and semi-open spaces provide significant spatial reserve for future adaptation, while the existing floor area, room geometry, and defined position of the *iža* limit extensive transformation (Figure 3, b).

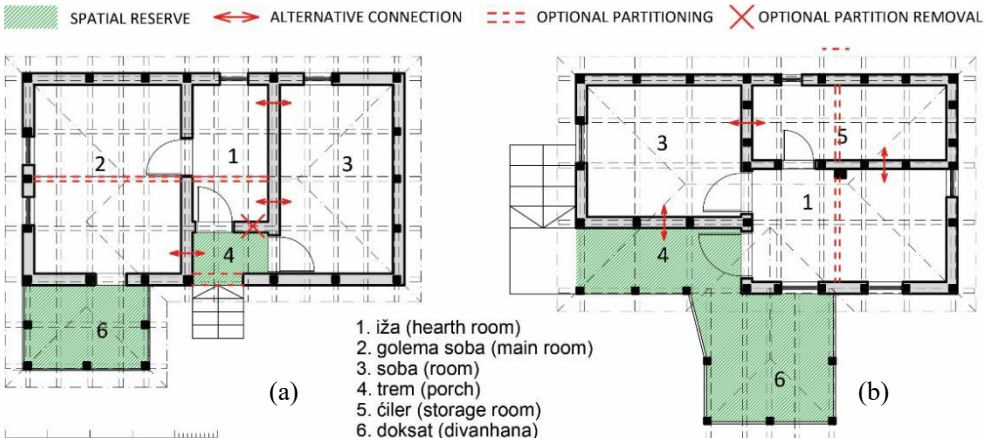


Figure 3. Analysed house plans: (a) Type 03, (b) Type 04 (drawn by the authors)

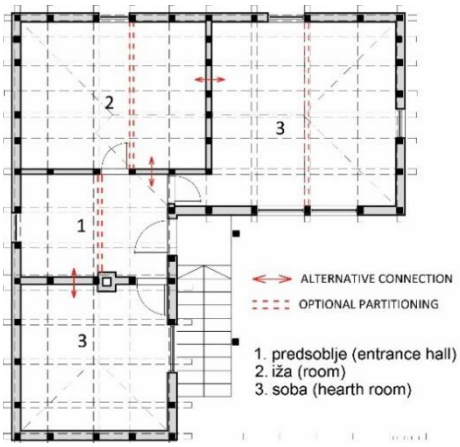


Figure 4. Analysed house plan: Type 05 (drawn by the authors)

3.3.5. Type 05: L-shaped house

Type 05 represents the stage in the evolution of the Stara Planina vernacular house, commonly known as the L-shaped house. Developed during the 1930s and 1940s, it reflects the transition from an agricultural dwelling towards greater residential comfort. The L-shaped plan is organized around a central entrance hall, which becomes the main circulation and organizational space. Although the stronger spatial hierarchy defines the relationship between rooms, the larger floor area and regular room geometry provide

significant potential for functional adaptation, partitioning, and changes in use. The larger floor area and entrance hall provide some spatial reserve for future modifications, without the flexible semi-open spaces of porches and *doksats* (Figure 4).

4. RESULTS: COMPARATIVE ANALYSIS

Table 2 presents the qualitative evaluation of the adaptive spatial potential of the analysed Stara Planina vernacular house types. The assessment applies the evaluation matrix defined in Section 2.2, using three levels of expression: low (●), moderate (●●), and high (●●●). The levels indicate the relative degree to which the spatial characteristics of each type support functional change, spatial transformation, polyvalency, neutrality, and spatial redundancy.

Table 2. Comparative assessment of adaptive spatial potential of vernacular house types

Adaptive spatial principle	Type 01	Type 02	Type 03	Type 04	Type 05
Functional adaptability	●●	●●●	●●	●●	●●●
Spatial transformability	●●	●●●	●●	●●	●●●
Polyvalency	●●	●●	●	●	●●
Neutrality	●●	●●	●	●	●●
Spatial redundancy	●	●●●	●●	●●●	●●

The comparative analysis shows that adaptive spatial potential is generally increased by regular and modular layouts, balanced relationships between living and circulation spaces, polyvalent rooms, and auxiliary or semi-open spaces that provide spatial reserves. Type 02 demonstrates the highest overall adaptive potential through the combination of these characteristics. Type 05 also shows strong potential due to its larger floor area, regular room proportions, and capacity for partitioning, although its stronger spatial hierarchy limits neutrality and polyvalency. Type 01 combines compactness, symmetry, and relatively neutral spatial relationships but has limited spatial reserves. Types 03 and 04 benefit from auxiliary and semi-open spaces, while stronger functional definition limits broader transformation. Overall, adaptive potential is highest where spatial regularity and polyvalency are combined with sufficient spatial reserves, and lower where functional definition and spatial hierarchy restrict change.

5. DISCUSSION

The comparative analysis demonstrates that the adaptive spatial potential of the Stara Planina vernacular house depends on the interaction between spatial organization, geometry, size, and typological characteristics. The highest adaptive potential is observed in types with regular modular layouts, flexible relationships between spaces, and sufficient spatial reserves. While compact plans organized around the *iža* benefit from greater neutrality and polyvalency, larger houses provide opportunities for adaptation through increased floor area and partitioning. However, stronger spatial hierarchy and defined functional organization can limit transformation potential.

The comparison of the five house types indicates that adaptability is embedded in the modular character of the traditional dwelling. Repeated spatial units, regular

proportions, and auxiliary or semi-open spaces support gradual functional modifications while preserving the overall spatial logic. In particular, the *ćiler*, porch, and *doksat* provide spatial reserves for additional or changing functions without substantially altering the primary residential organization. This shows that adaptive potential depends not only on the amount of available space, but on the balance between spatial flexibility, functional organization, and existing typological qualities. From the perspective of sustainable rural revitalization, these findings highlight the value of existing spatial qualities as a basis for future renewal and reuse while preserving regional identity.

6. CONCLUSION

This research examined the adaptive spatial potential of five representative types of the Stara Planina vernacular house through qualitative comparative analysis. The results demonstrate that adaptive potential is influenced by the interaction between spatial organization, building size, and typological characteristics, with particular importance given to the relationship between living spaces, circulation, auxiliary rooms, semi-open elements, and spatial reserves. The comparison shows that adaptability is not determined by size alone, but by the balance between functional organization, spatial transformability, and the presence of spaces that can support future adaptations. The identified spatial potentials provide a basis for adaptive reuse strategies that respect the architectural identity of vernacular housing while enabling its continued use under contemporary conditions. By extending the functional life of existing buildings and supporting their continued adaptation, these spatial potentials can contribute to sustainable rural revitalization while preserving the architectural heritage of the Stara Planina region.

The study is limited by the number of analysed typologies, the qualitative character of the assessment, and the absence of testing of specific adaptive reuse scenarios. Future research should further investigate the application of these spatial potentials through specific adaptive reuse projects, while also considering the social, economic, and institutional factors that influence the long-term revitalization of traditional rural settlements.

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Research paper

THE IMPACT OF INDUSTRIAL HERITAGE PROTECTION ON NATURE-BASED SOLUTIONS IMPLEMENTATION

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Abstract

This study investigates the possibilities of integrating Nature-Based Solutions (NBS) within industrial cultural heritage complexes in the cities of Niš and Belgrade. The intention is to improve microclimatic conditions and enhance the aesthetic and environmental values of open spaces, in accordance with different levels of protection. It is based on the premise that industrial sites are characterized by a high proportion of paved surfaces, a lack of greenery, and a pronounced urban heat island effect, all of which negatively affect the quality of use and experience of these spaces. Given the constraints arising from the preservation of industrial architecture, the potential for transformation is primarily directed toward the application of NBS interventions. Particular attention will be devoted to examining how different levels of cultural heritage protection influence the scope, feasibility, and types of NBS interventions that can be implemented within industrial heritage complexes.

The research methodology is based on a qualitative comparative analysis of four industrial complexes with different levels of heritage protection in Europe and Serbia. The study includes a review of relevant literature and best practice examples of Nature-Based Solutions (NBS) implementation within industrial heritage sites, comparing Landschaftspark Duisburg-Nord and the Sugar Refinery complex in Belgrade, both holding protected heritage status, with Western Harbour in Malmö and the Mechanical Industry complex in Niš, neither of which is officially protected.

The aim of this study is to examine the possibilities for implementing Nature-Based Solutions within these industrial complexes and to assess the extent to which cultural heritage status influences their implementation. Furthermore, the study compares different models of NBS application in industrial heritage contexts and identifies potential principles applicable to the local context. The findings indicate that the level of heritage protection primarily affects the typology of NBS, while ground-level interventions are broadly feasible in all cases.

Key words: *Nature-Based Solutions (NBS), Industrial Heritage, Sustainable Urban Development, Open Spaces, Microclimate Improvement*

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1. INTRODUCTION

Due to economic, political, and transitional challenges, as well as the resulting structural changes in the industrial sector, Serbia has experienced a growing number of abandoned and underutilized industrial complexes that have lost their original function as a consequence of deindustrialization processes [1]. Former industrial centers like Niš and Belgrade illustrate how brownfield sites can serve as valuable resources for sustainable urban land use, preserving local history and existing building stock [2], yet many of these sites remain neglected or insufficiently integrated into urban contexts.

Nature-Based Solutions (NBS) have emerged as a contemporary approach to urban regeneration, based on the integration of natural elements into the built environment in order to reduce the risks associated with natural hazards and climate change, while addressing societal challenges and contributing to human well-being and environmental sustainability [3]. Within industrial heritage sites, the application of NBS is of particular significance, as it enables the enhancement of the ecological and functional performance of these spaces while respecting the constraints imposed by heritage protection regimes and the need to preserve the authenticity of architectural structures. Considering both the necessity for the revitalization of industrial sites and the potential of Nature-Based Solutions to improve the quality of open spaces, this study addresses the following research question: To what extent does the level of industrial heritage protection influence the possibilities for implementing Nature-Based Solutions?

The research methodology is based on a qualitative comparative analysis of four case studies: two implemented European examples and two Serbian case studies, the former Sugar Refinery complex in Belgrade and the Mechanical Industry complex in Niš. The selected case studies were chosen to represent different levels of industrial heritage protection, enabling an analysis of how heritage-related conditions affect regeneration strategies. The comparative analysis was based on a predefined set of criteria (Table 1), ensuring a systematic and transparent evaluation of the selected cases, with a particular focus on assessing their potential for NBS integration. Each criterion was assessed descriptively, capturing the specific heritage, spatial, and regulatory context of each site within a systematic qualitative framework.

2. NATURE-BASED SOLUTIONS IN THE CONTEXT OF INDUSTRIAL HERITAGE REVITALIZATION

2.1. Theoretical Framework of Nature-Based Solutions

Nature-Based Solutions (NBS) have been developed as a response to the increasingly pronounced challenges of climate change, focusing on promoting sustainable urban development and restoring degraded ecosystems. They enable climate change adaptation and carbon reduction, while simultaneously improving risk management and system resilience. The European Commission defines Nature-Based Solutions as ‘‘living solutions inspired by, continuously supported by and using nature,

which are designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits ” (European Commission, 2015) [3]. Blue green infrastructure elements, particularly vegetation, water features, and vertical greening, make a significant contribution to microclimatic regulation and the mitigation of the urban heat island effect [4][5].

For the purposes of this study, the diverse NBS typologies identified in the literature are grouped into four categories: (1) vegetation and ground-level green areas; (2) water and stormwater management systems, such rain gardens, retention basins, underground water storage systems, and sustainable urban drainage systems; (3) greening of buildings, including green roofs and vegetated facades; and (4) soil restoration through bioremediation and related methods [3].

2.2. Sustainable Revitalization and Industrial Heritage Protection in Serbia

In contemporary cities, space for new parks and green areas is increasingly limited, while climate instability highlights the need for sustainable heritage revitalization [6]. Rather than demolishing existing structures, approaches that preserve industrial heritage as a spatial resource with potential for new functions, while integrating green infrastructure, are increasingly applied [7]. This requires careful planning that respects conservation requirements and existing spatial relationships [8]. As former industrial complexes are often perceived as isolated fragments of the urban fabric, their revitalization offers an opportunity to create spaces that harmonize the needs of diverse stakeholders with natural systems [9].

The legislative framework for the protection of cultural heritage in the Republic of Serbia is based on the Law on Cultural Heritage (“Official Gazette of the Republic of Serbia ”, No. 129/2021), which regulates the protection, conservation, and management of cultural heritage. Although industrial heritage is not explicitly defined as a separate category of cultural property, its protection is implemented within this legal framework, which defines the concept, types, and procedures for determining the status of cultural property, as well as the objectives and measures for its protection [10]. The Law particularly emphasizes protection objectives that are relevant to industrial heritage, including integrated conservation, sustainable use, and the management of cultural heritage resources. In the context of industrial heritage, which is the subject of this study, the former Sugar Refinery complex in Belgrade is protected as a cultural monument.

3. INTERNATIONAL EXAMPLES OF NATURE-BASED SOLUTIONS IN INDUSTRIAL HERITAGE SITES

3.1. Case study analysis: Landschaftspark Duisburg-Nord in Germany

Landschaftspark Duisburg-Nord represents post-industrial transformation through the integration of NBS principles, converting an abandoned industrial complex into a public park where former industrial structures were adapted for new recreational and

cultural functions within a contemporary landscape concept. Due to its protected heritage status, the fundamental principle of revitalization was the preservation of authentic industrial architecture through minimal interventions and only the necessary restoration works (figure 1). The complex operated as an industrial facility producing crude iron, primarily intended for further processing, from 1903 until 1985 [11]. Due to its industrial and technical heritage, the area was protected and later integrated into the Ruhr region revitalization program through the IBA Emscher Park (1990 – 1999). During the revitalization of the complex, the existing structures were repurposed for cultural, recreational, and administrative functions. The gasometer was turned into a diving center, the concrete bunkers and industrial structures into climbing and sports spaces, the Blower House Complex into a cultural venue with a theatre hall while preserving its original machinery, and the Main Switching House into a visitor and administrative center while preserving its structural integrity. In addition to individual structures, the entire complex is interconnected by a network of paths, elevated walkways, and green areas that enable movement through different parts of the landscape [12].



Figure 1. Landscape of Landschaftspark Duisburg-Nord Park, Sinter Gardens and Water Features as Part of the Water Management System Source: https://www.socotec.de/projekte/landschaftspark-duisburg-nord, https://www.landschaftspark.de/en/industrial-heritage-circuit/parklands/

In Landschaftspark Duisburg-Nord, NBS implementation includes three of the four categories identified in Section 2.1, resulting in a hybrid landscape that combines natural processes with industrial heritage. Vegetation and green areas are preserved and expanded through new systems like the Sinter Gardens and Stadtrandgarten, which contribute to biodiversity, soil stabilization, and improving microclimatic conditions, while providing spaces for recreational activities. Water and stormwater management is based on the adaptation of the existing river infrastructure, divided into five functional segments, as well as on the collection and controlled discharge of rainwater. Water is stored and released with a temporal delay, ensuring a stable hydrological regime even during dry periods. Additionally, an innovative feature is the wind turbine system located at Sinter Square, which combines renewable energy production with water management functions (figure 1) [12]. Building greening was not identified among the implemented interventions, as priority was given to industrial authenticity.

3.2. Case study analysis: Western Harbour in Malmö, Sweden

Western Harbour (Västra Hamnen) in Malmö, Sweden, represents a former industrial Kockum shipyard area that, by the late 1990s, entered a process of urban

regeneration as one of the city's first major transformation projects (figure 2). The approach was based on the formation of a densely built mixed-use urban structure, with an emphasis on public space design, aesthetics, energy efficiency, and the improvement of quality of life, combined with the application of nature-inspired interventions [13]. Architecturally significant brick buildings were preserved, while others were demolished and their materials reused, in line with circular economy principles [14]. Gjuteriet building, formerly a foundry for the production of metal castings for shipbuilding and bridges. Its eastern and western facades have been preserved as authentic elements of industrial heritage, while the interior has been adapted for office and public functions [15].



Figure 2. Aerial View of Varvsstaden, Green Wall and Water Features as Part of the Water Management System, Source: https://www.gehlpeople.com/projects/varvsstaden-public-space-plan/, https://www.google.com/maps, https://www.takemetosweden.com/vastra-hamnen-in-malmo/

In Western Harbour, NBS implementation includes all four categories, integrated through various typologies of urban interventions. Open stormwater drainage systems include channels, rain gardens, vegetated courtyards, and retention basins, enabling partial infiltration and the natural flow of water. Biotopes as urban natural structures are based on the use of native plant species in order to preserve ecosystems and enhance biodiversity (figure 2). Green roofs and facades, street trees, mobile planting systems, and other urban greenery, including vegetation on vertical and elevated structures, were applied to improve microclimate and provide shading [13]. Beyond physical interventions, the Western Harbour's development was supported by strategic planning instruments developed within Bo01 and applied in later phases and projects.

4. INDUSTRIAL HERITAGE SITES IN SERBIA

4.1. Protected Industrial Heritage Site: The Sugar Refinery Complex in Belgrade

The Sugar Factory is located in the municipality of Čukarica, within the Topčider spatial cultural-historical complex (figure 3). The factory was designated as a cultural property by the decision published in the "Official Gazette of the City of Belgrade", No. 23/84 [16][17]. Built in the late 19th century, during Belgrade's early industrialization, the complex soon developed into a technologically advanced industrial facility, in line with Western European industrial trends of the time [16]. From the perspective of architectural value, the oldest structures stand out, such as the machine hall, drying facility, boiler house, administrative building (today's restaurant "Šećerac"), workers'

and clerical housing, and warehouses. These buildings represent characteristic examples of late 19th-century industrial architecture, featuring brick as the primary construction material and simple facade articulation in the spirit of the Romantic style [16][18]. The machine hall represents the central building of the complex, characterized by an articulated form and a tall chimney as a dominant spatial element. The drying facility and boiler house feature functional design and simple architectural expression, with the brick-built drying facility connected to the machine hall. According to their cultural, historical, and architectural value, the buildings within the complex are classified into several protection categories, including the entire complex under strict protection measures, the most valuable structures, and buildings of ambient significance for which rehabilitation is permitted [16]. Today, the Sugar Factory complex is abandoned and deteriorated, with minimal functional use and insufficient maintenance that has led to its gradual decay, despite benefiting from good spatial connectivity with the city [19].



Figure 3. The Former Sugar Factory: Current Condition and Condition in 1979, Source: https://revita2017.wordpress.com/2017/05/13/prva-srpska-fabrika-secera/, https://scindeks-clanci.ceon.rs/data/pdf/1450-605X/2008/1450-605X0809267D.pdf

Within the spatial planning framework of the complex, NBS potential is reflected primarily through three categories. Vegetation and green areas are planned through the development of green, open areas at ground level, preserving existing vegetation, planting new trees, and forming new spatial units such as small "oases," plazas, and gardens. Water and stormwater management is envisaged through the introduction of water features as part of the planned public spaces. Environmental remediation are reflected in the potential integration of NBS to improve microclimatic conditions, reduce pollution, and mitigate noise levels [16]. Building greening remains significantly constrained by the structural condition of the historic buildings and by conservation requirements, limiting the potential for green roof and wall systems.

4.2. Non-Protected Industrial Heritage Site: The Mechanical Industry Complex in Niš

The Mechanical Industry Niš (MIN) was a significant industrial complex in Serbia, located near the historic center, along the Nišava River, the railway corridor, and the main railway station. Established in the late 19th century with the city's first machine workshops, this study focuses particularly on Donji MIN (Lower MIN), the most significant part of the complex, covering approximately 30 hectares and comprising around one hundred buildings of various functions and dimensions [20]. Today, the

complex is characterized by divergent physical conditions among its buildings, where some structures have been renovated and adapted for new uses, while others have significantly deteriorated due to long-term disuse and lack of maintenance. Although it possesses notable historical, architectural, and urban values, the complex is not formally protected as a cultural property [21].

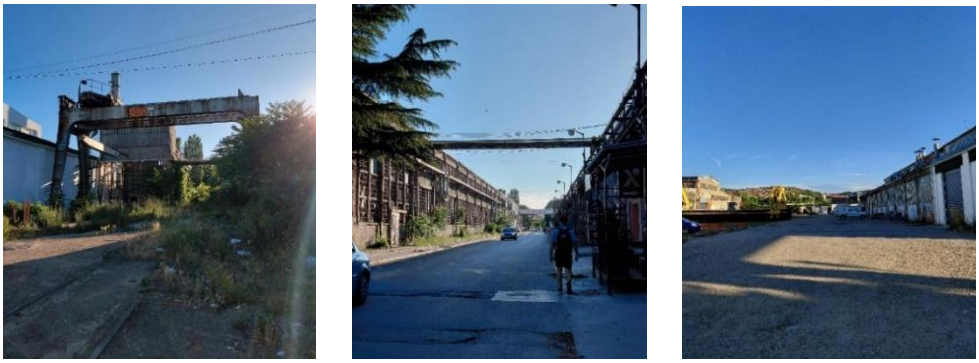


Figure 4. View of the Open Spaces within the Mechanical Industry Complex, Source: autors

The buildings are arranged along the central axis of the complex, accompanied by a network of internal roads, service platforms, and open working areas. The spatial structure consists of large industrial halls with wide spans and flexible layouts, constructed using reinforced concrete and steel structures. The site is characterized by extensive paved and asphalt surfaces and neglected green areas (Figure 4), suggesting potential for NBS implementation across all four categories. Vegetation and green areas could be expanded by converting underused surfaces into green spaces with enhanced microclimatic conditions, while water and stormwater management could be improved through systems adapted to these conditions. Building envelope greening, in the form of green walls, is identified as a potential intervention on deteriorated structures where structural condition allows. Soil remediation is also relevant, as the site, like other former industrial zones, is affected by past contamination, and properly implemented NBS could help improve soil quality [21].

4.3. Comparative analysis of industrial complexes in Europe and Serbia

A comparative analysis of the four case studies, based on the criteria in Table 1, is presented below to evaluate approaches to regeneration and NBS integration.

Table 1. Comparative analysis of chosen industrial heritage case studies in Europe and Serbia, Source: autors

Criterion	Landschaftspark Duisburg-Nord	Western Harbour	Former Sugar Factory	Mechanical Industry (MIN)
Location	Duisburg, Germany	Malmö, Sweden	Belgrade, Serbia	Niš, Serbia
Original industrial function	Ironworks, crude iron production	Port and shipyard (Kockums)	Sugar production	Energy, mining, and railway equipment manufacturing
Period of establishment	Early 20th century	Mid-20th century industrial peak	Late 19th century	Late 19th century

Protection status	Industrial heritage (protected within the IBA program)	Partially preserved industrial heritage, no formal protection	Cultural property since 1984	No formal protection
Degree of preservation of industrial heritage	High – preserved blast furnaces, gasometer, halls, bunkers, and infrastructure	Partial – selected structures and architectural elements preserved, some demolished	Most valuable buildings preserved, but in poor condition	Varying degree of preservation; some adapted buildings, others degraded
Architectural characteristics	Industrial architecture in the spirit of early functionalism	Industrial modernism	Late 19th-century industrial, Romantic style	Socialist modernism
Current function	Public park with cultural, recreational, tourism, and administrative functions	Mixed-use development with residential, commercial, and public functions	Partially used; mostly abandoned	Mixed use: commercial, production, storage, sports, healthcare, and retail
Current condition	Revitalized and actively used	Revitalized and actively used	Neglected and deteriorated, with minimal functional use	Mixed condition; some buildings adapted, others degraded
Regeneration approach	Maximum preservation of industrial structures with adaptive reuse	Selective preservation of industrial heritage combined with new construction	Planned revitalization with preservation of valuable buildings and public spaces	No unified regeneration strategy; potential recognized for future revitalization
NBS status: Implemented (European examples) / Planned (Serbian examples)	New and preserved green areas, stormwater and water system restoration, and renewable energy integration	Biotopes and street trees, rain gardens and drainage systems, and green roofs and facades	Preserved vegetation, with potential for NBS to improve microclimate, reduce noise, and reduce pollution	Preserved vegetation, potential green walls, stormwater management, and soil remediation
Synthesis	High protection status; NBS implemented within categories (1), (2), and (4)	Partial protection; NBS measures distributed across all four categories	Formal protection exists, but NBS potential (categories 1, 2, and 4) remains unrealized	No protection strategy; potential exists for implementation of all four NBS categories

The comparative analysis presented in Table 1 indicates that the level of heritage protection influences the scope and typology of NBS implementation, although it does not entirely prevent it. In protected complexes, conservation requirements direct interventions toward ground-level solutions, including green areas, preserved vegetation, stormwater management, and soil restoration, while sites without formal protection allow for more extensive structural adaptation, such as building greening.

5. DISCUSSION AND CONCLUSION

Based on the comparative analysis, NBS can be implemented irrespective of heritage protection status, although this status determines which typologies are feasible. In protected complexes, such as the Former Sugar Factory in Belgrade and Landschaftspark Duisburg-Nord, conservation requirements direct interventions toward vegetation and stormwater management, while building envelope greening remains largely unrealized due to structural and regulatory constraints aimed at protecting the original facades. As a consequence of long-term abandonment, spontaneous vegetation has often developed within these sites and has become an integral component of their landscape character. In contrast, industrial complexes without formal heritage protection, such as the Mechanical Industry Niš (MIN) complex and Western Harbour, allow greater flexibility in planning interventions. In Western Harbour, the prevailing approach involved the partial removal of existing structures and the construction of new developments, with industrial heritage elements selectively retained and NBS integrated as part of a contemporary urban framework. However, in the case of the MIN complex, retaining a larger proportion of the existing physical structures is justified, given their significant spatial and architectural value.

In conclusion, NBS are most widely applicable at ground-level, while the implementation of green roofs and green walls is more dependent on the protection regime and the physical condition of existing buildings. The level of protection also influences the overall strategy for industrial heritage preservation, with protected complexes prioritizing the conservation of authenticity and existing structures, whereas unprotected sites allow for more radical transformations while still retaining elements of their industrial identity. These findings suggest that, for the Serbian context, the successful integration of NBS in protected complexes like the Sugar Refinery requires planning instruments that balance conservation with ground-level NBS strategies, while unprotected complexes like MIN could combine selective structural preservation with a broader range of NBS interventions.

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Research paper

INTERPRETING VERNACULAR ARCHITECTURE THROUGH CONTEMPORARY TIMBER STRUCTURES: THE CASE OF THE NOVO SEOSKO ZBORIŠTE PAVILION IN POKREVENIK

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Abstract

Vernacular architecture embodies knowledge accumulated through generations of building practice, reflecting the relationship between local communities, available materials, environmental conditions, and cultural landscapes. In the villages of the Stara Planina region in southeastern Serbia, timber-based construction systems played a significant role in shaping architectural forms, settlement patterns, and local identity. Although developed in a different technological context, many of the principles embedded in vernacular architecture remain relevant to contemporary architectural practice. This paper explores the potential of vernacular construction principles to inform contemporary architectural practice through the use of timber structures. The research combines a review of relevant literature, field-based research into the vernacular architecture of the Stara Planina region, and a case study of the Novo Seosko Zborište pavilion in the village of Pokrevenik. The principles underlying the existing vernacular architecture of the Stara Planina region are examined, with particular emphasis on the use of local materials, adaptation to topography and climate, modularity, and integration with the landscape. The case study pavilion critically re-examines these principles through a lightweight, prefabricated, and low-impact construction system that reinterprets the constructive logic of traditional bondruk structures. Its design was developed within a participatory design-build process involving students, faculty members, carpenters, and local residents. The findings indicate that vernacular architecture provides a valuable framework for sustainable design in rural cultural landscapes and that contemporary timber construction can successfully reinterpret traditional principles while responding to present-day functional and community needs. The study highlights the potential of combining vernacular knowledge with contemporary construction technologies as a strategy for creating context-sensitive and environmentally responsible architectural interventions.

Key words: *vernacular architecture; timber construction; hybrid structures; sustainable design; cultural landscape; Stara Planina*

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1. INTRODUCTION

Vernacular architecture is the result of a long process of adaptation between communities, available materials, climatic conditions, and the cultural landscapes in which settlements developed. In the villages of the Stara Planina region in southeastern Serbia, timber played a central role in shaping architectural forms, structural solutions, and the visual identity of rural settlements. Beyond its historical value, vernacular architecture demonstrates efficient material use, adaptability to local conditions, and strong integration with the landscape, making it a relevant reference for contemporary sustainable architecture. Recent advances in engineered timber, prefabrication, and hybrid structural systems have further expanded the potential of timber construction, enabling lightweight, durable, and reversible interventions in environmentally sensitive contexts.

This paper explores the relationship between vernacular architecture and contemporary timber construction through the case of the *Novo Seosko Zborište* pavilion in Pokrevenik, located in the Stara Planina region. It examines how vernacular construction principles can inform contemporary architectural design and be reinterpreted through a lightweight timber structure designed for community use.

The research is guided by two questions:

1. Which vernacular construction principles of the Stara Planina region are relevant for contemporary sustainable design?
2. How can these principles be reinterpreted through a lightweight timber pavilion designed for community use in Pokrevenik?

2. METHODOLOGY

Methodologically, the research is based on a qualitative case study approach. It combines a review of literature on vernacular architecture, sustainable construction, and contemporary timber systems with field-based documentation of vernacular buildings in the Stara Planina region. The Novo Seosko Zborište pavilion was selected as a representative case study due to its explicit reinterpretation of vernacular architectural principles through contemporary timber construction. To ensure a systematic analysis, an analytical framework was developed based on recurring principles identified in the reviewed literature. These principles were translated into a set of evaluation criteria (*Table 1*) encompassing materiality, structural logic, construction process, spatial organization, relationship with the cultural landscape, and community participation. The framework was then applied to assess how vernacular principles are reinterpreted in the pavilion's design, construction, and use, enabling a structured comparison between traditional architectural values and their contemporary expression.

Table 1. Analytical framework used for evaluating the reinterpretation of vernacular architecture

Analytical dimension	**Evaluation criteria**	**Literature basis**
Material use	Selection and origin of construction materials	Vernacular architecture theory
Structural system	Structural organization and load-bearing logic	Vernacular architecture theory
Construction method	Building process and assembly	Vernacular architecture theory
Joints	Type and reversibility of connections	Vernacular architecture theory
Adaptation to terrain	Integration with topography	Vernacular architecture theory
Relationship with landscape	Visual and environmental integration	Cultural landscape theory
Community building	Participation in construction and use	Participatory architecture
Maintenance and repair	Durability, adaptability and reparability	Sustainable design principles

3. VERNACULAR ARCHITECTURE OF STARA PLANINA AS A MODEL OF SUSTAINABLE BUILDING

3.1. Vernacular architecture and sustainability

Traditional architecture demonstrates numerous characteristics that are today associated with the principles of sustainable building. The use of locally available materials, such as timber, stone, earth, and straw, reduced transportation requirements and the associated embodied energy. Many of these materials were natural, non-toxic, biodegradable, and capable of returning to natural cycles at the end of a building's life span. Furthermore, traditional buildings were adapted to local climatic conditions through careful site selection, solar orientation, protection from prevailing winds, and the use of material properties to regulate temperature and humidity. The construction process generated minimal waste, while building materials were often reused or recycled. These characteristics indicate that vernacular architecture represents an important model of sustainable resource management and a harmonious relationship between the built and natural environment. [1]

3.2. Vernacular architecture of Stara Planina

Traditional architecture in the Stara Planina region was based on the use of locally available natural materials, primarily stone, timber, and earth, which together formed a construction system closely adapted to local environmental conditions [2]. The most common residential building type in the Pirot area was a rectangular or square house built using a timber-frame (bondruk) construction system. The structural framework

consisted of wooden posts and beams, while wall infill was typically made of woven branches coated with mud or, in later examples, timber planks and adobe blocks. Stone was widely used for foundations and, in some villages, for roof coverings in the form of large stone slabs, reflecting the availability of local resources. Timber served as the primary structural material for walls, floors, roofs, and joinery, while earth, often mixed with straw, was applied as infill and finished with mud plaster. Roofs were generally four-pitched with gentle slopes and covered with straw, reed, shingles, or stone slabs. [3]

One of the fundamental characteristics of Balkan vernacular architecture is its close relationship with the surrounding environment, expressed through the principles of materialization and mimetic adaptation. Building materials were selected directly from the immediate natural context, resulting in structures whose materiality reflected the geological and ecological characteristics of the landscape. As a consequence, vernacular buildings visually and physically blended into their surroundings through the use of local materials, colors, and textures. [4]



Figure 1. Bondruk construction system in Pokrevenik, author

4. CONTEMPORARY TIMBER AND HYBRID STRUCTURES IN CULTURAL LANDSCAPES

4.1. Timber and hybrid structures and sustainable construction

In recent decades, timber has re-emerged as a key construction material due to its environmental benefits, structural efficiency, and compatibility with contemporary building technologies. Hybrid timber systems combining wood with steel or concrete optimize structural performance while reducing greenhouse gas emissions by approximately 25–35%. Timber-concrete composites improve load-bearing capacity, stiffness, seismic performance, and indoor comfort, whereas steel-timber hybrids enable rapid prefabrication, material efficiency, and high architectural quality. Despite the need for optimized connections and consideration of long-term material behaviour, hybrid systems represent a promising strategy for low-carbon, resource-efficient architecture. [5]

Owing to its renewable nature, carbon storage capacity, and low environmental impact, timber has become a cornerstone of sustainable architecture. Beyond its structural and ecological advantages, wood contributes to cultural identity, sensory quality, and user well-being, making it an important material for creating environmentally responsible and context-sensitive built environments. [5]

4.2. Lightweight and demountable structures in sensitive environments

One of the key advantages of timber construction is the possibility of prefabrication, which enables a high degree of precision, shorter construction times, reduced on-site work, and lower overall construction costs. The relatively low weight of timber elements simplifies transportation and assembly, making timber structures particularly suitable for remote, sensitive, or difficult-to-access locations. Combined with modern manufacturing technologies, these characteristics allow for the rapid erection of durable and resource-efficient buildings while minimizing disturbance to the surrounding environment. As a result, interest in timber-frame and engineered wood construction has grown significantly in recent years. [6]

The lightweight nature of timber, together with the possibility of prefabrication and dry assembly, makes it particularly suitable for interventions in environmentally and culturally sensitive landscapes. Such systems generally require less intensive site preparation, generate less construction waste, and can often be assembled and dismantled with limited impact on the existing terrain. These characteristics align with contemporary principles of minimum intervention, reversibility, and design for disassembly, which are increasingly recognized as important strategies for balancing architectural development with the preservation of natural and cultural values.

5. CASE STUDY: *NOVO SEOSKO ZBORIŠTE*, POKREVENIK

Pokrevenik is a small village located on the slopes of Stara Planina Mountain near Lake Zavoj and the Smilovica viewpoint. Despite its proximity to the city of Pirot, the village has experienced significant depopulation and today has only 32 inhabitants. Its traditional architecture, characterized by stone ground floors, timber-framed upper levels, and locally sourced materials, forms an important part of the cultural landscape of the Stara Planina region. However, many former public facilities have lost their function, leaving the village without a central communal gathering space.

Since 2018, at the Faculty of Architecture, University of Belgrade, Within the course Architects and Civic Initiatives for Sustainable Development, taught by Associate Professor dr Danijela Milovanović Rodić, students have been involved in the informal initiative *Stara kao nova*, which explores how contemporary architecture can contribute to the revitalization of rural settlements in the Stara Planina region while preserving their cultural and environmental values. Through field research, design studios, and collaboration with local communities, the initiative investigates the potential of vernacular architecture and traditional building knowledge to inform contemporary architectural interventions. [7]

Within this framework, a collaboration with the residents of Pokrevenik was established in 2023, leading to the development of the *Novo Seosko Zborište* pavilion. Located in the courtyard of the abandoned village school, the project sought to reactivate this historically important site through a lightweight timber structure designed for community, cultural, and educational activities. Drawing inspiration from vernacular construction principles and the surrounding landscape, the pavilion aims to strengthen local identity, support social interaction, and contribute to the revitalization of village life.

5.1. Educational Design-Build Process

The development of the *Novo Seosko Zborište* pavilion followed a participatory design process that combined research, design, and community engagement. The process began with a desktop study of the village of Pokrevenik and the development of initial design proposals by student groups. This was followed by a field visit, during which students and faculty members documented the site and discussed local needs and challenges with residents. Based on field observations, vernacular architecture analysis, and community feedback, the proposals were revised and developed into a final design solution. After securing project funding, the pavilion was constructed through a collaborative effort involving students, faculty members, volunteers, carpenters and local residents, transforming the courtyard of the abandoned village school into a new community gathering space.

5.2. Architectural and Structural Solution

The architectural concept of the *Novo Seosko Zborište* pavilion is based on the reinterpretation of vernacular construction principles characteristic of the Stara Planina region. The structural modules were inspired by the traditional bondruk system with horizontal timber planks (talpe), commonly found in local residential and agricultural buildings. Rather than directly replicating traditional forms, the project translates their constructive logic into a contemporary architectural language.

The pavilion consists of a series of modular timber frames that define an open and flexible gathering space. Through repetition of identical structural elements, the design achieves simplicity of construction, efficient material use, and the possibility of prefabrication and future adaptation. The lightweight timber structure also minimizes intervention in the existing site and preserves the character of the surrounding cultural landscape.

Given the dimensions of the pavilion (4 × 8 m), a flat roof was selected as the most appropriate solution for creating a multifunctional covered space. The roof structure is formed by timber beams with a subtle dual-pitch slope of 2% on each side, ensuring adequate drainage while maintaining a visually lightweight and unobtrusive appearance. This approach allowed the pavilion to establish a contemporary identity while remaining closely connected to the scale, materials, and constructive traditions of the village environment.

5.3. Construction and Realization

The pavilion was conceived as a prefabricated timber structure to simplify construction, reduce on-site work, and minimize intervention within the sensitive rural setting. Concrete pad foundations were prepared in advance, while timber modules were manufactured off-site and transported to Pokrevenik for assembly. The structure was erected through a collaborative design-build process involving professional and traditional carpenters, local residents, a faculty member, and architecture students. Owing to the prefabricated system and collective effort, the pavilion was completed within three days, demonstrating the potential of lightweight timber construction as a fast, adaptable, and community-oriented building approach.

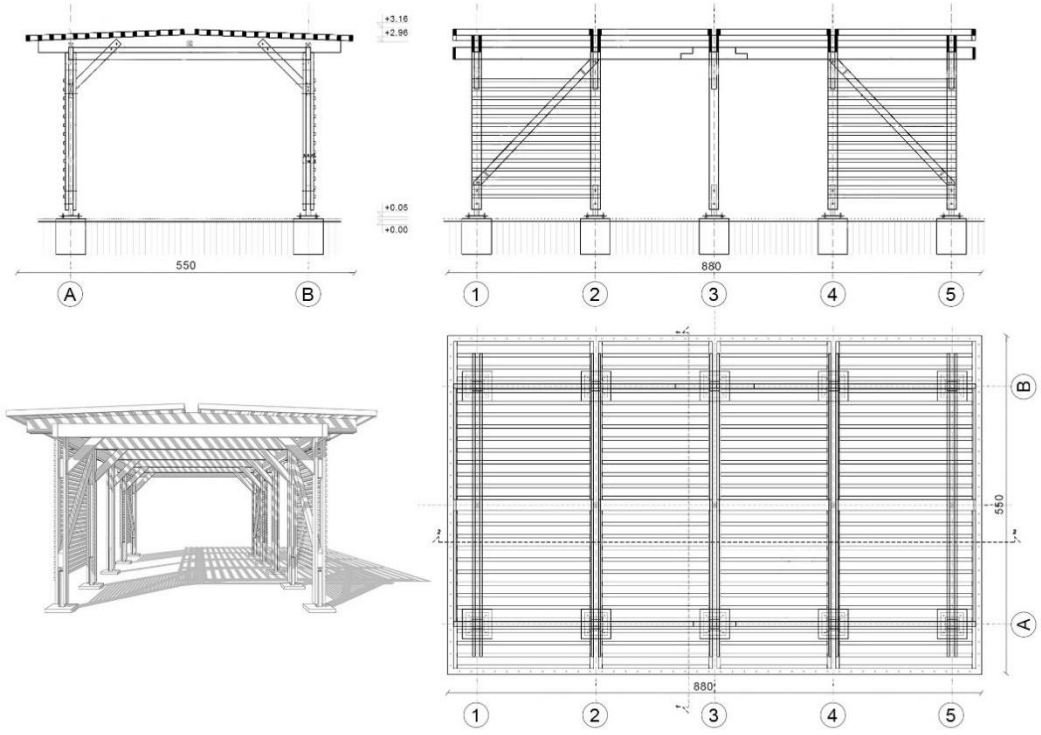


Figure 2. Technical drawings and 3D model, authors

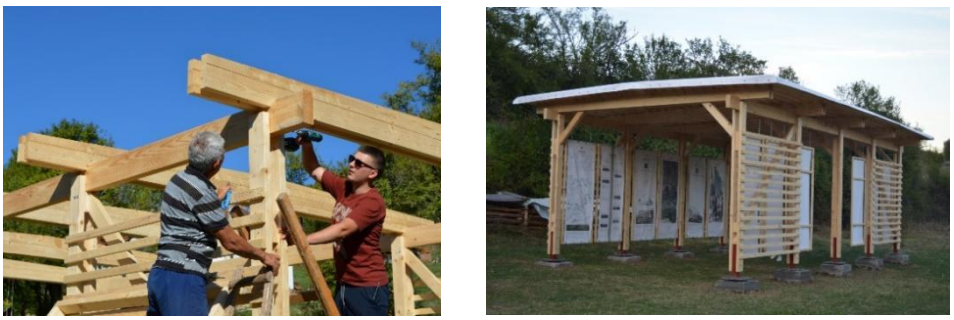


Figure 3. Construction process and completed appearance of the Novo Seosko Zborište, authors

6. RESULTS AND DISCUSSION

6.1. Interpretation of vernacular principles

The analysis of traditional construction systems reveals a number of principles that can be transferred to contemporary architectural practice. Particularly significant are modularity, the possibility of disassembly and reassembly, the use of prefabricated elements, and the ease of maintenance and repair. Traditional timber houses employed joints that allowed individual components to be replaced without affecting the overall structural integrity. Building elements were designed to be easily separated, repaired, and reused, extending the lifespan of structures and reducing resource consumption. Traditional builders also relied on locally available materials, simple construction systems, and careful adaptation to topography and climatic conditions. [1] These findings are consistent with previous studies emphasizing that the value of vernacular architecture lies in the reinterpretation of its construction principles rather than the replication of traditional forms. The comparison demonstrates that these principles can be successfully translated into contemporary timber architecture while responding to present-day technical and functional requirements. *Table 2* summarizes how the identified vernacular construction principles were reinterpreted through the design and construction of the Novo Seosko Zborište pavilion.

Table 2. Comparison of Vernacular Construction Principles and Their Contemporary Interpretation in the Novo Seosko Zborište

	Vernacular architecture of Stara Planina	**Contemporary interpretation in Novo Seosko Zborište**
Material use	Local stone, timber, earth, straw	Timber structure, steel connectors, concrete pad foundations
Structural system	Bondruk timber frame	Modular prefabricated timber frame
Construction method	On-site manual construction	Prefabricated and rapidly assembled system
Joints	Traditional timber joints and carpentry	Steel hybrid joints and mechanical fasteners
Adaptation to terrain	Buildings positioned according to topography	Minimal intervention and isolated foundations
Relationship with landscape	Natural materials and colors blend with surroundings	Timber structure adapted to the landscape context
Community building	Collective construction and communal spaces	Participatory design-build process involving students and residents
Maintenance and repair	Replaceable timber elements and easy repair materials	Modular and repairable structural components

6.2. Contribution to sustainable construction

The *Novo Seosko Zborište* pavilion reflects the environmental advantages of contemporary timber construction identified in previous research, particularly through lightweight prefabricated elements, modular construction, and the possibility of future disassembly. At the same time, the case study confirms that hybrid solutions involve certain trade-offs, as the use of transported prefabricated elements and concrete foundations increases embodied energy. These findings are consistent with recent studies on timber-hybrid systems, which emphasize both their environmental benefits and practical limitations. [5]

6.3. Contribution to cultural landscape preservation

The pavilion contributes to the preservation of the cultural landscape by reinterpreting vernacular construction principles rather than directly replicating traditional forms. This approach is consistent with contemporary research arguing that the continuity of vernacular architecture depends on preserving its spatial, environmental, and cultural principles rather than reproducing historical forms. Through the use of timber, a modular structural system inspired by bondruk construction, and a minimal-impact architectural intervention, the project establishes continuity with the local building tradition. Its scale, materiality, and careful placement within the former school courtyard allow the structure to integrate into the rural setting while reactivating an abandoned community space and strengthening the social and cultural identity of the village. [1]

Beyond its material and environmental aspects, the project also contributes to social sustainability. In a village with only 32 permanent inhabitants, the pavilion provides a shared gathering place that supports everyday social interaction, local events, and the transmission of knowledge between residents, students, and visitors. These findings reinforce previous studies that identify community participation and the activation of local public spaces as essential components of sustainable cultural landscape preservation. The case study therefore demonstrates that preserving cultural landscapes depends not only on conserving physical structures, but also on sustaining the social practices and community relationships that give them meaning. [1]

7. CONCLUSION

The case study demonstrates three key findings. First, vernacular principles can be transferred into contemporary design not through formal imitation, but through the reinterpretation of constructive logic, modularity, material clarity, and repairability. Second, lightweight prefabricated timber systems are particularly suitable for small-scale interventions in rural cultural landscapes because they reduce on-site disturbance and enable rapid collective construction. Third, the design-build process extends the sustainability of the project beyond material performance by creating social value through participation, knowledge exchange, and the reactivation of a former public space.

Overall, the research confirms that vernacular architecture remains a valuable source of knowledge for contemporary sustainable design. By combining traditional construction principles with prefabricated timber systems and a participatory design-build approach, context-sensitive interventions can simultaneously preserve cultural landscapes, support local communities, and promote environmentally and socially sustainable architectural practice.

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Research paper

PASSIVE CLIMATE-ADAPTIVE PRINCIPLES FROM TRADITIONAL ARCHITECTURE FOR SUSTAINABLE DESIGN

Ivanka Marinova[1]

Abstract

Growing demands for lower energy consumption and reduced environmental impact have increased the importance of architectural solutions that improve building performance through passive climate-responsive design. This paper investigates the potential for applying passive climate-adaptive principles derived from traditional residential architecture to contemporary sustainable design.

The study is based on the premise that the value of traditional architecture lies not in replicating historical forms but in understanding and adapting universal physical principles that enable indoor thermal comfort with minimal energy demand. The research examines key passive strategies, including compact building form, thermal mass, earth integration, natural ventilation, solar control, and the creation of protected microclimates.

The methodology combines a comparative analysis of representative traditional dwellings from different climatic regions with the identification of their underlying physical mechanisms. An analytical matrix is developed to establish relationships between passive design principles, their traditional applications, contemporary architectural interpretations, and their contribution to sustainable building performance. The proposed analytical framework is subsequently applied to selected contemporary architectural case studies that reinterpret these principles through modern materials, construction methods, and design approaches.

The findings demonstrate that climate-responsive principles developed in traditional residential architecture remain highly relevant for contemporary sustainable design. The proposed analytical matrix provides a practical framework for transferring traditional architectural knowledge into modern energy-efficient design practice.

Key words: *climate-adaptive design, passive design, vernacular architecture, sustainable architectural design, energy efficiency, analytical matrix*

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1. INTRODUCTION

Improving building energy performance is a major challenge in contemporary architectural design. According to the International Energy Agency (IEA) and the United Nations Environment Programme (UNEP), buildings account for a substantial share of global energy consumption and greenhouse gas emissions, increasing the need for strategies that reduce energy demand from the earliest design stages [4,5]. Alongside efficient building technologies and mechanical systems, passive climate-adaptive strategies exploit local climatic conditions and natural resources to achieve indoor comfort while minimizing operational energy use. In bioclimatic design, sustainable performance depends on the effective interaction between buildings and their environment rather than on active systems alone [1,6]. Traditional residential architecture provides valuable accumulated environmental knowledge. Developed through long-term climatic adaptation, vernacular buildings embody transferable principles that remain relevant to contemporary sustainable design [2,3]. This study investigates how these passive principles can be transferred to contemporary architectural practice to improve energy efficiency and environmental performance..

1.1. Research Hypothesis

This study is based on the hypothesis that the enduring value of traditional residential architecture lies in its passive climate-adaptive principles rather than in the replication of historical architectural forms. Identifying, systematizing, and reinterpreting these principles within contemporary construction technologies can contribute to reducing building energy demand while enhancing environmental sustainability and indoor comfort [1,3].

1.2. Research Objectives

To test this hypothesis, the study pursues the following objectives:

- to identify the principal passive climate-adaptive principles embodied in traditional residential architecture;
- to examine how these principles are expressed in representative vernacular dwellings from different climatic regions;
- to develop an analytical matrix linking passive principles, their underlying physical mechanisms, traditional architectural solutions, and contemporary design interpretations;
- to apply the analytical matrix to selected contemporary architectural projects and examine how the identified passive climate-adaptive principles are reinterpreted in current architectural practice.

1.3. Research Methodology

The research adopts a qualitative comparative-analytical methodology comprising three stages: identification of passive climate-adaptive principles in traditional residential architecture from different climatic contexts; systematization of their

physical mechanisms and architectural manifestations in an analytical matrix linking traditional strategies with contemporary sustainability criteria; and application of the matrix to selected contemporary case studies. The case studies are used as documented architectural applications rather than for statistical validation of the matrix. The analysis identifies six passive principles—building compactness, thermal mass, integration with terrain, natural ventilation and passive cooling, solar radiation control, and protected microclimates—and examines their architectural expression. The comparison focuses on patterns of application rather than numerical scoring or performance ranking. Where documentation is insufficient, a principle is recorded as not evidenced rather than inferred.

1.4. Scope and Limitations

The study is exploratory and analytical and does not include quantitative building performance simulations. Traditional and contemporary case studies are selected as representative examples of different climatic contexts rather than as an exhaustive survey. The research therefore focuses on universal passive climate-adaptive principles and their potential integration into contemporary sustainable design. The contemporary case studies demonstrate the applicability of the analytical framework rather than verify its predictive accuracy. No independent measurements, simulation-based comparisons, statistical testing, or control cases are undertaken. Accordingly, the case-study analysis represents an application and comparative illustration of the framework, not empirical validation of its effectiveness.

2. PASSIVE CLIMATE-ADAPTIVE PRINCIPLES

Passive climate-adaptive principles encompass architectural strategies that use local climate, topography, solar radiation, prevailing winds, building form, orientation, and material properties to create comfortable indoor environments while minimizing energy demand [1,4,5]. Unlike active building systems, passive strategies integrate climatic responsiveness into the architectural design itself. As established by Victor Olgyay's theory of bioclimatic design, adapting buildings to local climatic conditions can improve energy efficiency before reliance on active systems [1].

Based on the comparative analysis, six recurring principles are identified across traditional residential architecture:

- building compactness — minimizing the envelope-to-volume ratio (A/V) to reduce heat transfer;
- thermal mass — storing and gradually releasing heat to moderate temperature fluctuations;
- terrain integration — using the ground as a thermal buffer through partial or complete earth sheltering;
- natural ventilation and passive cooling — using air movement, pressure differences, and night-time cooling;

- solar radiation control — managing solar heat gains through orientation and external shading;
- protected microclimates — creating courtyards and transitional spaces that support daylighting, ventilation, and thermal comfort.

These principles were selected for their recurring character and potential applicability across different materials, construction systems, and architectural traditions. As argued by Amos Rapoport and Paul Oliver, similar climatic conditions may generate comparable architectural responses in geographically distant regions, indicating the influence of environmental and physical constraints on residential forms [2,3]. In this study, passive climate-adaptive principles constitute the primary analytical framework, while traditional residential buildings provide evidence of their practical manifestation. The following sections examine their expression in vernacular architecture and their potential reinterpretation in contemporary sustainable design..

3. MANIFESTATION OF PASSIVE CLIMATE-ADAPTIVE PRINCIPLES IN TRADITIONAL RESIDENTIAL ARCHITECTURE

Traditional residential architecture represents design knowledge developed through long-term adaptation to environmental and climatic conditions. Previous research by the author showed that similar climatic challenges can generate comparable passive architectural responses despite geographical and cultural differences [7]. This supports Rapoport's view that residential form is primarily shaped by human–environment interaction, while culture influences its architectural expression [2].

3.1. Optimized Building Compactness

Compact building form reduces the envelope-to-volume ratio (A/V), thereby limiting heat transfer and heat loss. This principle occurs in igloos, yurts, and traditional timber and stone dwellings in northern and mountainous regions, despite differences in construction techniques (Fig. 1).



Figure 1. Representative Traditional Housing Types in: (1) Northern Eurasia; (2) Alaska; (3) Russia; (4) Northern Japan

3.2. Thermal Mass Utilization



Figure 2. Representative Traditional Housing Types in: (a) Desert Climate—Tunisia (Africa) and Iran; (b) Temperate Mountain Regions—Bulgaria and China

Heavy masonry, earth, and adobe walls absorb heat during warm periods and gradually release it as temperatures decline, moderating daily fluctuations and improving indoor thermal comfort. This principle is common in vernacular houses across mountainous regions of Europe and Asia and desert settlements of the Middle East and North Africa (Fig. 2). Thermal mass is considered an effective passive mechanism for indoor climate regulation [1].

3.3. Integration with the Terrain as a Thermal Buffer

Earth-sheltered and semi-buried dwellings take advantage of the relatively stable temperature of the surrounding ground to reduce winter heat losses and prevent summer overheating. By incorporating the terrain into the building envelope, these structures use the earth itself as a natural insulating medium. This principle can be observed in igloos, yurts (Fig. 1), and various traditional dwellings in mountainous regions (Fig. 2).

3.4. Natural Ventilation and Passive Cooling

In warm climates, traditional architecture relies on natural air movement to dissipate accumulated heat. Courtyards (Fig. 3), wind towers, solar chimneys (Fig. 2), high interior spaces, and cross-ventilation (Fig. 3) promote continuous airflow without mechanical assistance. In humid tropical regions, these strategies are complemented by elevated floor structures and highly permeable building envelopes that further enhance natural ventilation.



Figure 3. Representative Traditional Housing Types: (a) Courtyard Houses—Beijing, China, and Southern Spain; (b) Stilt Houses in Equatorial Regions—Indonesia and the Amazon Rainforest

3.5. Solar Radiation Control

Traditional dwellings employ a variety of architectural features to regulate solar exposure according to climatic conditions. Deep roof overhangs, loggias, wooden lattice screens, and carefully considered building orientation reduce unwanted solar heat gains while maximizing beneficial solar radiation during colder periods. Although these elements differ in form across regions, they all embody the same passive principle of solar control.

3.6. Creation of Protected Microclimates

Courtyards and transitional semi-open spaces (Fig. 2) create localized environmental conditions that improve natural ventilation, daylight availability, and thermal comfort. Courtyard and peristyle houses across the Mediterranean, Middle East, China, and India demonstrate the recurring use of such spatial configurations as responses to hot climates. As noted by Paul Oliver, courtyards are among the most enduring elements of vernacular housing because they regulate the microclimate while enhancing living conditions [3].

The comparative analysis identifies a limited set of recurring passive climate-adaptive principles that provide the basis for the analytical matrix developed in the following section.

4. ANALYTICAL MATRIX

The analysis identifies universal passive principles that remain applicable beyond their original historical and cultural contexts. Their transferable value lies in the underlying physical and environmental mechanisms rather than in the replication of traditional forms. Accordingly, the analytical matrix links traditional architectural strategies, their physical principles and mechanisms, and their contribution to contemporary sustainability objectives (Table 1).

Table 1. Integrated Analytical Matrix of Traditional Architectural Strategies, Their Underlying Physical Principles, Operating Mechanisms, and Contributions to Sustainable Building Assessment Criteria

Physical Principle	Traditional Design Strategy	Underlying Mechanism	Expected Impact on Building Performance	Contribution to Contemporary Sustainability Assessment Criteria
Ground Thermal Stability	Partial / complete earth sheltering	Stabilization of the thermal environment surrounding the building	Reduced energy demand for heating and cooling	LEED: Energy & Atmosphere; BREEAM: Energy; DGNB: Environmental Quality; Level(s): Operational Energy
Heat Loss Minimization	Compact building form	Reduced building envelope area relative to enclosed volume	Lower transmission heat losses	LEED: Optimize Energy Performance; BREEAM: Energy; DGNB: Energy Efficiency

High Thermal Mass	Massive earth and stone walls	Heat storage and gradual heat release	Reduced indoor temperature fluctuations and peak thermal loads	LEED: Energy Performance; BREEAM: Thermal Comfort; DGNB: Indoor Environmental Quality
Passive Solar Utilization	South-facing building openings	Maximization of winter solar heat gains	Reduced heating and lighting energy demand	LEED: Daylight; Energy & Atmosphere; BREEAM: Health & Wellbeing; DGNB: Sociocultural Quality
Controlled Natural Ventilation	Naturally driven airflow	Improved air exchange through passive ventilation	Reduced cooling demand and improved indoor air quality	LEED: Indoor Environmental Quality; BREEAM: Health & Wellbeing; DGNB: Indoor Air Quality
Protection from Climatic Exposure	Compact form and sheltered façades	Reduced exposure to wind and temperature extremes	Lower energy losses and improved building resilience	LEED: Sustainable Sites; BREEAM: Resilience; DGNB: Climate Adaptation
Integration with Topography	Adaptation to the natural terrain	Utilization of local microclimatic conditions	Improved microclimate and reduced environmental impact	LEED: Sustainable Sites; BREEAM: Land Use & Ecology; DGNB: Site Quality
Integrated Passive Design	Combined use of multiple natural environmental factors	Synergy between building form, materials, and climate	Maximum utilization of passive environmental resources with minimum energy demand	LEED: Integrative Process; BREEAM: Management; DGNB: Integrated Design; Level(s): Life Cycle Thinking

5. APPLICATION OF THE ANALYTICAL FRAMEWORK TO CONTEMPORARY CASE STUDIES

The analytical matrix developed in the preceding section is applied to selected contemporary architectural projects in order to examine how passive climate-adaptive principles derived from traditional architecture are interpreted within current architectural practice. The purpose of this analysis is not to validate the matrix statistically or to establish causal relationships between individual design strategies and building performance. Rather, the case studies provide documented examples through which the analytical categories can be examined in built architectural contexts. (Fig. 4).

The presented case studies do not aim to provide an exhaustive overview of contemporary projects incorporating passive climate-adaptive principles derived from traditional residential architecture, but represent a selected sample of relevant examples demonstrating how vernacular knowledge can be transformed into innovative architectural solutions.



Figure 4. Contemporary architectural case studies selected for application of the analytical framework: (a) Gando Primary School, Burkina Faso; (b) METI Handmade School, Bangladesh; (c) Mapungubwe Interpretation Centre, South Africa; (d) Bait Ur Rouf Mosque, Bangladesh.

5.1. Case Study Selection and Application Procedure

The case studies were selected based on four criteria: identifiable passive climate-adaptive strategies; sufficient documentation; contemporary reinterpretation rather than direct reproduction of traditional forms; and diversity of climatic and cultural contexts. The analysis established qualitative correspondence between documented project features and six principles: (1) building compactness; (2) thermal mass; (3) terrain integration; (4) natural ventilation and passive cooling; (5) solar control; and (6) protected microclimates. Relevant features were classified accordingly. No numerical scoring or ranking was applied. The analysis examines how these principles are adapted to different climates, programmes, materials, construction resources, and site conditions.

5.2. Examples Analysis

Gando Primary School, designed by Francis Kéré and completed in 2001 in Burkina Faso, combines traditional knowledge with contemporary construction [8]. Clay/cement bricks provide thermal mass, while the ventilated roof structure enables hot-air escape. Wide overhangs provide solar and rain protection. The project demonstrates thermal mass, passive cooling, natural ventilation, and solar control.

The METI Handmade School in Rudrapur, Bangladesh, designed by Anna Heringer and Eike Roswag and completed in 2006, reinterprets traditional earth and bamboo construction [9]. Thick earthen walls provide thermal mass, while the lighter bamboo upper floor enhances ventilation and permeability. The case illustrates material adaptation and spatial organization alongside passive environmental strategies.

The Mapungubwe Interpretation Centre, designed by Peter Rich Architects and completed in 2009 in South Africa, combines local materials and traditional construction knowledge with contemporary technology [10]. Its vaulted earth-tile spaces demonstrate thermal mass, climatic and solar protection, and site integration.

The Bait Ur Rouf Mosque, designed by Marina Tabassum and completed in 2012 in Dhaka, Bangladesh, uses contemporary spatial strategies to reinterpret regional traditions [11]. Light courts, porous brick walls, and a skylight provide protected microclimates, natural ventilation, and controlled daylight.

5.6. Comparative Application of the Analytical Matrix

The matrix shows that the selected projects combine multiple passive climate-adaptive principles, expressed through different architectural solutions according to climate, site, programme, materials, and technology. Their comparison supports the matrix as a classification and interpretation tool, but does not constitute empirical validation of its predictive performance.

Table 2. Application of the Analytical Matrix to Contemporary Case Studies

Passive principle	Gando Primary School	METI Handmade School	Mapungubwe Interpretation Centre	Bait Ur Rouf Mosque
Building compactness	—	Present	—	Present
Thermal mass	Present	Present	Present	Present
Integration with terrain	—	—	Present	—
Natural ventilation / passive cooling	Present	Present	Present	Present
Solar radiation control	Present	Present	Present	Present

6. DISCUSSION

The comparative application shows that the passive climate-adaptive principles identified in traditional residential architecture remain transferable to contemporary architectural practice. Their application is not dependent on reproducing traditional forms, but on adapting the underlying physical mechanisms to current materials, technologies, programmes, and climatic conditions.

The case studies also demonstrate that the principles are context-dependent. Building compactness, thermal mass, solar control, natural ventilation, terrain integration, and protected microclimates may be combined in different ways according to local environmental conditions and architectural requirements. The same principle can therefore generate substantially different contemporary solutions.

The analytical matrix is consequently most useful as a classification and interpretation framework for identifying transferable passive strategies. The case studies demonstrate its applicability, but do not provide empirical validation of its predictive effectiveness. Such validation would require further research involving building performance simulation, measured data, or comparative testing.

7. CONCLUSIONS

The study demonstrates that traditional residential architecture provides transferable passive climate-adaptive principles whose relevance extends beyond historical forms and construction systems.

The analytical matrix establishes relationships between passive principles, their physical mechanisms, traditional manifestations, and contemporary architectural applications. Its application to selected case studies demonstrates that these principles can be reinterpreted through different materials, technologies, and spatial configurations according to climatic and functional conditions.

The proposed matrix should therefore be understood as a conceptual analytical and design-support tool rather than as a validated predictive model. Further empirical research involving simulation, measured performance, and comparative testing is required to assess its predictive effectiveness.

7.1. Scientific Contribution

The principal scientific contribution is the development of an analytical matrix that systematizes the transfer of passive climate-adaptive principles from traditional residential architecture to contemporary sustainable design. By linking physical mechanisms, traditional architectural strategies, and contemporary applications, the matrix provides a structured basis for identifying and interpreting transferable passive design solutions.

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TOPIC 05

WATER, ENVIRONMENT & BLUE-GREEN INFRASTRUCTURE

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

PERFORMANCE AND ECONOMIC VALUE OF NATURE-BASED SOLUTIONS FOR FLOOD RISK REDUCTION IN THE TAMNAVA RIVER BASIN

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Abstract

Flood risk management is evolving from sole reliance on traditional grey infrastructure towards nature-based solutions (NBS), which work with natural processes to reduce flood impacts while providing additional environmental and socio-economic benefits. However, we still lack evidence on their effectiveness and economic viability at the catchment scale. This paper presents an ex-ante assessment framework that integrates hydrological and hydrodynamic modelling with economic evaluation of flood damage reduction and selected co-benefits. The framework is applied to the Tamnava River basin using a coupled modelling chain (3DNet-Catch and HEC-RAS) to assess flood hazard, vulnerability and risk under three scenarios: a baseline or "do nothing" scenario, a grey scenario with retention ponds only, and a hybrid green-grey scenario combining retention ponds with afforestation, floodplain restoration, riparian buffer strips and removal of flow obstacles. Flood risk reduction is evaluated for design floods with return periods from 5 to 1000 years using high-resolution, micro-scale hazard and risk mapping. Economic performance is assessed through expected avoided annual damage and a life-cycle cost-benefit analysis including monetised co-benefits. The results show that retention ponds dominate in peak attenuation for extreme floods, while NBS enhance risk reduction for low- and medium-magnitude events. The hybrid scenario proves to be cost-effective when co-benefits are included, highlighting the importance of multi-benefit evaluation of flood mitigation measures.

Key words: *flood risk assessment, hybrid infrastructure, cost-benefit analysis, co-benefits*

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1. INTRODUCTION

In response to the increasing frequency and intensity of extreme weather events caused by climate change, nature-based solutions (NBS) are introduced as a paradigm shift away from sole reliance on traditional grey infrastructure [1]. NBS are defined as actions to protect, sustainably manage, and restore natural or modified ecosystems to address societal challenges effectively and adaptively [2] [3]. The main advantage of NBS is their multi-functionality. Unlike grey infrastructure, NBS provide a range of co-benefits such as carbon sequestration, biodiversity enhancement, improved water quality, and socio-economic opportunities like recreation, public health improvements, and green job creation.

In flood- prone rural catchments, large-scale NBS offer a promising complementary or alternative strategy. The effectiveness of large-scale NBS in mitigating floods is increasingly supported by scientific evidence, which shows that NBS performance is highly sensitive to watershed scale, flood intensity and type of intervention [4]. On the other hand, widespread implementation of NBS is often hindered by a lack of evidence regarding their long-term economic viability, which would aid the decision-makers in comparing investment alternatives [3][5]. Traditional assessments often focus narrowly on expected annual damage (EAD) reduction, which can lead to the conclusion that NBS are economically inefficient, and neglect the co-benefits of NBS [6]. Recent reviews indicate that NBS can be as effective as grey solutions, with many studies finding them consistently more cost-effective when the full suite of co-benefits is considered [3] [7]. When co-benefits are integrated into a life-cycle cost-benefit analysis (CBA), interventions such as afforestation and retention ponds frequently demonstrate positive net economic impacts [6]. Furthermore, a social CBA perspective is essential to capture the value of these investments for the broader community, including environmental and social impacts that extend beyond direct economic effects [8][9][3].

Building a compelling business case for investors and policymakers in new NBS projects requires a rigorous ex-ante assessment. However, ex-ante planning typically faces problems such as a lack of baseline data for evaluating benefits and a lack of standardised methods for monetary valuation, particularly for integrating intangible social and ecological outcomes. The methods applied therefore range from rapid assessments using the value transfer approach to high-resolution probabilistic risk modelling.

This paper presents a methodological framework for the ex-ante assessment of NBS, focusing on combining performance modelling with monetary evaluation of both primary risk reduction benefits and a set of co-benefits. Using the Tamnava River basin as a case study, the paper investigates whether the existing grey measures can be effectively complemented by NBS to reduce flood risk, improve ecosystem services and achieve economic viability. Specifically, the paper aims to (i) assess flood risk under current conditions and alternative intervention scenarios and quantify the effectiveness of these intervention strategies, (ii) evaluate primary benefits and selected environmental and social co-benefits, and (iii) assess economic feasibility through cost-benefit analysis. Overall, the paper aims to provide a systematic roadmap for practitioners to identify, predict, and value the multiple benefits of NBS for flood risk

reduction in similar projects. Such a holistic approach is expected to support broader integration of NBS into climate resilience and sustainable development strategies.

2. DATA AND METHODS

2.1. Study area

The Tamnava River is a 78.5 km long left tributary of the Kolubara River (Figure 1), draining a catchment area of 726 km². Elevations range from about 470 m above sea level in the upper basin to 64 m at the confluence with the Kolubara. Agricultural land dominates the basin (around 79%), primarily located in wide alluvial floodplains along the Tamnava and its major tributaries, the Ub and Gračica rivers. Urban land cover is limited (around 1.2%) and concentrated in the towns of Ub and Koceljeva.

The hydroclimatic regime in the catchment is characterised by strong seasonality. High flows typically occur in early spring due to combined rainfall and snowmelt, and in early summer as a result of intense convective storms. Streamflow measurements from three gauging stations show modest mean annual discharges but very high peak flows during extreme events, underscoring the basin's flash- flood character and its sensitivity to short- duration rainfall.

Frequent flooding is therefore the primary hazard affecting the Tamnava River basin. The most catastrophic event occurred in May 2014, while other significant floods were recorded in 1999, 2006, 2009, 2021, and 2023. Since Tamnava is one of the downstreammost tributaries of the Kolubara River, attenuation of flood peaks within its basin is crucial for reducing flood risk further downstream, particularly at the town of Obrenovac at the confluence with the Sava River.

Existing flood protection in the basin relies mainly on embankments near populated areas and the Gračica-Ub bypass channel. Following the May 2014 floods, three large retention ponds were planned by Serbian water authorities [10].

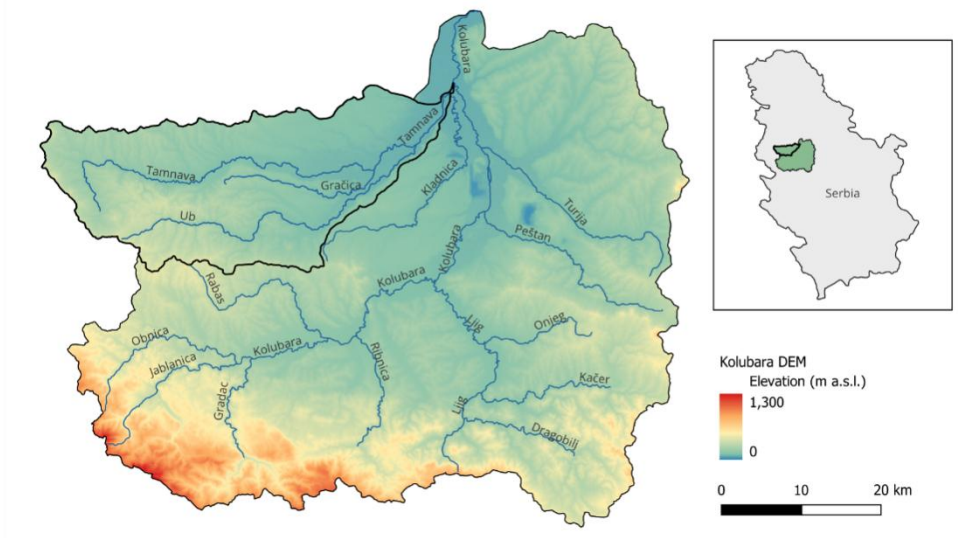


Figure 1. The Tamnava River basin delineated within the Kolubara River basin

2.2. Mitigation scenarios

Suitable flood mitigation interventions were selected using the Measure Selector Tool and the GIS-based NBS spatial suitability tool developed within the RECONECT project [11][12][13][14], previous studies [15][16], field inspections and stakeholder consultations [17]. The final set of measures includes (Figure 2):

- Retention ponds, already planned in spatial planning documents;
- Afforestation and reforestation, primarily in upper catchment areas;
- Floodplain restoration, focused on reconnecting abandoned or disconnected floodplain areas;
- Buffer strips along selected river reaches to increase hydraulic roughness and enhance retention;
- Removal of flow obstacles, especially road embankments and bridge constrictions, identified during field surveys.

Three mitigation scenarios were analysed for design floods with return periods ranging from 5 to 1000 years:

- S0 – Baseline or "do nothing" scenario: current setup of flood defences with no additional measures implemented;
- S1 – Hybrid green-grey scenario: retention ponds combined with all selected NBS;
- S2 – Grey scenario: retention ponds implemented as a stand-alone measure.

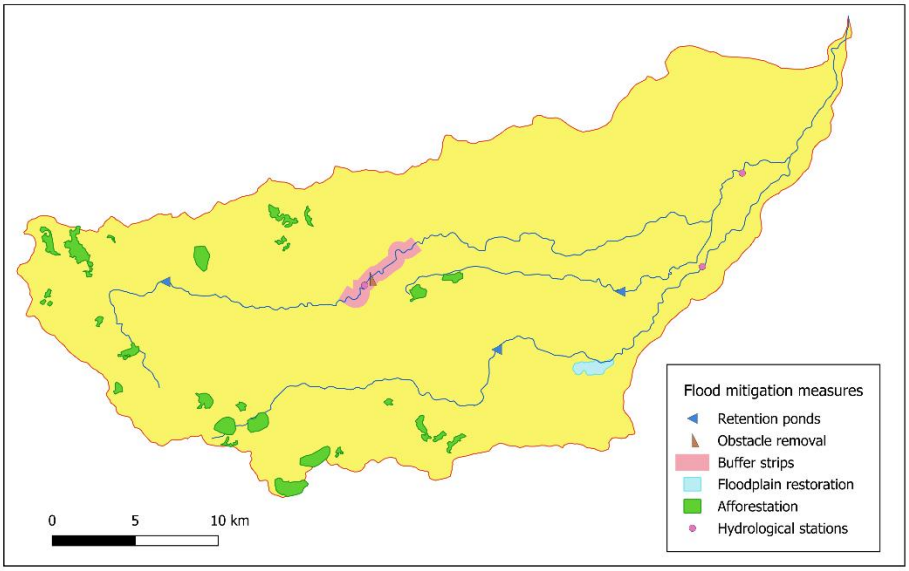


Figure 2. Planned flood mitigation measures in the Tamnava River basin

2.3. Hydrological and hydrodynamic modelling

Flood hazard was assessed using a modelling chain combining a semi-distributed hydrological model (3DNet-Catch [18]) and a coupled 1D-2D hydrodynamic model (HEC-RAS [19]). The hydrological model simulates runoff generation in 21 sub-basins in hourly time steps, while the hydrodynamic model computes flood wave propagation

and inundation across river channels and floodplains. Figure 3 shows the computational domain of the hydrodynamic model.

Both models were calibrated and validated against the observed flood events, including the extreme flood of May 2014 and more recent events, showing good reproduction of observed discharges, water levels, and inundation extents (see Figure 4). In calibration, the hydrological model achieved Nash–Sutcliffe efficiency (NSE) ranging from 0.64 to 0.85 and relative runoff volume bias from −0.9% to 17.6% across the gauging stations. In validation, NSE ranged from 0.50 to 0.89, and the volume bias from −21.2% to 24.3%.

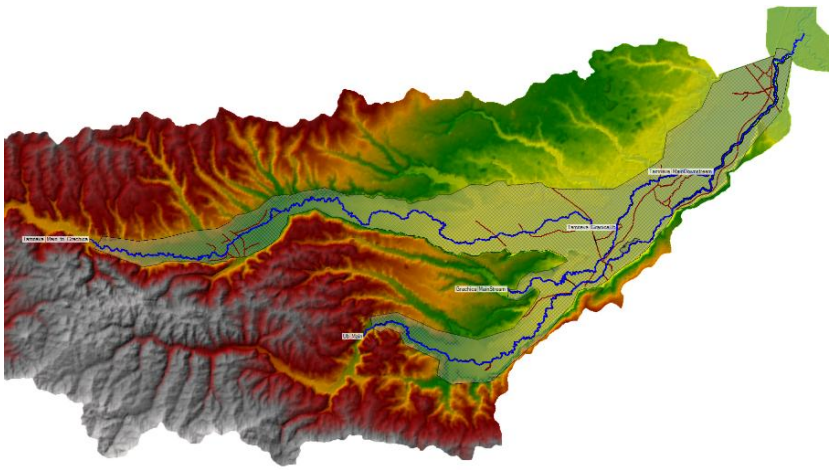


Figure 3. Computational domain of the HEC-RAS hydrodynamical model of the Tamnava River basin

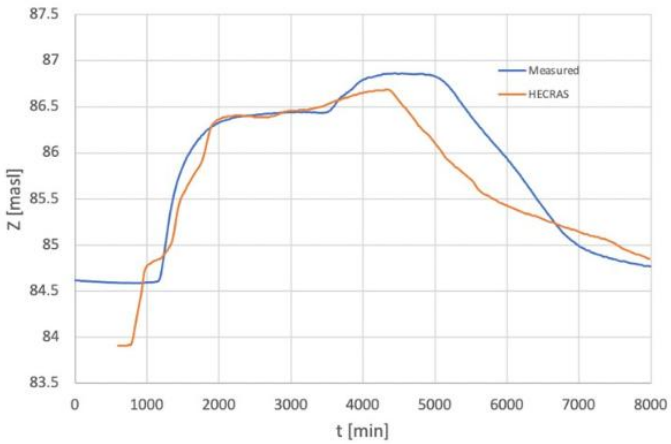


Figure 4. Simulated vs. observed stage hydrograph at Ćemanov most during the June 2020 flood

2.4. Hazard, vulnerability and risk assessment

Flood hazard maps were generated as raster layers of maximum water depth for each scenario and return period. Flood hazard was classified by water depth into four hazard classes following the national regulation [20], ranging from low hazard when water depth is less than 0.5 m, moderate between 0.5 m and 1.5 m, high between 1.5 m and 4 m, and very high (extreme) when it exceeds 4 m.

Vulnerability was assessed using an index-based approach that combines physical, economic, environmental, social, and institutional indicators. Flood risk was then calculated as the product of normalised hazard and vulnerability, resulting in spatially explicit risk maps. The effectiveness of alternative mitigation scenarios in reducing flood risk relative to the baseline was measured by the Flood Risk Reduction Index (FRRI), an index computed by comparing risk classes in each pixel of the flooded area [21].

2.5. Benefit and cost assessment

Primary benefits were quantified as expected avoided annual damage (EAAD), computed using a micro-scale GIS-based damage model [15] (Figure 5). Damages were estimated for buildings, crops, transport infrastructure, and the temporarily displaced population. Selected co-benefits of NBS were monetised using value transfer methods, including carbon sequestration, habitat creation, air quality improvement, and educational value [6]. The cost-benefit analysis was carried out over a 30-year time horizon using a 5% discount rate.

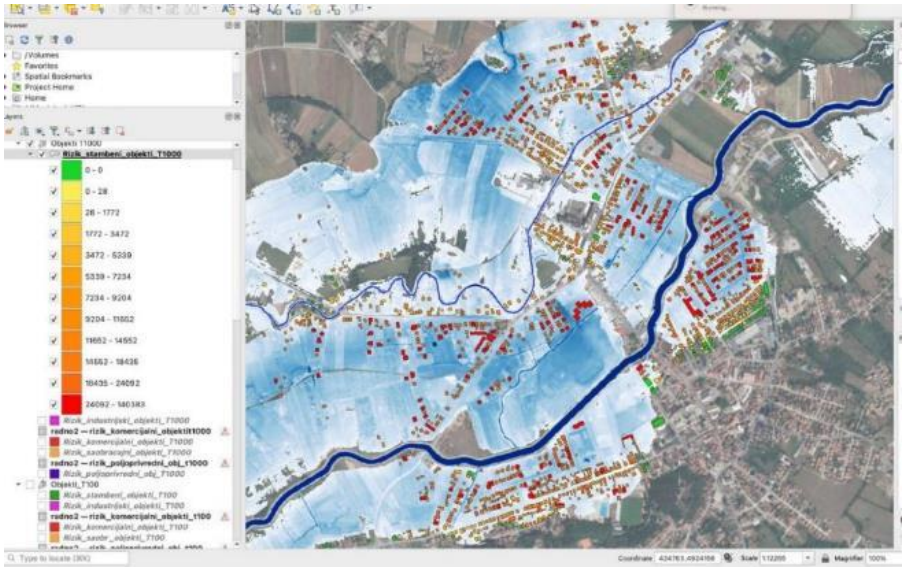


Figure 5. GIS-based micro-scale assessment of damages.

3. RESULTS

3.1. Flood hazard and risk reduction

Both intervention scenarios reduce flood peaks and flood extents relative to the baseline for all considered flood probabilities. This is illustrated in Figure 6, which shows flood hazard maps for the area near the town of Ub during the 1000-year design flood. The scenarios perform similarly because retention ponds play a dominant role in attenuating high-magnitude floods, reducing peak flows by up to 25% during extreme events. NBS included in S1 further enhance flood risk reduction for lower-magnitude floods by increasing catchment retention and floodplain storage.



Figure 6. Flood hazard near the town of Ub for the 1000-year flood for scenarios S0, S1, and S2.

Figure 7 shows the composite risk maps for the whole Tamnava basin from the 100-year design flood, shown in four classes from low to very high risk. Reduction of the flood risk is especially visible in the populated areas of Koceljeva and Ub for both mitigation scenarios. Computation of FRRI provides a more precise evaluation of flood risk reduction (Table 1). FRRI results show that both S1 and S2 reduce overall flood risk across all return periods. The hybrid scenario S1 performs better for low- to- moderate floods and for environmental and physical vulnerability components, while differences between S1 and S2 diminish for the most extreme floods.

Table 1. Flood risk reduction index for three characteristic return periods.

Mitigation scenario	Return period		
	20 yr	100 yr	500 yr
Scenario S1 (hybrid grey-green – all measures)	0.054	0.065	0.081
Scenario S2 (grey – retention ponds only)	0.051	0.068	0.079

3.2. Economic performance

Expected annual damage (EAD) under the baseline scenario S0 is estimated at approximately €1.9 million. Both S1 and S2 lead to substantial reductions, with EAD decreasing to 62% and 66% of the baseline EAD under S1 and S2, respectively. However, avoided damages alone are insufficient to justify investments in large retention ponds.

Table 2 shows the costs and benefits broken down into the primary benefit of avoided damage and co-benefits. When co- benefits are included, the economic performance changes markedly for both scenarios. Scenario S1 achieves a benefit-cost ratio (BCR) greater than one, indicating overall cost- effectiveness over the project lifetime. In contrast, BCR for retention ponds alone (S2) remains lower than 1 even when co- benefits are considered.

Table 2. Results of the cost-benefit analysis over a 30-year time horizon.

Present values (million EUR)	Benefit from avoided damage only		With co-benefits	
	Scenario S1	Scenario S2	Scenario S1	Scenario S2
Costs	48.1	35.5	48.1	35.5
Benefit from avoided damage	12.3	11.0	12.3	11.0
Co-benefits			58.3	15.1
Total benefits	12.3	11.0	70.7	26.0
Benefit-cost ratio	0.26	0.31	1.47	0.73

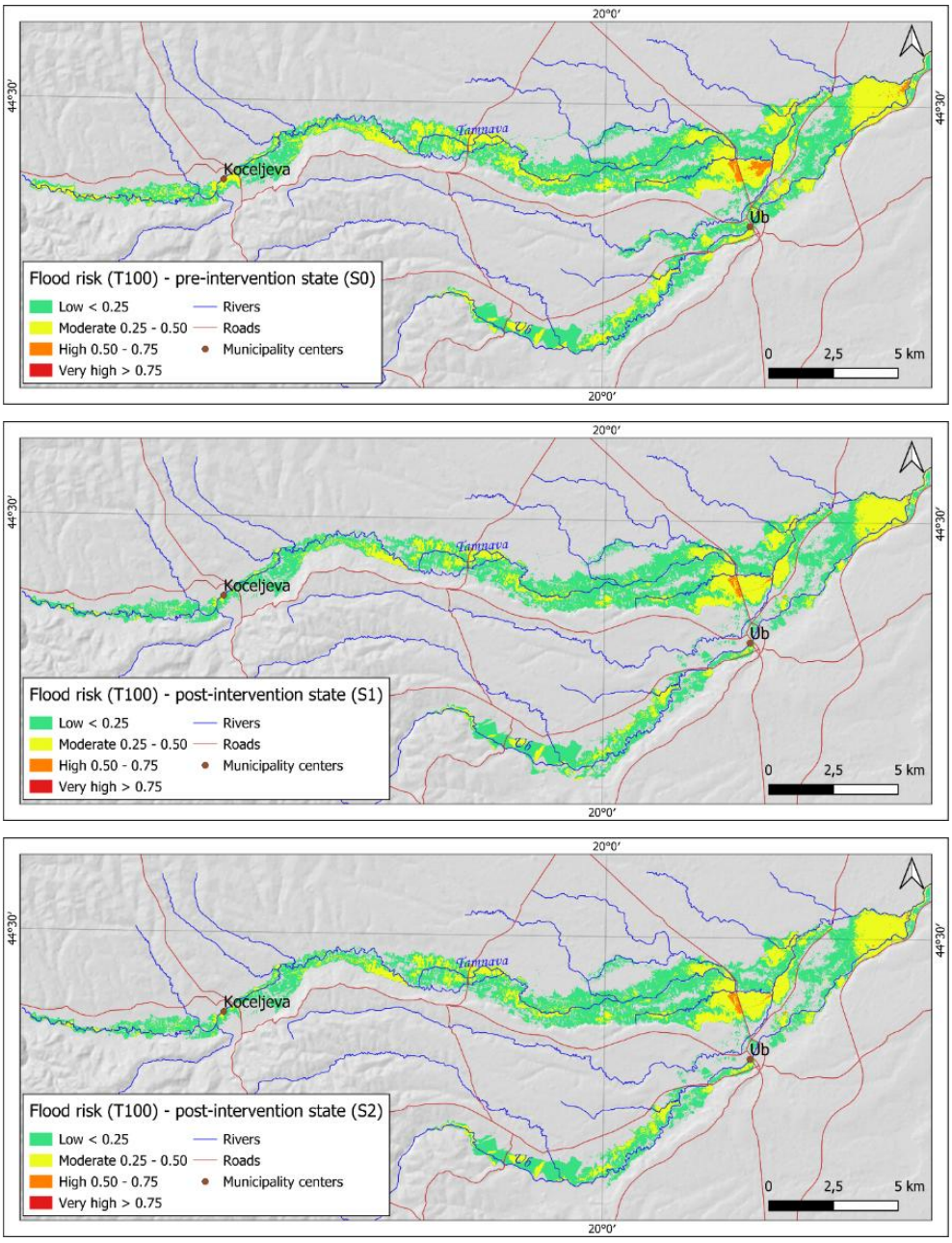


Figure 7. Risk maps of the Tamnava River basin for the 100-year flood under scenarios S0, S1, and S2.

4. CONCLUSIONS

This study highlights the importance of adopting a holistic, multi-benefit perspective in flood risk management. While large grey measures are necessary for controlling extreme floods, NBS provide additional benefits that improve economic efficiency and provide significant environmental advantages. The Tamnava case study

demonstrates that hybrid green-grey solutions can outperform purely grey approaches, especially when evaluated over broader benefit categories, and can therefore enhance project feasibility. Key conclusions include:

- Retention ponds are effective in reducing flood peaks, especially for extreme events, but are not cost-effective as stand-alone measures;
- NBS such as afforestation, floodplain restoration, and buffer strips provide additional risk reduction and substantial environmental co-benefits;
- Accounting for co-benefits is crucial for demonstrating the economic viability of hybrid flood management strategies;
- A multidisciplinary, stakeholder-engaged approach is essential for successful NBS implementation.

These findings provide quantitative evidence supporting the mainstreaming of nature-based solutions as integral components of flood risk management under both engineering and socio-economic criteria. The results may encourage wider adoption of such strategies in similar rural catchments across Southeast Europe and beyond. The integrated modelling framework and evaluation approach presented in this paper provide a sound basis for decision-making under current planning assumptions. However, uncertainties about future land-use changes and climate variability remain and highlight the need to integrate them into future feasibility assessments for long-term resilience planning.

ACKNOWLEDGMENT

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Review paper

PREDICTION WITHOUT PRECISION - SENSITIVITY AND UNCERTAINTY PRACTICES IN BGI HYDROLOGICAL MODELING

Žana Topalović[1]

Abstract

Hydrological models are essential tools for designing and evaluating Blue-Green Infrastructure (BGI) for urban stormwater management. Their reliability depends on proper parameter estimation, sensitivity analysis (SA) and uncertainty quantification (UA) – diagnostic practices that characterize predictive uncertainty and identify influential parameters. In conventional hydrological modeling (defined here as established best practices in catchment-scale hydrology featuring rigorous calibration, formal UA, global SA and independent validation), SA and UA are standard practices, justified by scientific rigor and essential for credible hydrologic modeling. Yet, a striking gap exists in BGI modeling: despite the proliferation of studies over the past decade, rigorous SA and UA remain rare. This systematic review examines 38 peer-reviewed studies to characterize the current state of SA and UA in BGI modeling, identify persistent methodological gaps, and propose best practices. The findings reveal that while a small subset of studies demonstrates exemplary practice by employing global SA methods (Sobol, VARS, eFAST) and formal UA (GLUE, Bayesian approaches), the vast majority rely on manual calibration, local SA and no UA. Only 26% of studies performed formal uncertainty analysis and only 53% conducted split-sample model validation. This "prediction without precision" undermines the reliability of BGI planning decisions involving significant public and private investment. We conclude that the BGI modeling community must adopt the methodological standards of conventional hydrology, namely formal UA, global SA, rigorous calibration and independent validation to fulfill its potential as a credible decision-support tool for sustainable urban flood management.

Key words: *Blue-green infrastructure; hydrological modeling; parameter uncertainty; sensitivity analysis, model calibration; systematic review*

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1. INTRODUCTION

Cities worldwide are investing billions in Blue-Green Infrastructure (BGI) to manage urban stormwater, mitigate flooding, and adapt to climate change [1,2]. These nature-based solutions mimic natural hydrological processes by promoting infiltration, evapotranspiration, and runoff detention, offering co-benefits including urban cooling, biodiversity enhancement and improved human wellbeing [3,4]. Yet, the reliability of BGI performance predictions remains largely unquantified, despite significant public and private investment depending on these projections.

Hydrological models, particularly the USEPA Storm Water Management Model (SWMM) and HYDRUS-1D, are indispensable for designing, evaluating and optimizing BGI systems [5,6]. However, these models contain parameters that are difficult or impossible to measure directly: soil hydraulic conductivity, porosity, field capacity, wilting point and surface roughness. These must be estimated through calibration [7,8]. In this paper, the term "conventional hydrological modeling" is used to refer to established best practices in catchment-scale hydrological modeling, characterized by: (1) rigorous calibration using automatic algorithms rather than manual trial-and-error; (2) formal uncertainty analysis using established frameworks such as GLUE, Bayesian inference, or ensemble approaches; (3) global sensitivity analysis methods that capture parameter interactions; (4) independent split-sample validation as a minimum standard; and (5) assessment of parameter transferability and structural uncertainty [7-11]. This definition encompasses both rural and urban catchment modeling, as the methodological standards (while developed largely in rural catchments) are equally applicable to urban systems. In conventional hydrological modeling, rigorous calibration, sensitivity analysis (SA) and uncertainty analysis (UA) are standard practices expected by journals and practitioners [9-11]. SA identifies influential parameters, while UA quantifies prediction confidence, acknowledging equifinality [12].

Despite a proliferation of BGI studies over the past decade, rigorous SA and UA remain conspicuously absent. Most studies rely on manual calibration, local SA and no UA, presenting model outputs without uncertainty bounds. While two recent reviews have examined GI modeling practices [2,13], neither focused specifically on the parameter uncertainty. Pons et al. [13] found UA and SA methods are "limited and not justified when applied," but their sample predated many recent studies showing encouraging trends. Moreover, their sample predated many recent studies (published up to April 2020) that show encouraging trends toward global SA methods.

This paper provides the first systematic review focused explicitly on parameter calibration, SA and UA in BGI hydrological modeling from 2019-2026. This review characterizes current practices, identify persistent gaps, benchmark BGI against conventional hydrology and propose evidence-based recommendations. Focus is set specifically on hydrological modelling of BGI in urban stormwater management contexts rather than large-scale nature-based interventions or rural applications. Our scope excludes agricultural BMPs, river restoration and large-scale afforestation projects, as these involve fundamentally different hydrological processes and modeling frameworks.

2. SYSTEMATIC LITERATURE REVIEW METHODOLOGY

Following PRISMA 2020 guidelines [14], review is guided by four research questions concerning the current state of practice, sensitive parameters, methods employed, and persistent gaps. A comprehensive search was performed in Google Scholar and Scopus for peer-reviewed English articles from 2019 onwards. The search string comprised of ("parameter uncertainty" OR "sensitivity analysis" OR "uncertainty analysis" OR "model calibration") AND ("green infrastructure" OR "blue-green infrastructure" OR "sponge city" *OR "nature based solutions"*) AND ("SWMM" OR "hydrological model").

The search string included ("SWMM" OR "hydrological model") because SWMM is the most widely documented and standardized platform for urban stormwater modeling [5,13], and we aimed to capture studies using this dominant platform alongside other hydrological models. Author acknowledge that this search condition may introduce some bias toward SWMM-based studies. However, the search was not exclusive to SWMM—the "hydrological model" term was included to capture studies using alternative platforms (HYDRUS-1D, MUSIC, HEC-HMS/HEC-RAS, DRAINMOD-Urban, and custom conceptual models), which we indeed identified (21% of studies).

Inclusion criteria required: (1) a focus on urban BGI or nature-based solutions for stormwater management, (2) hydrological modeling of BGI performance and (3) some form of calibration, SA or UA. The PRISMA screening process was followed and a standardized data extraction template was used. Data were synthesized using frequency analysis, identification of sensitive parameters and thematic analysis of methodological gaps.

3. RESULTS

3.1. Overview of selected studies

A total of 38 papers were selected, spanning 2019–2026, with 68% published in 2022–2025. The reviewed papers cover diverse BGI typologies: green roofs (74%), bioretention/rain gardens (32%), permeable pavement (21%), and vegetated swales (11%). Approximately 42% examined multiple BGI types. Studies spanned temperate (42%), subtropical (32%), tropical (16%), and cold (10%) climates across Europe, Asia, North America, and Australia.

SWMM dominated as the modeling platform (79% of studies), consistent with the search string's inclusion of "SWMM". Other models captured through “hydrological model” term included HYDRUS-1D, MUSIC, HEC-HMS/HEC-RAS, DRAINMOD-Urban and custom conceptual models. The prevalence of SWMM in our sample may partially reflect search bias, but also aligns with documented trends in urban stormwater modeling [13].

Calibration was performed in 84% of studies. Among calibrated studies, 56% employed manual calibration, 28% used automatic algorithms and 16% used hybrid approaches. Manual calibration remains dominant despite its subjectivity and non-

reproducibility. Studies using automatic calibration achieved higher performance (median NSE = 0.82 vs. 0.77 for manual).

Split-sample validation, which is usually the minimum standard for model credibility, was performed in only 53% of studies. The remaining studies either performed no validation (16%) or used the same dataset for calibration and validation or validated against field measurements (31%).

3.2. Sensitivity analysis (SA) practices

Sensitivity analysis was performed in 28 of 38 studies (74%), reflecting growing recognition of its importance. However, the methods employed varied considerably in sophistication: (1) Local (one-at-a-time, OAT) methods are used in 16 studies (57% of SA studies). While are computationally efficient they cannot capture parameter interactions and may misidentify sensitive parameters when nonlinearity exists [15]; (2) Global methods are used in 12 studies (43% of SA studies), including Sobol, VARS, eFAST and Morris. This represents a substantial increase over time: only 17% of pre-2021 studies employed global methods, compared to 58% of post-2022 studies.

Across all studies, a consistent set of parameters emerged as most influential for BGI hydrological performance, with some variation by BGI type (Table 1). Key findings from studies using advanced SA include: (1) parameter sensitivity is scale-dependent and varies with perturbation scale [16]; (2) sensitivity varies temporally, both seasonally and with rainfall intensity [17,18]; and (3) sensitivity can vary spatially across catchments, with implications for BGI placement [17].

Table 1. Most sensitive parameters for different BGI type

BGI type	Most sensitive parameter	Key studies
Green roofs	Porosity	[19]–[23]
	Field capacity	[19], [20]
	Saturated hydraulic conductivity	[23], [24]
	Initial substrate water content	[23]
	Soil thickness	[22], [23], [25]
	Storage berm height	[20], [22], [25], [26]
	Surface resistance	[20]
	Crop factor Kc	[27]
Bioretention	Hydraulic conductivity	[16], [21], [24]
	Porosity	[21], [22], [26], [28]
	Soil thickness	[21], [22], [26], [28]
	Storage berm height	[16], [21], [26]
Permeable pavements	Pavement permeability	[26]
	Soil porosity	[26]
	Surface depression storage	[28]
General urban catchments	Impervious fraction	[29]–[31]
	Manning's roughness for impervious areas	[29]–[32]
	Conduit roughness	[29], [30]

3.3. Uncertainty Analysis Practices

Uncertainty analysis was performed in only 10 of 38 studies (26%), representing a significant gap in the BGI modeling literature. GLUE (Generalized Likelihood Uncertainty Estimation) is used in 3 studies [18,33,34]. Bootstrap/resampling methods that quantify uncertainty by resampling from the original data or parameter distributions to construct confidence intervals are used in 3 studies [16,25,35]. Scenario-based uncertainty is used in 3 studies [36–38]. These studies assessed uncertainty by running the model under different scenarios (e.g., climate change scenarios, different rainfall depths, or different parameter values). While practical and computationally efficient, scenario-based approaches do not provide formal probabilistic uncertainty bounds.

Studies that performed UA consistently documented equifinality, with multiple parameter sets producing acceptable simulations. For instance, Pang et al. [33] identified 1,598 behavioral parameter sets out of 10,000 Monte Carlo runs. Furthermore, research demonstrated that calibrated effective parameters (hillslope width factor k_width and connected impervious fraction φ_idc in PySWMM) are often condition-dependent and not transferable to novel conditions [39]. Calibrating on a single objective (e.g., runoff only) was shown to exacerbate parameter uncertainty, which could be reduced by multi-objective approaches [40].

4. DISCUSSION

4.1. Critical gap analysis

This review reveals a fundamental gap between available uncertainty methods and their application in BGI modeling. The 26% UA adoption rate is alarmingly low, comparing to the state of catchment hydrology in the 1990s, not the 2020s. In conventional hydrology, formal UA has been standard for over three decades.

The consequences are substantial. BGI planning decisions involving significant investments are based on deterministic predictions without uncertainty quantification. Decision-makers cannot assess performance shortfall risks, evaluate trade-offs under uncertainty or quantify prediction confidence. The absence of uncertainty quantification creates a false sense of precision that can lead to suboptimal investment decisions, unexpected performance shortfalls and compromised urban flood resilience.

Structural uncertainty receives minimal attention. Broekhuizen et al. [41] demonstrated that model structural differences can produce runoff variations of up to 33 percentage points, which is larger than differences between soil types. Yet 79% of studies rely exclusively on SWMM without assessing whether its structure adequately represents BGI processes. SWMM's documented limitations in reviewed papers: rectangular drainage hydrographs [42], inability to separately initialize soil and storage layer moisture [38], failure at zero slope [21] and oversimplified ET [20], introduce systematic errors that parameter calibration cannot correct.

Equifinality is pervasive but rarely quantified. Studies that investigated it [33], [34], [40] found it to be widespread. Pang et al. [33] identified 1,598 behavioral parameter

sets out of 10,000 (16%). Sytsma et al. [39] demonstrated that calibrated parameters are condition-dependent, with prediction errors up to 60% when applied to novel conditions. This directly challenges the common practice of using site-calibrated models for future predictions without uncertainty quantification.

Manual calibration dominates (56% of calibrated studies), despite being subjective, non-reproducible and unable to explore the full parameter space. Studies employing automatic calibration achieved higher performance (median NSE = 0.82 vs. 0.77). Only 53% performed split-sample validation. Without independent validation, there is no assurance that predictive performance extends beyond calibration conditions.

Sensitivity analysis shows progress (74% of studies) with encouraging trends toward global methods (17% pre-2021 vs. 58% post-2022). However, several gaps persist: (1) most studies still employ local OAT methods that cannot capture parameter interactions; (2) temporal and spatial variability of sensitivity is rarely considered, though sensitivity varies seasonally and with rainfall characteristics [17,18]; (3) the link between SA and UA remains weak - SA identifies influential parameters but does not quantify prediction uncertainty.

4.2. Comparison with conventional hydrological modeling

The contrast between BGI and conventional hydrological modeling is stark. In catchment hydrology, formal UA has been standard practice for over three decades, with established frameworks including GLUE [12], Bayesian inference [43] and ensemble approaches [44]. The 26% UA adoption rate in BGI modeling is comparable to catchment hydrology in the 1990s, not the 2020s. This gap is concerning because BGI systems are fundamentally more uncertain: greater parameter uncertainty (non-standardized design), greater data scarcity (recent emergence of monitoring) and greater structural uncertainty (adaptation of models for new applications). Author acknowledges that the quality of practice within "conventional hydrology" is not uniform as many catchment studies still fall short of best practices. However, the key distinction is that the methodological standards (global SA, formal UA, automatic calibration, independent validation) are well-established within researchers and practitioners, whereas in BGI modeling these practices remain exceptional rather than normative.

Conventional hydrology standards such as split-sample validation, multi-objective calibration and formal uncertainty assessment are not yet adopted in BGI modeling. Parameter transferability, extensively studied in conventional hydrology [45,46], is rarely assessed in BGI studies despite Sytsma et al. [39] showing prediction errors up to 60% when transferred to novel conditions.

Structural uncertainty, addressed through ensemble modeling in conventional hydrology [47,48], is largely ignored in BGI modeling. The dominance of SWMM (79%) means structural uncertainty is effectively unquantified.

5. CONCLUSIONS AND RECOMMENDATIONS

This review of 38 peer-reviewed studies on hydrological modeling of Blue-Green Infrastructure (BGI) has revealed critical gaps in uncertainty analysis, sensitivity analysis, calibration practices and validation protocols when compared against conventional hydrological modeling standards, defined here as the established best practices in catchment-scale hydrology, including formal UA, global SA, automatic calibration, and independent validation [8,9,11,12]. Only 26% of reviewed studies performed formal uncertainty analysis, despite the well-documented challenges of parameter equifinality, data scarcity, and structural uncertainty that characterize BGI systems. The consequences of this gap are profound: BGI planning decisions involving significant financial investments are being made based on deterministic model predictions that present a false sense of precision. Decision-makers cannot assess the risk of performance shortfalls, evaluate trade-offs under uncertainty or quantify confidence levels in predicted benefits.

Manual calibration remains the dominant practice (56% of calibrated studies), despite being subjective, non-reproducible, and unable to adequately explore parameter space. Only 53% of studies performed split-sample validation with the number of studies that calibrate and validate on the same dataset that would be unacceptable in conventional hydrology.

Sensitivity analysis was performed in 74% of studies, with encouraging temporal trends toward global methods (17% pre-2021 vs. 58% post-2022). However, temporal and spatial variability of sensitivity is rarely considered, despite evidence that sensitivity varies seasonally, with rainfall characteristics and spatially across catchments. The link between sensitivity analysis and uncertainty analysis remains weak: SA identifies influential parameters but does not quantify prediction uncertainty.

The following recommendations stem from this review:

1. Formal uncertainty analysis should become standard practice in BGI modeling.
2. Global SA methods should replace local OAT approaches and be conducted both before calibration (to identify sensitive parameters and reduce dimensionality) and after calibration (to assess uncertainty influence).
3. Implement rigorous calibration and validation.

The tools and methods are available, what is needed is commitment to use them. The BGI modeling community has an opportunity to move from historically deterministic practice to rigorous, uncertainty-aware modeling that provides better support for sustainable urban flood management. By adopting the methodological standards of conventional hydrology, BGI modeling can fulfill its potential as a reliable decision-support tool for sustainable urban planning.

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Research paper

FIRST-YEAR MONITORING OF THE HYDROLOGICAL RESPONSE OF A MODULAR BLUE-GREEN ROOF UNDER MEDITERRANEAN CLIMATE

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Abstract

Blue–Green Roofs (BGRs) have emerged as an advanced evolution of conventional green roofs by integrating vegetated substrates with engineered detention layers to improve stormwater management and enhance the environmental performance of buildings. Although their adoption is increasing, long-term experimental observations under Mediterranean climatic conditions remain limited. This study presents the first-year monitoring results of a full-scale modular Blue–Green Roof installed at the University of Tuscia (Central Italy). The system was continuously monitored from July 2025 to June 2026 through high-resolution measurements of precipitation, runoff, and substrate volumetric water content. The analyses focused on the seasonal hydrological response of the roof, with particular emphasis on runoff retention and substrate volumetric water content dynamics. During the monitoring period, the roof received 1017.8 mm of precipitation while generating only 255.2 mm of runoff, corresponding to an annual Retention Index of 0.75. The system exhibited a clear seasonal variability, with the highest retention efficiencies recorded during spring and summer and lower values during the wetter winter months. Continuous substrate volumetric water content observations confirmed the strong influence of Mediterranean climatic conditions on the hydrological response of the roof. These findings demonstrate the effectiveness of modular Blue–Green Roofs as Nature-Based Solutions for reducing rooftop runoff and improving the hydrological performance of sustainable buildings, while providing a valuable experimental dataset for future performance assessment, hydrological modelling and the optimization of Blue–Green Roof design.

Key words: *Blue–green roof, Stormwater management, Experimental monitoring, Mediterranean climate, Nature-based solutions*

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1. INTRODUCTION

Urbanization and climate change are increasing the frequency and severity of urban flooding while exacerbating heat stress and environmental degradation. The widespread replacement of natural surfaces with impervious materials alters the hydrological response of urban catchments, leading to larger runoff volumes and higher peak discharges during storm events. To address these challenges, Nature-based Solutions (NbS) have gained considerable attention as sustainable strategies capable of enhancing urban resilience while providing multiple environmental and societal benefits [1–4].

Among NbS, green roofs (GRs) are recognized as one of the most effective measures for managing stormwater at the building scale. By combining vegetation, engineered substrates, and drainage layers, GRs can reduce runoff volumes, delay peak flows, improve building energy efficiency, mitigate urban heat island effects, and promote urban biodiversity [5,6].

However, their hydrological performance is influenced by several interacting factors, including substrate characteristics, vegetation type, rainfall properties, antecedent moisture conditions, and local climatic conditions [7–9].

Mediterranean regions represent a particularly challenging environment for green roof applications because prolonged dry periods alternate with short, high-intensity rainfall events. Under these conditions, the seasonal evolution of substrate volumetric water content strongly affects the available storage capacity and consequently the runoff retention efficiency of the system [10,11].

Continuous field observations are therefore essential for understanding the long-term hydrological behaviour of green roofs operating under Mediterranean climates.

Blue–Green Roofs (BGRs) represent an evolution of conventional green roofs by incorporating engineered detention layers beneath the vegetated substrate. These additional storage elements temporarily retain excess rainfall, delay runoff release, and improve stormwater management without substantially increasing substrate thickness [12–14].

Although recent studies have demonstrated the hydrological potential of BGRs through both experimental investigations and numerical modelling, long-term field observations remain limited, particularly for modular systems installed under Mediterranean climatic conditions [11,13,15,16].

This paper presents the first-year monitoring results of a full-scale modular blue–green roof installed at the University of Tuscia (Central Italy). Continuous measurements of rainfall, runoff, and substrate volumetric water content were used to characterize the seasonal hydrological response of the system.

As a preliminary contribution, the study focuses on rainfall retention performance and substrate volumetric water content dynamics, providing experimental evidence that will support future investigations on water balance, storage processes, and hydrological modelling.

2. DATA AND METHODS

2.1 Study site and experimental roof

The study was carried out at the Hydrological Experimental Site of the University of Tuscia, located in Viterbo, Central Italy. The experimental facility hosts a full-scale modular Blue–Green Roof (BGR) manufactured by Sempergreen (The Netherlands), designed to combine vegetation with engineered stormwater detention.

The investigated BGR, shown in Figure 1, covers an area of 16 m² (4 × 4 m) and has a total thickness of approximately 170 mm. From top to bottom, the roof assembly consists of a 25 mm Sempergreen Sedum Blanket, providing immediate vegetation cover and rainfall interception; a 40 mm S40 Substrate Roll, which acts as the primary growing medium; a 40 mm Urbanscape Green Roll, made of stone wool and designed to increase water retention while promoting root development; a 60 mm HC60 Storage Layer, providing the main temporary stormwater storage capacity; and a 5 mm T5 Detention Layer, installed directly above the waterproofing membrane to regulate the release of excess water. This passive multilayer configuration combines vegetation, substrate, retention and storage components to temporarily retain rainfall, reduce runoff peaks and improve the hydrological performance of the roof without requiring active flow-control devices. The roof is installed on an elevated wooden structure with a surface slope of approximately 2%, allowing excess water to drain towards a monitored outlet.



Figure 1. The investigated Blue–Green Roof.

2.2. Monitoring system

The BGR has been continuously monitored since June 2025. The analyses presented in this paper refer to the first complete monitoring year, spanning from 1 July 2025 to 30 June 2026.

Precipitation was measured using the nearby macro-rain gauge station installed at the experimental site [17]. Roof runoff was continuously monitored at the outlet through an automatic tipping-bucket flow gauge, while substrate volumetric water

content was measured using a dielectric soil moisture sensor installed at the bottom of the S40 Substrate Roll. Soil temperature was also monitored for environmental characterization.

All sensors were connected to a Campbell Scientific CR1000X data logger, and measurements were acquired every five minutes. The original observations were subsequently aggregated to daily values for the analyses presented in this work.

2.3 Data analysis

The preliminary hydrological performance of the roof was evaluated using continuous observations of precipitation, runoff, and substrate volumetric water content.

Runoff retention was quantified by means of the Retention Index (RI), defined as [18]:

$$RI = 1 - Q/P \quad (1)$$

where *P* (mm) is the daily precipitation depth and *Q* (mm) is the corresponding daily runoff depth measured at the roof outlet.

To investigate the seasonal hydrological behaviour of the system, daily substrate volumetric water content observations were analysed together with precipitation and runoff records. Annual and seasonal runoff coefficients together with the Retention Index were computed to assess the overall stormwater mitigation performance of the roof.

3. RESULTS

3.1 Hydro-meteorological conditions

During the monitoring period (1 July 2025–30 June 2026), the experimental site received a cumulative precipitation depth of 1017.8 mm, approximately 28% higher than the long-term annual average (810 mm yr^{-1}) recorded at the site [17]. The monitoring period exhibited the characteristic seasonal variability of Mediterranean climates, with prolonged dry conditions during summer followed by a marked increase in rainfall from late autumn to early spring.

The monthly distribution of precipitation and roof runoff is presented in Figure 2. Winter accounted for more than half of the annual precipitation (537.8 mm, corresponding to approximately 52% of the yearly total), whereas spring and summer received 117.2 mm and 201.0 mm, respectively. January 2026 was by far the wettest month, with 331.8 mm of precipitation, while rainfall remained limited throughout the summer months despite occasional rainfall events.

A cumulative runoff depth of 255.1 mm was measured at the roof outlet during the study period, corresponding to an annual runoff coefficient of 0.251. Monthly runoff closely followed the seasonal distribution of precipitation, with the highest discharges recorded during January (117.3 mm) and February (59.4 mm). Conversely, runoff remained negligible during most summer months and was absent in April, despite

measurable precipitation, indicating an efficient retention of rainfall by the roof under relatively dry conditions.

Overall, the comparison between monthly precipitation and runoff highlights the substantial runoff mitigation provided by the monitored BGR throughout the monitoring period. While runoff increased during the wetter months, it consistently represented only a fraction of the incident rainfall, confirming the effectiveness of the system in reducing stormwater discharge under Mediterranean climatic conditions.

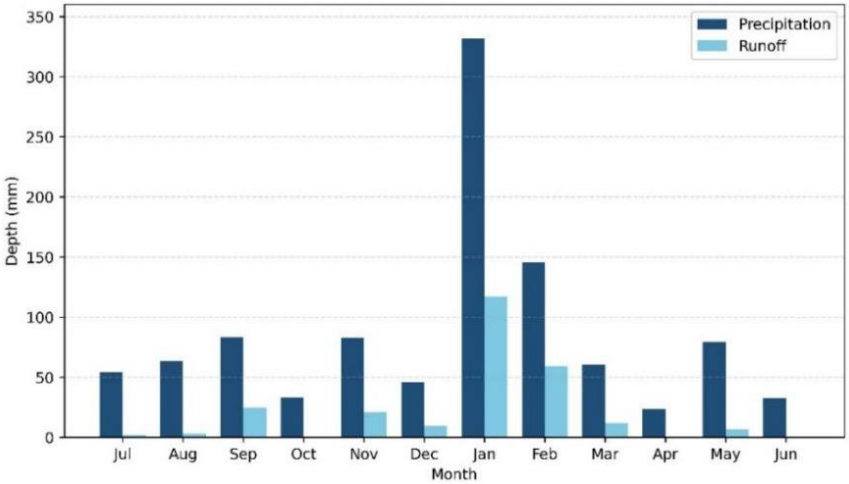


Figure 2. Monthly precipitation (P) and runoff (Q) measured during the monitoring period (July 2025–June 2026). The figure highlights the seasonal distribution of rainfall and the corresponding runoff generated by the monitored BGR.

3.2 Seasonal evolution of substrate volumetric water content

The seasonal distribution of daily substrate volumetric water content (θ) is reported in Figure 3. Water content exhibited a pronounced seasonal variability, reflecting the alternation between dry and wet periods typical of Mediterranean climates.

The driest conditions occurred during summer, when the median substrate volumetric water content was approximately 0.17 $m^3\ m^{-3}$ and daily values frequently remained below 0.15 $m^3\ m^{-3}$, reaching minimum values close to 0.08 $m^3\ m^{-3}$. These low water content levels resulted from the combined effect of limited rainfall and high atmospheric evaporative demand, which progressively depleted the water stored within the growing medium.

Substrate volumetric water content conditions progressively increased during autumn, with a median value of approximately 0.24 $m^3\ m^{-3}$. This season also exhibited the largest interquartile range, reflecting the transition from dry summer conditions to the wetter period characterized by increasingly frequent rainfall events. Daily volumetric water content values ranged from approximately 0.09 to 0.35 $m^3\ m^{-3}$, indicating repeated wetting and drying cycles.

The highest volumetric water content levels were observed during winter, when the median value reached approximately 0.33 $m^3\ m^{-3}$ and most observations remained above 0.30 $m^3\ m^{-3}$. Maximum values approached 0.37 $m^3\ m^{-3}$, indicating that the substrate remained close to saturation during prolonged wet periods.

During spring, substrate volumetric water content progressively decreased as rainfall became less frequent and evapotranspiration increased. Although the seasonal median (≈0.16 m^3 m^{-3}) was comparable to that observed during summer, the distribution was considerably wider, with values ranging from approximately 0.09 to 0.33 m^3 m^{-3}. This behaviour reflects the alternation of rainfall events and subsequent drying phases, which produced a greater variability than that observed during the persistently dry summer period.

Overall, the boxplots clearly demonstrate that substrate volumetric water content followed a well-defined seasonal cycle, with progressively increasing water content from summer to winter and a subsequent decline during spring. These observations indicate that the hydrological state of the roof varied substantially throughout the year and provide a physical explanation for the seasonal differences in runoff generation and retention performance discussed in the following section.

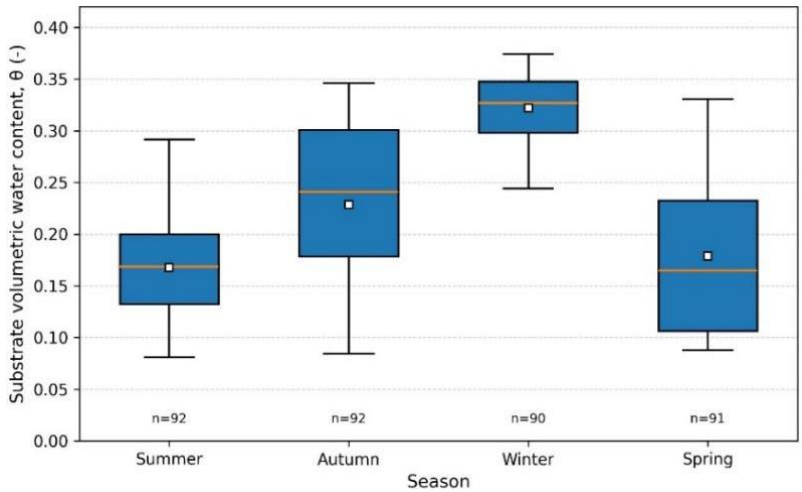


Figure 3. Seasonal boxplots of daily substrate volumetric water content (ϑ) measured in the BGR during the monitoring period (1 July 2025–30 June 2026). Boxes represent the interquartile range, the central line the median, whiskers the data range excluding outliers, and open squares the seasonal mean.

3.3 Hydrological performance

The monitored BGR exhibited a high capacity to reduce rooftop runoff throughout the monitoring period. Over the one-year observation period, the roof received a cumulative precipitation depth of 1017.8 mm while generating only 255.1 mm of runoff, corresponding to an annual runoff coefficient of 0.251 and an overall Retention Index (RI) of 0.749. These values indicate that approximately three quarters of the incident precipitation were retained within the roof system, confirming the effectiveness of the modular Blue–Green Roof in mitigating stormwater runoff under Mediterranean climatic conditions.

Seasonal differences in retention performance were also evident. The highest runoff mitigation was observed during spring (RI = 0.944), followed by summer (RI = 0.853) and autumn (RI = 0.811), whereas the lowest retention efficiency occurred during winter (RI = 0.649). Although winter accounted for more than half of the annual precipitation, the roof was still able to retain nearly two thirds of the incoming rainfall,

demonstrating a satisfactory hydrological performance even under prolonged wet conditions.

The relationship between daily precipitation and runoff is shown in Figure 4, where each point represents a rainfall day with daily precipitation greater than or equal to 4 mm. As expected, runoff generally increased with increasing rainfall depth; however, all observations remained well below the Q = P reference line, confirming that the roof consistently reduced runoff generation irrespective of rainfall magnitude.

A marked dispersion of the observations can be observed for rainfall depths ranging approximately from 10 to 30 mm, where similar precipitation amounts generated substantially different runoff volumes. Moreover, the seasonal clustering of the data reveals a clear influence of climatic conditions on roof performance. Events recorded during spring and summer generally produced lower runoff volumes than rainfall events of comparable magnitude occurring during autumn and winter. This behaviour is consistent with the seasonal variability of substrate volumetric water content discussed in the previous section and highlights the importance of antecedent moisture conditions in controlling the runoff response of Blue–Green Roof systems.

Overall, the monitored system demonstrated stable runoff mitigation throughout the entire monitoring period, confirming the suitability of modular Blue–Green Roofs as an effective Nature-Based Solution for improving stormwater management at the building scale.

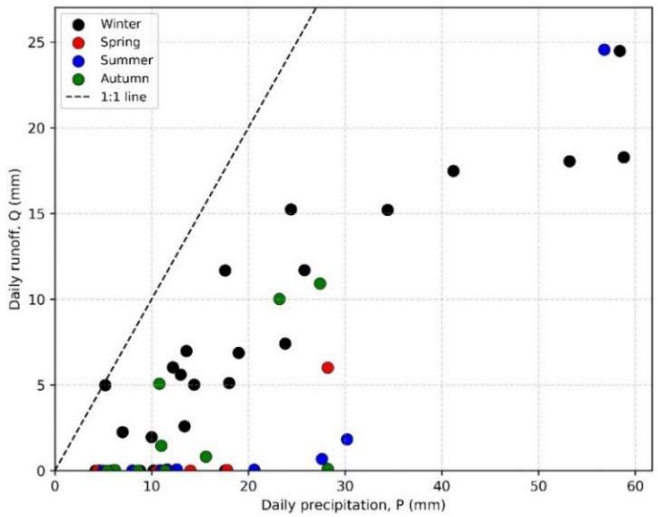


Figure 4. Scatter plot of daily runoff (Q) versus daily precipitation (P) for rainfall days with P ≥ 4 mm. Colours identify the four seasons, while the dashed line indicates the 1:1 relationship. The separation of the observations below the 1:1 line demonstrates the runoff retention capacity of the Blue–Green Roof and reveals the seasonal variability of its hydrological performance.

4. DISCUSSION

The first year of monitoring demonstrates that the investigated modular Blue–Green Roof provides an effective solution for mitigating rooftop stormwater runoff under Mediterranean climatic conditions. Despite a monitoring period characterized by annual precipitation approximately 25% higher than the long-term average, the system

retained about three quarters of the incoming rainfall, confirming its capability to reduce the hydrological impact of buildings on urban drainage systems.

The observed annual retention efficiency is consistent with the range reported for multilayer Blue–Green Roofs operating under different climatic conditions, where long-term retention values generally vary between 60% and 80% depending on roof configuration, storage capacity and rainfall regime [11–16]. These findings further support previous investigations demonstrating that the introduction of dedicated detention layers substantially improves the hydrological performance of extensive vegetated roofs without requiring thicker substrates [11–14, 19,20].

A clear seasonal variability emerged from both substrate volumetric water content observations and runoff measurements. The highest retention efficiencies were recorded during spring and summer, whereas winter exhibited larger runoff volumes associated with more frequent and persistent rainfall. These results confirm that Mediterranean climatic conditions strongly influence the performance of Blue–Green Roofs and should therefore be explicitly considered during design and performance assessment. Similar seasonal behaviour has been reported for other green roof systems operating under semi-arid and Mediterranean climates [10,11].

From the perspective of sustainable building design, the results demonstrate that Blue–Green Roofs can effectively contribute to the implementation of Nature-Based Solutions by reducing runoff generation directly at the building scale. Unlike conventional stormwater management approaches, which convey runoff downstream, detention roofs temporarily retain rainfall within the building envelope, decreasing the hydraulic load transferred to urban drainage networks during rainfall events. This characteristic makes these systems particularly suitable for climate-adaptation strategies aimed at increasing the resilience of densely urbanized areas [1–4].

The continuous monitoring approach adopted in this study also highlights the importance of collecting long-term experimental datasets for evaluating the real performance of innovative green building technologies. Performance-based assessments derived from field observations provide valuable information for designers, planners and decision makers, supporting the optimization of roof configurations and facilitating the wider implementation of Blue–Green Roofs in sustainable and climate-resilient buildings.

Although this paper presents only the first monitoring results, the collected dataset represents a robust experimental basis for future investigations. Further analyses will focus on the detailed characterization of storage processes, event-scale hydrological behaviour and physically based modelling, providing additional support for the design and optimization of Blue–Green Roof systems.

5. CONCLUSION

This study presented the first-year hydrological monitoring results of a full-scale modular Blue–Green Roof installed under Mediterranean climatic conditions. Continuous observations of precipitation, runoff and substrate volumetric water content provided an experimental assessment of the roof performance over a complete annual cycle.

The monitored system demonstrated a high capacity for stormwater mitigation, retaining approximately 75% of the annual precipitation despite a monitoring period characterized by rainfall well above the long-term average. The results also highlighted a marked seasonal variability, with the highest retention efficiencies observed during spring and summer and lower values during the wetter winter months. These seasonal differences were consistent with the observed evolution of substrate volumetric water content throughout the monitoring period.

The experimental evidence confirms that modular Blue–Green Roofs can effectively contribute to reducing rooftop runoff while enhancing the hydrological performance of buildings. As Nature-Based Solutions integrated into the building envelope, these systems represent a practical strategy for improving the climate resilience of urban areas and supporting more sustainable stormwater management.

The continuous monitoring dataset presented in this work provides a valuable benchmark for evaluating the long-term performance of Blue–Green Roofs operating under Mediterranean climatic conditions. Future work will extend the present analysis by investigating the mechanisms controlling roof hydrological behaviour through detailed water balance analyses, event-scale investigations and physically based modelling, thereby supporting the optimization of Blue–Green Roof design and their wider implementation in sustainable buildings.

ACKNOWLEDGMENT

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Research paper

NEAR-NATURAL RIVER ENGINEERING IN URBAN WATERCOURSES

Nina Vidojković[1], Ilija Ilić[2], Aleksandra Ilić[3]

Abstract

This paper examines the application of near-natural river engineering in urban watercourse management, with emphasis on protecting infrastructure from the adverse effects of water-level fluctuations. The intensified impacts of climate change and ecosystem degradation increasingly expose the limitations of standard river training based on rigid engineering structures, directing attention toward solutions that align training works with natural fluvial processes. The study addresses a reach of the Trgoviški Timok River in Knjaževac, Serbia, where a bridge constrains the training works to the bridge zone. The adopted near-natural solution comprises river training structures built from natural materials: bank protection on the left and right banks using geocells, and three grade-control weirs of hand-placed quarried stone set in concrete, each with an energy-dissipation apron of the same material. For the hydraulic analysis, three numerical models were developed using the HEC-RAS software: a natural channel model, a trained channel model without the bridge structure, and a trained channel model including the bridge. The results were compared in order to assess the influence of the bridge and of the training measures on water levels along the reach. The results indicate a water-level reduction of approximately 14 cm at the bridge cross-section, together with a localized backwater effect of about 10 cm immediately upstream of the bridge. Minor local increases in water levels were observed at several cross-sections downstream of the bridge due to channel geometry adjustments. Beyond its hydraulic performance, the proposed solution preserves the natural form of the river and supports conditions favorable for ecological improvement while increasing the resilience of the reach to extreme flows expected under a changing climate.

Keywords: *near-natural river training, HEC-RAS, geocells, backwater effect, urban watercourse management*

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1. INTRODUCTION

Urban environments are facing increasing challenges in water resources management. Climate change, manifested through altered precipitation patterns and an increasing frequency of extreme hydrological events, together with urbanization and spatial constraints imposed by infrastructure, has intensified the risks of flooding, bank erosion, and ecosystem degradation in river systems [1 - 4].

Historically, river training within urban areas was primarily implemented through concrete channelization and rigid bank protection measures designed to ensure flood conveyance and infrastructure safety [3, 5, 6]. Although hydraulically effective, these approaches have frequently altered natural river morphology, degraded habitats, and reduced biodiversity [5, 7, 8].

Recognition of these shortcomings has encouraged the development of near-natural river engineering, which combines engineering objectives with ecological considerations. Besides ensuring flood protection and channel stability, this approach emphasizes the preservation of rivers as dynamic natural systems and their ecological and social functions [8 - 10]. Accordingly, the planning and design process incorporates not only hydrological, hydraulic, and morphological analyses but also ecological and biological assessments while minimizing interventions and preserving natural channel characteristics wherever possible [6, 8, 9].

A defining feature of near-natural river engineering is the use of natural and locally available materials, such as stone, wood, and vegetation, for river training structures. These measures integrate more effectively into the river landscape, improve bank stability, promote vegetation development, and create favorable habitats for aquatic and riparian species [6, 8, 9, 10]. Recent studies have further demonstrated that nature-based and ecosystem-oriented river management strategies can provide substantial ecological benefits while maintaining hydraulic functionality and reducing flood risks [4, 10, 11].

Although near-natural engineering measures are most commonly applied to smaller watercourses, their implementation in urban environments remains limited due to the challenge of balancing hydraulic performance, spatial constraints, and infrastructure protection requirements [3, 4, 6].

This paper presents a quantitative assessment of the impacts of near-natural river training and infrastructure on the hydraulic regime of the Trgoviški Timok River in Knjaževac and evaluates the applicability of near-natural river engineering principles in urban conditions. The proposed solution is based on the use of river training structures constructed predominantly from natural materials, providing infrastructure protection and channel stability while preserving the natural characteristics of the watercourse and promoting the development of a healthy river ecosystem.

2. METHODS AND CALCULATIONS

2.1. Study Reach and Input Data

The analyzed reach of the Trgoviški Timok River is located in the municipality of Knjaževac, Serbia, and extends over approximately 750 m. The reach includes a bridge structure carrying the State Road IB No. 36 (Knjaževac–Zaječar), which represents a key infrastructure facility and may significantly influence the hydraulic flow conditions (Figure 1).



Figure 1. Orthophoto view of the analyzed reach of the Trgoviški Timok River
Source: Google Earth

The bridge piers located within the riverbed (Figure 2) cause a local upstream backwater effect, characterized by reduced flow velocities and sediment transport capacity, which may promote sediment bar formation near the structure. Despite these effects, the overall channel morphology remains relatively stable.



Figure 2. Bridge zone within the analyzed reach of the Trgoviški Timok River

Upstream of the bridge (Figure 3), the left bank has been trained through the formation of a wide floodplain area and a flood protection levee designed to protect the nearby settlement, while a levee constructed along the right bank serves to protect adjacent agricultural land. The riverbanks themselves remain unlined and retain their natural characteristics, consisting predominantly of gravel-sandy material and native riparian vegetation.



Figure 3. Left and right banks of the analyzed reach of the Trgoviški Timok River

The analysis was based on geodetic, hydrological, geological-geotechnical, sedimentological, and biological datasets. The geodetic database included a topographic survey of the natural channel, cross-sectional profiles, and a longitudinal profile of the river reach. Hydrological input data comprised the design discharge $Q_{1\%}$ = 306 m³/s, determined from long-term discharge records at the Donja Kamenica gauging station, according to the documentation from 2004 and 2007.

Biological surveys required for the planning of near-natural river training included an inventory of native vegetation species (Table 1) and characteristic fish species inhabiting the river reach (Table 2).

Table 1. Characteristic plant species suitable for bank stabilization and ecological enhancement along the Trgoviški Timok River

Photo					
Common name	Perennial ryegrass	Red fescue	Kentucky bluegrass	White clover	Common mallow
Scientific name	*Lolium perenne*	*Festuca rubra*	*Poa pratensis*	*Trifolium repens*	*Malva neglecta*

Table 2. Characteristic fish species inhabiting the Trgoviški Timok River

Photo					
Common name	Brown trout	Barbel	Chub	Spirlin	Gudgeon
Scientific name	*Salmo trutta fario*	*Barbus barbus*	*Squalius cephalus*	*Alburnoides bipunctatus*	*Gobio gobio*

2.2. Hydraulic Modeling of the Open Channel in HEC-RAS

Water surface profiles for the design discharge were computed under steady, gradually varied flow conditions using the HEC-RAS v. 6.5 hydraulic modeling software [12].

The computational procedure implemented in HEC-RAS is based on the solution of the one-dimensional energy equation between adjacent cross-sections. Energy losses are represented through friction losses calculated using Manning's roughness coefficient and local losses associated with flow contraction and expansion.

Figure 4 shows the energy equation applied between adjacent cross-sections, U upstream and D downstream. In Equation (1), the left-hand side refers to U and the right-hand side to D.

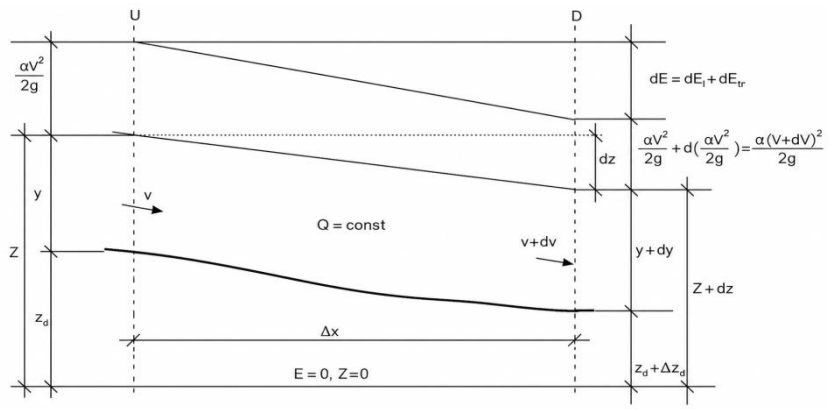


Figure 4. Application of the energy equation between the upstream (U) and downstream (D) cross-sections along a reach of length Δx

Energy equation:

$$Z+\frac{\alpha v^2}{2g}=Z+dz+\frac{\alpha v^2}{2g}+\alpha \cdot d\left(\frac{v^2}{2g}\right)+dE \quad (1)$$

Where:

dE - differential energy head loss between two adjacent cross-sections (friction plus local contraction/expansion losses) (m);

dz - differential change in water-surface elevation between two adjacent cross-sections, U and D (m);

g - gravitational acceleration (m/s²);

v - mean (cross-sectional average) flow velocity (m/s);

Z - water-surface elevation above a horizontal datum (potential head) (m);

α - energy (velocity-distribution) coefficient, dimensionless;

$\frac{v^2}{2g}$- velocity head (m).

For the purposes of the analysis, three characteristic hydraulic models were developed:

- Natural Channel Model – representing the existing channel geometry without the bridge structure and including a total of 17 surveyed cross-sections.
- Trained Channel Model Without Bridge – in which the bridge cross-section was removed from the model geometry and hydraulic continuity was maintained through interpolation between the upstream and downstream cross-sections.
- Trained Channel Model With Bridge – incorporating the bridge cross-section together with all structural elements, thereby enabling simulation of the bridge influence on hydraulic flow conditions.

The model geometry was generated using geodetic survey data, cross-sectional profiles, and the longitudinal profile of the analyzed river reach. In the first two models the bridge is omitted to provide a common bridge-free baseline; it is introduced only in the third model, so that the effects of the channel reshaping and of the bridge can be isolated through successive comparisons. River stationing increases in the upstream direction, so the most downstream cross-section carries the lowest and the most upstream cross-section the highest station value, and this convention is applied consistently in all three models and in the presentation of the results.

Observed water surface elevations for the analyzed reach were not available for model calibration. In the absence of measured data, the roughness coefficients were determined from a combination of field reconnaissance and published reference tables. Based on the observed bed material, channel condition and floodplain vegetation, values of $n = 0.040\ m^{-1/3}s$ and $n = 0.055\ m^{-1/3}s$ were adopted for the main channel and the floodplain, respectively. The coefficients were kept unchanged in all scenarios due to identical bed material and floodplain characteristics, allowing isolation of the effects of geometric modifications and river training measures on hydraulic behavior.

The longitudinal bed slope of both the natural and trained channels was 0.40%.

Flow conditions were classified as subcritical, which was confirmed through hydraulic computations performed for the natural channel. Consequently, the downstream boundary condition was defined using the normal depth approach, with an energy slope of 0.40% imposed identically in all three models, so that the computed water-level differences reflect the effect of the training works and not a difference in the downstream boundary condition.

2.3. Channel Design and Near-Natural Engineering Measures

Channel reshaping along the analyzed reach of the Trgoviški Timok River resulted in a designed channel length of approximately 737 m, shortening the alignment by 12 m compared with the existing condition. Although the average channel width was estimated at 19 m, a bottom width of 21 m was adopted based on hydraulic analysis as the optimal solution. Combined with side slopes of 1:1.5, this geometry provides adequate hydraulic capacity while ensuring channel stability.

The proposed solution applies near-natural river engineering principles by integrating engineering and biotechnical measures with natural materials and riparian vegetation restoration (Table 1) [6, 8, 9].

To stabilize the riverbanks within the bridge zone, bank protection structures are designed on both banks using HDPE geocells, which represent three-dimensional cellular confinement systems [13]. Such geocells are placed on a prepared foundation soil, anchored to the slope, filled with well-graded friable topsoil suitable for vegetative applications [15] and subsequently seeded. In this study, a two-layer anchored TG356 geocell system (cell dimensions 259 × 224 mm, height 150 mm, total thickness 300 mm), with an additional 150 mm topsoil cover and native vegetation, is adopted for the 1:1.5 bank slope and the expected hydraulic loading, in accordance with the manufacturer's technical specifications [14] (Figures 5 and 6).

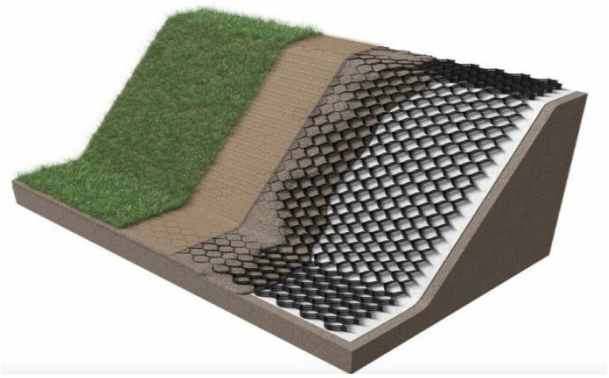


Figure 5. Installation of geocells for riverbank stabilization [16]

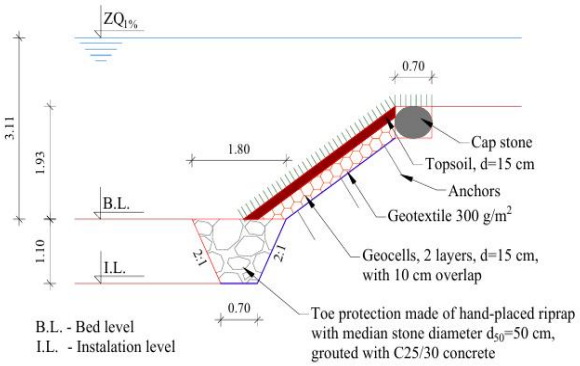


Figure 6. Detail of the riverbank protection made of geocells, proposed solution.

A 300 g/m^2 geotextile layer is included beneath the protection to prevent fine-particle washout and improve filtration conditions. The toe is protected by hand-placed quarried stone (d_{50} = 50 cm) set in C25/30 concrete below the anticipated scour depth, capped with semi-dressed stone overlapping the adjacent terrain by 70 cm.

Three grade-control weirs, made of the same stone material set in C25/30 concrete, are designed upstream and downstream of the bridge and at the upstream boundary of the reach to reduce flow energy, stabilize the channel slope and limit erosion. Each weir is provided with a 5 m downstream energy dissipation apron, adopted according to standard engineering practice, as local scour assessment was beyond the scope of the study.

3. RESULTS AND DISCUSSION

Hydraulic simulations in HEC-RAS were performed for the three defined modeling scenarios under the 100-year design discharge ($Q_{1\%}$). The resulting water surface elevation profiles along the analyzed reach of the Trgoviški Timok River are presented in Figure 7.

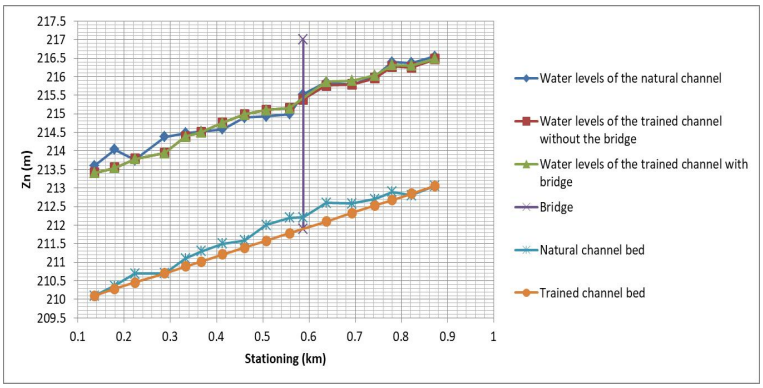


Figure 7. Comparative water surface elevation profiles for $Q_{1\%}$ under different channel modeling scenarios

The comparative analysis evaluates the influence of near-natural measures and the bridge structure on water level distribution under extreme flow conditions.

Significant differences can be observed between the natural and trained channel configurations. Overall, the implementation of the proposed measures resulted in a favorable modification of water levels compared with the existing natural channel, with lower water levels observed along most of the analyzed reach. However, at several cross-sections downstream of the bridge, minor local increases in water levels of up to approximately 18 cm occurred due to channel geometry adjustments. Farther downstream, the water levels were lower than in the natural channel, with a maximum reduction of approximately 50 cm. At the bridge cross-section, the water level in the trained channel is approximately 14 cm lower than in the natural channel. This reduction is a consequence of channel reshaping and the resulting increase in flow conveyance capacity, which enables more efficient passage of high flows through the analyzed reach.

The bridge structure induces a localized backwater effect accompanied by an increase in water levels immediately upstream of the crossing. The simulations indicate an increase of approximately 10 cm compared with the trained channel model without the bridge structure. This is the expected response to the reduced effective flow area at the bridge piers.

Downstream of the bridge, flow conditions rapidly stabilize and the differences between the models with and without the bridge become negligible, so the hydraulic influence of the bridge remains confined to its immediate vicinity.

These findings indicate that the proposed river training concept ensures satisfactory hydraulic performance under the design discharge conditions while simultaneously preserving the ecological and morphological characteristics of the watercourse.

Following implementation, ecological monitoring is recommended to assess riparian vegetation development and aquatic communities. The establishment of native riparian vegetation (Table 1) and maintenance of suitable in-channel conditions for characteristic fish species (Table 2) contribute to balancing erosion control and preservation of natural river functions [7 - 10].

4. CONCLUSION

The application of near-natural river engineering measures along the analyzed reach of the Trgoviški Timok River provided a design solution aimed at ensuring channel stability and erosion protection. Compared with the existing natural condition, the proposed measures modified the water level distribution along the reach, with generally lower water levels and increased hydraulic conveyance capacity, although minor local increases were observed at several cross-sections due to channel geometry adjustments. The bridge structure caused a localized backwater effect, with an increase of 10 cm in water level immediately upstream of the crossing. However, its hydraulic influence remained limited to the bridge vicinity.

The results demonstrate that near-natural measures can provide effective infrastructure protection while preserving natural channel characteristics and supporting river ecosystem functions. Post-construction ecological monitoring is recommended to verify these expected benefits over time, in accordance with the adaptive management principles of nature-based solutions.

The proposed solution represents a sustainable balance between hydraulic requirements and ecological objectives in urban watercourses. The approach has considerable potential for wider application on similar watercourses, although reaches containing hydraulic structures require particularly careful hydraulic verification, which is a limitation of the present study. Future research should extend the methodology through two-dimensional (2D) hydraulic modeling to provide a more comprehensive assessment of flow patterns and ecosystem interactions.

5. SUSTAINABLE DEVELOPMENT GOALS

The proposed approach contributes to SDG 11 and SDG 13, by protecting urban infrastructure and maintaining flood resilience under intensifying hydrological extremes, and to SDG 15, by preserving the natural channel, the riparian zone and aquatic habitats.

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Research paper

URBAN LANDSCAPE EVAPOTRANSPIRATION IN THE CITY OF NIŠ

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Abstract

Rapid urbanization and climate uncertainty, caused by climate change, present cities with new environmental challenges. Urban landscapes are recognized as one of the measures for mitigating the adverse environmental issues, caused by rapid urbanization, as well as for improving urban sustainability. A heterogeneous urban environment has complex microclimatic conditions, which can lead to pronounced water requirements for urban landscapes. Such water requirements can vary due to different vegetation types, the influence of buildings and water management. Evapotranspiration is a key element for the optimal estimation of plant water requirements, because it links water and energy cycles, i.e. urban evapotranspiration controls the hydrological performance of urban green areas.

The aim of the paper is to analyze landscape evapotranspiration (ET_L) in the urban conditions of the city of Niš, Serbia, during the period of 2022-2024. The Water Use Classifications of Landscape Species (WUCOLS) approach was used to estimate ET_L, for the crop growing season. The results show that the maximum ET_L value was in July 2022, while the minimum ET_L was in April 2023, with average daily values of 3.703 mm day^{-1} and 0.911 mm day^{-1}, respectively. This approach provides the necessary data for sustainable water management and improved water use efficiency in urban areas.

Key words: *landscape evapotranspiration, WUCOLS, Niš, Serbia*

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1. INTRODUCTION

Urbanization is a complex process in which a rural environment is transformed into an urban one. This process occurs through functional environmental changes, characterized by pronounced structural and morphological transformations. Sustainable urban development implies the construction of diverse structures and green spaces. Urban vegetation mimics natural green areas and represents a strategy for combating urban vulnerability. Owing to its great cooling potential, green infrastructure is a primary adaptation measure for climate change in urban areas. In order to enable the most effective development of green infrastructure, it is necessary to apply an integral approach to water management.

Sustainable water management requires a better understanding of water requirements for the purpose of preventing environmental risks and increasing water use efficiency, especially in urban conditions [1]. Water conservation in urban areas is vital, due to limited water resources, rising temperatures, droughts and population growth. Therefore, it is necessary to develop strategies that combine the efficiency of water use with minimal plant water requirements.

Precise calculations of water demands are essential since drinking water is often used for irrigation, and since over-irrigation frequently occurs in private urban landscapes [2,3]. Urban water requirements are similar to those in agriculture, but they are modified according to the specificities of vegetation in the green infrastructure. In terms of the water quantity, there are two main differences between agricultural crops and landscape species [4]: the characteristics of urban landscape ecosystems (heterogeneity, small yards, vegetation types, impact of structures and microclimatic conditions) and irrigation objectives (agriculture focuses on the production of high-quality crop yields, whereas urban areas prioritize plant aesthetics and health).

Optimal irrigation efficiency of urban vegetation can be achieved through a reliable estimation of landscape evapotranspiration [5]. According to [6], the measurement and modeling of evapotranspiration represents a challenge in urban areas due to heterogeneous vegetation and surrounding structures. There are numerous papers in which urban landscape evapotranspiration was analyzed [5,7,8,9,10]. A detailed review of different studies on measuring the water requirements of urban landscapes is presented by Nouri et al. (2013) [5]. The authors concluded that the Water Use Classifications of Landscape Species (WUCOLS) method is a practical approach for initially estimating the urban landscape water demand, but emphasized that it should be further refined. The health and aesthetic condition of the vegetation should be the main criterion for further improvement. Furthermore, the authors recommended calibrating the WUCOLS method with the soil water balance method.

Two approaches, i.e. the WUCOLS and the Landscape Irrigation Management Program (LIMP), were investigated by Shojaei et al. (2018) [10] to measure the water demand of a botanic garden and a sparse forest park. Comparative results showed that the annual water requirements estimated by WUCOLS were 5% lower for the garden and 44% lower for the park than those calculated by LIMP. Moreover, the results revealed that water savings for irrigation can be achieved by applying the LIMP method.

The paper presents an analysis of landscape evapotranspiration (ET_L) for an urban area. The landscape evapotranspiration is defined as the product of reference evapotranspiration (ET_0) and the landscape coefficient (K_L).

2. MATERIALS AND METHODS

2.1. Study area and data

The study focuses on the urban part of Niš (Serbia). The city of Niš is located in the southeastern part of Serbia. The climate in this region is humid subtropical with continental influences (moderately hot summers and cold winters). The wettest month is June, while the driest month is February. The average annual precipitation is approximately 600 mm. Precipitation is slightly more concentrated during late spring and early summer than in other seasons. The average air temperature is approximately 11 °C and the sunniest month is August, while the cloudiest one is December. The average daily temperature in August is 29.8 °C and the average insolation is approximately 300 hours per month.

The data used for this study were collected from an automatic weather station located in the urban area of Niš (43°19' N, 21°56' E and 197.2 m a.s.l.). The weather station is equipped with several sensors for: air temperature and relative humidity (HC2S3-L, Campbell Scientific), wind monitor (05103-5 RM Young, Campbell Scientific) and pyranometer (CS300-L, Campbell Scientific). The datalogger (CR1000, Campbell Scientific) was used for data acquisition and control of the entire automatic weather station. Daily data were used in the study and the analyzed time period covers 2022 (July-September) and the crop growing period for 2023 and 2024.

2.2. Water use classifications of landscape species method

The Water Use Classifications of Landscape Species method was developed to estimate urban landscape evapotranspiration, while maintaining an acceptable appearance and health of the plants [11]. This approach is based on the Landscape Coefficient Method to determine the water requirements of urban landscapes. According to the WUCOLS, urban landscape evapotranspiration can be calculated using the following equation:

$$ET_L = K_L ET_0 \quad (1)$$

where:

ET_L – landscape evapotranspiration [mm day^{-1}]
K_L – landscape coefficient
ET_0 – reference evapotranspiration [mm day^{-1}]

The landscape coefficient includes three main factors that determine the evapotranspiration of heterogeneous vegetation, which usually characterizes urban landscapes, i.e. the species factor, the density factor and the microclimate factor:

$$K_L = k_s k_d k_{mc} \quad (2)$$

where:

k_s – species factor

k_d – density factor

k_{mc} – microclimate factor

The k_s factor accounts for the differences in a species' water requirements. What is more, WUCOLS provides a list of estimated water requirements for over 4000 urban species, which are classified into four categories, such as high, moderate, low and very low. This classification is based on the studies of water use for different landscape species, rather than the vegetation type (groundcover, shrub, tree, etc.).

k_d accounts for variations in vegetation density across different urban landscapes. Vegetation density is defined by the collective leaf area of all plants. The k_d factor is assigned average values when the tree canopy cover is greater than 70% (for shrubs, it is 90%). This classification is based on orchard studies, which demonstrated that water loss from orchards did not increase when the canopy cover increased from 70% to 100% [11]. However, if the canopy cover falls below 70%, water loss is reduced (there is a significant portion of bare soil, which directly receives solar radiation).

k_{mc} refers to the microclimate conditions in the urban environment. The microclimate of urban areas is distinct due to the influence of buildings, streets, pavements, etc. on temperature, wind and solar radiation; thus, k_{mc} accounts for the impact of all climate parameters.

2.3. Reference evapotranspiration

The FAO 56 Penman-Monteith equation was used for the determination of reference evapotranspiration [12]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

where:

ET_0 – reference evapotranspiration [mm day^{-1}]

R_n – net radiation at the crop surface [MJ m^{-2} day^{-1}]

G – soil heat flux density [MJ m^{-2} day^{-1}]

T – air temperature at 2 m height [°C]

U_2 – wind speed at 2 m height [m s^{-1}]

e_s – saturation vapour pressure [kPa]

e_a – actual vapour pressure [kPa]

e_s-e_a – saturation vapour pressure deficit [kPa]

Δ – slope vapour pressure curve [kPa °C^{-1}]

γ – psychrometric constant [kPa °C^{-1}]

3. RESULTS AND DISCUSSION

3.1. Water use classifications of landscape species coefficients

The values of the species factor are determined according to the water requirement recommendations for the different species, given in the WUCOLS methodology [11]. k_s is defined for each vegetation cover, and the final values are then calculated by weighting according to the corresponding area, Table 1. Owing to the changes in the vegetation cover area during the analyzed period, the monthly factor is determined as the average value for each month of the growing period across the study years and the observed area. The corresponding species areas for each month are determined via on-site observations. Trifolium repens has the highest value of the k_s factor and is the most prevalent species, which accounts for approximately 50% of the vegetation in the study area. Rosmarinus officinalis has the lowest k_s value (0.2) and occupies approximately 2% of the vegetation.

Table 1. List of the common plants at the study area and assigned species factors (Gc – groundcover, S – shrub, P – perennial, V – vine, T - tree)

Species	Plant type	k_s
Trifolium repens	Gc	0.7
Buxus sempervirens	S	0.4
Rosmarinus officinalis	S/P	0.2
Melissa officinalis	P/Gc	0.5
Vinca major variegata	Gc	0.4
Rosa	S	0.4
Malus domestica	T	0.4
Vitis vinifera cardinal	V	0.3

The k_d values are defined according to species density (percentage share). In this context, it is important to highlight that study area is covered by vegetation, including groundcovers, shrubs, perennials, vines and trees. The percentage share of plants is determined through field observations. Furthermore, plant density was not the only parameter for defining k_d. In fact, ground coverage by tree canopy and leaves played a significant role, exerting a direct impact on the assigned k_d values on monthly basis. Foliage development in deciduous plants was specifically taken into account during the crop growing period. A comprehensive survey of the study area reveals that the vegetation is divided into two layers, which are complemented and provide full groundcover. The first layer consists of groundcovers and shrubs. Trifolium repens is the dominant groundcover species, while Buxus sempervirens and Vinca major variegate are the dominant shrub/groundcover species. Rosmarinus officinalis and Melissa officinalis are the species with the lowest density, accounting for 2% and 3% of the vegetation, respectively. The second layer consists of taller species, such as vines and trees, i.e. Malus domestica and Vitis vinifera cardinal. Malus domestica has a higher k_d value due to its coverage of approximately 60% of the second layer. According to [11], mixed-species plantings have a greater collective leaf area than single-species plantings. These plantings are assigned a k_d factor in the high category (1.1 – 1.3). The assigned k_d factor value in this study is 1.2 during the peak of the vegetation period.

The values of k_{mc} are fixed at 1.1 during the entire analyzed period, considering the impact of urban conditions. The k_{mc} value is derived from on-site observations and the WUCOLS recommendations [11]. Plantings surrounded by heat-absorbing surfaces, reflective surfaces, or exposed to windy conditions, would be assigned high values (1.1 – 1.4). The main part of the study area is sunny during the entire day and it is located south of the urban family houses. A small part of the area is on the east side of the houses and it is sunny only until noon. In addition, there is no atypical (extremely strong) wind. There are situations with a slightly stronger wind from the south. Moreover, the analyzed area is surrounded by family houses and intersected by streets, parking lots and pavements. The results of the established factor values are presented in Table 2.

The K_L value of 0.752 indicates the highest plant water requirement, i.e. considering the time of the year, the species are the most sensitive to water scarcity in July and August. April is the month when species adapt relatively well to available water (K_L is 0.449).

Table 2. Coefficients of the WUCOLS method

	Apr	May	Jun	Jul	Aug	Sep
k_s	0.51	0.53	0.56	0.57	0.57	0.53
k_d	0.8	1	1.1	1.2	1.2	1.1
k_{mc}	1.1	1.1	1.1	1.1	1.1	1.1
K_L	0.449	0.583	0.678	0.752	0.752	0.641

3.2. Landscape evapotranspiration

The landscape evapotranspiration values are shown in Figure 1. The maximum values of ET_L are during the summer period (June, July and August). July stands out as the month with the highest ET_L, whereas April is the month with the lowest ET_L values, for the whole observed period. The maximum ET_L (average daily value on a monthly basis) of 3.703 mm day^{-1} is reached in July 2022, while the lowest value is in April 2023 (0.911 mm day^{-1}). A comparison between ET_0 and ET_L demonstrates that the percentage difference is the highest in April (55.12%), while the lowest one is in July and August (24.76%). This relationship between ET_0 and ET_L is expected, considering the K_L values in Table 2.

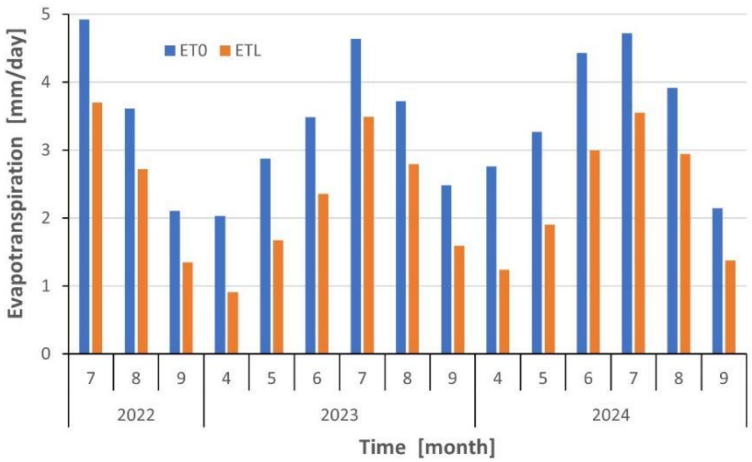


Figure 1. Monthy mean landscape evapotranspiration for the observed period

The maximum daily ET_L i.e. the value of 4.132 mm day^{-1}, occurred on 8th July 2024, while the minimum one was 0.314 mm day^{-1} on 5th April 2023. There is a significant dispersion of ET_L values during the first half of the analyzed period (April, May and June), Figure 2. Moreover, the same pattern of ET_L behavior is observed across the three analyzed years, i.e. there is a pronounced vegetation water requirement during the summer period.

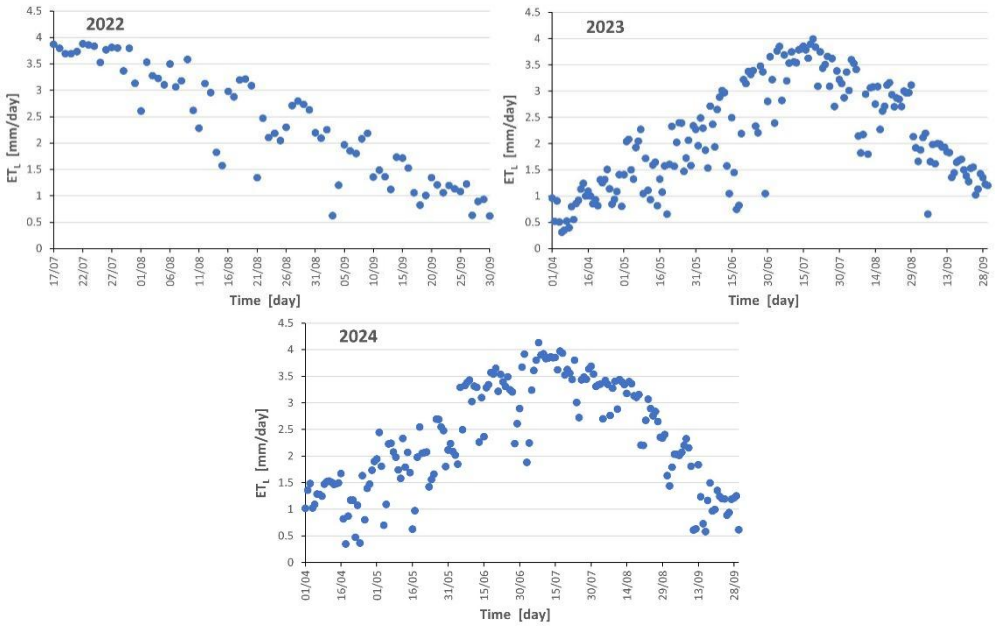


Figure 2. Daily landscape evapotranspiration for the analyzed period

4. CONCLUSION

The landscape evapotranspiration was analyzed in the urban conditions of Niš using the WUCOLS methodology. The methodology was based on three estimated factors which characterized the urban landscape. The FAO-56 Penman-Monteith equation was used for defining the reference evapotranspiration. According to the landscape coefficient, the analyzed species are the most sensitive to water scarcity during July and August, i.e. landscape evapotranspiration reaches the maximum values during the summer period (especially in July).

Urban vegetation planning poses an increasingly significant challenge for optimal cooling and water resource conservation. To better adapt to climate change, it is necessary to understand how different species respond to meteorological parameters. Moreover, spontaneous species whose water requirements are met by precipitation require specific evaluation within the urban environment to serve as a basis for future urban planning.

Further study will be oriented towards the application of other methods for estimating urban landscape evapotranspiration. Additionally, special attention will be paid to urban climate factors and their changes.

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Review paper

GREEN MEASURES FOR CLIMATE ADAPTATION OF BUILDINGS AND INFRASTRUCTURE DURING DROUGHT PERIODS

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Abstract

Drought is increasingly recognized as a significant climate-related stressor for the built environment, particularly in regions with expansive soils and pronounced seasonal moisture variability. This paper explores how green and nature-based adaptation measures influence drought resilience by examining their interactions with soil moisture dynamics, vegetation processes, groundwater fluctuations, and structural performance. Through a thematic review of research papers, recent European initiatives on drought-resilient green infrastructure, the extensive French experience with clay shrink–swell damage, and evolving geotechnical considerations in the second-generation Eurocode 7, the study synthesizes current knowledge on the opportunities and constraints associated with vegetation-based, blue-green, soil-focused, and building-scale interventions. The paper highlights the importance of context-sensitive application of green measures in drought-prone settings. The findings point to the need for more refined assessment tools capable of capturing coupled processes that govern soil–vegetation–structure behavior under changing climate conditions.

Key words: *Green measures, Nature-based measures, Drought adaptation, Buildings and infrastructure*

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1. INTRODUCTION

Projections indicate that more frequent and prolonged droughts, often combined with heatwave hazards, create severe risk conditions for cities, settlements, and infrastructure. Urban populations are particularly vulnerable, as combined droughts and heatwaves significantly increase the risk of water scarcity [1]. Recent European droughts have demonstrated the accelerating impacts of climate change on water availability, with the extreme 2003 event marking a turning point in how drought risk is conceptualized across sectors [1]. While earlier assessments focused primarily on agricultural and hydrological losses, the 2003 drought revealed substantial vulnerabilities within the built environment, including soil subsidence, infrastructure deformation, and structural damage. This shift has since driven European policy and research toward a broader, cross-sectoral understanding of drought as a systemic climate hazard [2] [3].

Recent studies indicate that the economic costs of drought-related damage to buildings and infrastructure have increased across Europe, particularly in regions underlain by expansive clayey soils. In France and the United Kingdom, repeated drought-induced shrink–swell cycles have become a major cause of damage to residential buildings and shallow foundations. In some regions, the associated economic losses are comparable to those caused by flood hazards, highlighting drought as an emerging geotechnical risk under climate change [4] [5] [6] [7]. These developments emphasize the need to extend drought adaptation beyond traditional water-resource and agricultural management toward protecting buildings and critical infrastructure.

Today, drought is increasingly treated as a geotechnical, hydrological, and infrastructure hazard, reflecting its capacity to alter soil moisture regimes, groundwater levels, and the mechanical behavior of foundation soils [8]. These processes can compromise the stability and serviceability of buildings, transportation networks, and lifeline infrastructure, placing drought alongside other major climate-induced risks [9]. As a result, adaptation frameworks now integrate nature-based solutions (NBS), land-management strategies, and infrastructure resilience planning to address the full spectrum of drought-related impacts [10].

In recent years, the expansion of green and nature-based adaptation measures has become a central component of global climate-resilience strategies [1] [11]. However, alongside their environmental benefits, these measures may introduce potential conflicts with structural safety, particularly where vegetation, soil moisture dynamics, and foundation behavior interact. Such tensions were notably observed during the 2003 drought especially in the United Kingdom, when widespread clayey soil shrink–swell movements and thus induced infrastructure deformation highlighted the need to reassess the relationship between ecological adaptation and the built environment [1] [4] [12].These observations have contributed to a growing recognition of drought as not only an environmental or hydrological phenomenon but also a geotechnical and infrastructure hazard with direct implications for structural performance [3] [10]. Prolonged soil desiccation, changes in groundwater regimes, and altered mechanical properties of foundation soils increasingly affect buildings, transportation systems, and

lifeline infrastructure. This evolving understanding provides the core motivation for the presented research, which examines the mechanisms and consequences of drought-induced impacts on construction assets [12].

This paper aims to review green and nature-based adaptation measures that are directly relevant to buildings and infrastructure, with attention to their performance under drought conditions. The study evaluates both the positive environmental contributions and the potential adverse structural effects that may arise during prolonged soil desiccation and groundwater table decline.

2. METHODOLOGY AND ASSESSMENT FRAMEWORK

This paper is based on a thematic review of green and nature-based climate-adaptation measures relevant to drought conditions and their implications for the built environment. The review draws upon scientific literature, technical guidance documents, policy reports, and recent developments in engineering practice related to drought resilience and green infrastructure.

The analysis focuses on adaptation measures that can contribute to improving environmental conditions in urban areas while potentially reducing the adverse effects of drought on the built environment. The identified measures are classified according to their primary functions and qualitatively assessed in terms of their potential benefits and challenges. The assessment considers environmental, technical, and maintenance aspects, as well as possible interactions with buildings and infrastructure under drought conditions.

3. GREEN MEASURES FOR DROUGHT ADAPTATION

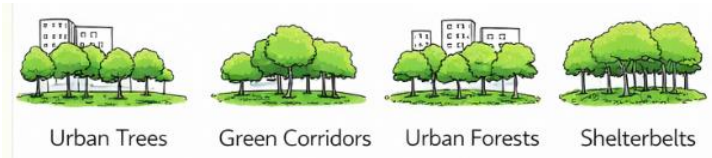
Green and nature-based adaptation measures have become central to contemporary climate-resilience strategies, particularly in regions increasingly exposed to prolonged droughts [1]. These measures rely on ecological processes such as vegetation growth, soil regeneration, and natural water retention to enhance the capacity of landscapes and urban areas to cope with reduced water availability [10]. Their appeal lies in the combination of environmental co-benefits, long-term sustainability, and the potential to mitigate multiple climate-related risks simultaneously, including heat stress, biodiversity loss, and hydrological imbalance [2], [15]. In the context of the built environment, these measures are increasingly considered not only for their ecological value but also for their potential interactions with soil moisture regimes, groundwater dynamics, and infrastructure performance during drought periods.

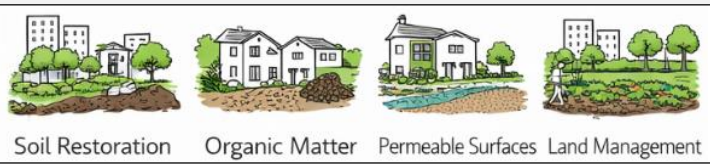
Within drought-adaptation practice, green measures encompass a broad spectrum of interventions operating across different spatial and functional scales. They include vegetation-based approaches that regulate microclimate and soil moisture, blue-green systems that enhance natural water retention, soil-focused practices that improve infiltration and water-holding capacity, and building-scale solutions that integrate green elements into the constructed environment [3] [16]

[17]. Although these measures are widely promoted for their environmental and social benefits, their influence on the built environment can be complex: depending on local soil conditions, vegetation type, and hydrological context, they may either support or challenge the stability and performance of buildings and infrastructure during drought.

Given this diversity, the following analysis organizes green adaptation measures into four conceptual groups and evaluates each in terms of its primary functions, main benefits, and potential risks during drought conditions. This structured approach enables a clearer understanding of how different nature-based interventions contribute to drought resilience, while also highlighting circumstances in which they may inadvertently affect soil stability, groundwater regimes, or the performance of buildings and infrastructure [1]. Table 1 provides illustrative examples for each group of measures, together with their key advantages and potential limitations.

*Table 1. Classification of green measures for drought adaptation**

A. Vegetation-based measures	
Illustration	
Primary Function	Microclimate and soil moisture regulation
Main Benefits	Microclimate regulation and shading: Trees and shrubs reduce surface temperatures and evapotranspiration stress around buildings, improving thermal comfort and lowering cooling demand. Soil protection and water retention: Root systems enhance soil structure, infiltration, and organic matter, which can increase water-holding capacity and reduce erosion during drought–flood cycles.
Potential Risks	Shrink–swell amplification near foundations: Deep-rooted vegetation can intensify desiccation of expansive clays, increasing differential settlements and damage to shallow foundations. Root-related structural interactions: Roots may affect retaining structures, buried infrastructure, and pavements, particularly where planting is not coordinated with geotechnical conditions and foundation design.
References	[2] [10] [15] [16] [17] [18] [19] [20]
B. Blue-green measures	
Illustration	
Primary function	Natural water retention and drainage
Main Benefits	Natural water retention and delayed runoff: Swales, rain gardens, ponds, and sustainable drainage systems (SuDS) attenuate peak flows, promote infiltration, and support groundwater recharge, thereby moderating drought impacts on local water availability.

	Multi-hazard resilience: Blue-green infrastructure simultaneously addresses pluvial flooding, heat stress, and ecological degradation, contributing to overall urban resilience.
Potential Risks	Load and leakage effects on structures: Poorly detailed storage elements or ponds near buildings may alter groundwater regimes, induce localized softening, or increase loads on retaining structures and subgrades. Performance degradation under prolonged drought: Extended dry periods can reduce vegetation cover in blue-green systems, leading to cracking, settlement of filter media, and reduced hydraulic performance, with possible consequences for adjacent pavements and utilities.
References	[2] [14] [15] [16] [17] [18] [20]
C. Soil-focused measures	
Illustration	
Primary function	Soil infiltration and water-holding capacity improvement
Main Benefits	Improved soil structure and water-holding capacity: Conservation tillage, mulching, organic amendments, and erosion-control practices enhance porosity, aggregate stability, and moisture retention, buffering drought impacts on both natural and semi-urbanized soils. Reduced erosion and subsurface instability: Stabilized soils are less prone to desiccation cracking, gullying, and slope degradation, which can indirectly protect infrastructure platforms, embankments, and foundations.
Potential Risks	Unintended changes in soil moisture regime near structures: Measures that significantly increase water infiltration or storage in the near-foundation zone may modify seasonal moisture cycles in expansive or collapsible soils, affecting settlement patterns. Over-reliance without geotechnical verification: Applying generic soil-improvement practices without site-specific investigation can mask or shift geotechnical problems rather than resolve them, complicating future design and remediation.
References	[10] [13] [16] [20] [21]
D. Building-scale measures	
Illustration	
Primary function	Green elements integration into constructed environment
Main Benefits	Local microclimate and runoff management: Green roofs, green façades, and courtyard planting reduce surface temperatures, intercept rainfall, and delay runoff, thereby easing pressure on drainage systems during variable hydro-climatic conditions. Enhanced building-level resilience: Integrated water-saving and storage systems (e.g., rainwater harvesting, on-site reuse) can improve water security for buildings during drought episodes.
Potential Risks	Additional structural loads and moisture effects: Green roofs and façade systems introduce extra dead loads, water storage, and potential leakage

	paths, which may be critical for existing or lightly designed structures, especially under changing climate load combinations. Interface vulnerabilities: Poor detailing at the interface between green elements and the primary structure (e.g., fixings, waterproofing, drainage outlets) can lead to localized deterioration, cracking, or serviceability issues, particularly when drought–rainfall cycles induce repeated wetting–drying of materials.
References	[2] [15] [16] [17] [18] [19]
** The visual elements (pictograms), were generated with the assistance of an AI language model designed to create images based on descriptive prompts.*	

4. DISCUSSION

4.1. Recent European initiatives

Recent UK guidance emphasizes that drought resilience must be understood as part of a broader integrated water-management strategy, in which green infrastructure plays a central role in regulating runoff, enhancing infiltration, and stabilizing soil moisture regimes [4]. Blue-green systems such as SuDS, rain gardens, and vegetated corridors are highlighted for their capacity to deliver multi-hazard benefits, but it is also noted that their performance can deteriorate under prolonged dry periods, leading to settlement of filter media, cracking, and reduced hydraulic efficiency [4]. These insights underscore the importance of designing green infrastructure with explicit consideration of drought cycles and their implications for adjacent buildings and infrastructure.

France provides one of the most instructive European examples of drought-related impacts on the built environment, particularly due to the widespread presence of expansive clayey soils. The 2003 drought triggered extensive shrink–swell movements of clayey soils, resulting in differential settlements, façade cracking, and serviceability failures across thousands of residential buildings [7] [10]. Subsequent analyses confirmed that vegetation management, especially the proximity and rooting depth of trees, plays a critical role in controlling desiccation around foundations [10]. These findings highlight the need to integrate geotechnical, hydrological, and vegetation-related considerations when applying green measures in clay-rich regions.

Driven by the scale of drought-induced building damage, France has become a leading European example of how climate-related soil hazards can reshape regulatory practice. Shrink–swell of clay soils now affects a substantial portion of the national building stock, prompting the introduction of new prevention policies, mandatory soil investigations, and zoning requirements that classify areas according to drought-related geotechnical risk [10] [22]. These developments demonstrate how lessons from extreme drought events can accelerate the integration of climate resilience into land-use planning, building codes, and adaptation strategies.

The ongoing development of the second-generation Eurocode 7 increasingly recognizes climate-driven variability in groundwater levels, soil moisture regimes, and soil–vegetation interactions as factors that must be explicitly considered in geotechnical design [8]. These emerging provisions signal a shift toward climate-resilient geotechnical practice, where green and nature-based measures are evaluated not only for their environmental benefits but also for their potential structural implications.

4.2. Dimensions of Green measures

The four groups of green measures outlined in this paper offer a practical framework for categorizing nature-based interventions focused on water management. In comparison, McPhillips et al. [23] present a more complex and multidimensional approach. While here presented classification groups measures primarily by type or function, McPhillips et al. [23] extend this by "coloring" (brown, green, turquoise, and blue) or differentiating measures according to their primary water-related functions, but also by considering additional dimensions such as ecological characteristics, technological integration, size, and location. This richer, multidimensional framework allows for a more complex understanding of how nature-based solutions operate within urban water systems, emphasizing their varied roles and scales. Therefore, while the groups presented in Table 1 provide clear categories for practical application, the approach of McPhillips et al. [23] highlights the complexity and versatility of NBS in enhancing water resilience, helping guide more tailored and context-specific implementation strategies.

There is not universally optimal green or nature-based measure for drought adaptation, because the performance of each intervention is highly dependent on local environmental and infrastructural conditions. Climate characteristics, soil type and plasticity, groundwater regime, urban density, and the nature of nearby buildings or infrastructure all shape how a measure behaves in practice. A solution that performs exceptionally well in one setting, such as deep-rooted vegetation for microclimate regulation or blue-green systems for runoff attenuation, may behave very differently under contrasting geotechnical or hydrological conditions. Similarly, infiltration-enhancing systems may be advantageous for water management but problematic where groundwater fluctuations or collapsible soils affect structural performance. These interactions highlight the need for site-specific assessment and integrated design approaches that evaluate both ecological benefits and potential impacts on the built environment.

The wider adoption of green measures and particularly NBS is still hindered by gaps in financing and governance arrangements within EU Member States, indicating that substantial policy and institutional efforts are required to fully realize their adaptation potential [24].

Unlike broader classifications of nature-based solutions, the framework proposed in this paper explicitly incorporates potential interactions between adaptation measures and the built environment under drought conditions. By considering both environmental benefits and possible geotechnical consequences, the framework provides a practical basis for evaluating drought adaptation strategies from an infrastructure resilience perspective.

5. CONCLUSIONS

This paper has examined the role of green and nature-based measures in enhancing drought resilience, with particular attention to their interactions with soil behavior, groundwater dynamics, and the built environment. By reviewing recent European experiences and synthesizing evidence from geotechnical, hydrological, and environmental perspectives, the study highlights both the benefits and the potential challenges associated with these measures. The findings underscore the importance of context-specific assessment and integrated planning when applying green solutions in drought-prone regions. The following can be concluded:

1. Green measures can significantly improve drought resilience of urban areas, and provide multiple environmental and social benefits, provided that their design includes practical engineering steps such as controlled irrigation regimes, root-barrier installation, and selection of species with low water demand.
2. Some measures may also introduce risks for buildings and infrastructure, particularly in drought-prone areas with shrink-swell clayey soils, which calls for routine monitoring of soil moisture, minimum safe planting distances, and pre-installation geotechnical checks.
3. Future adaptation strategies should integrate environmental, hydrological, and geotechnical considerations, including coordinated planning between landscape architects and geotechnical engineers, early-stage subsurface investigations, and the use of coupled soil–vegetation–water models in design practice.

The review demonstrates that the effectiveness of green adaptation measures cannot be evaluated solely through environmental performance indicators. Their interaction with soil moisture dynamics, groundwater regimes, and structural systems must also be considered. Future research should therefore focus on developing integrated assessment methodologies capable of quantifying both the resilience benefits and potential geotechnical risks of nature-based solutions under increasing drought pressure.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

HYDRAULIC RESILIENCE AS A GREEN BUILDING STRATEGY IN INSULAR URBAN TERRITORIES: MACHICO AND RIBEIRA BRAVA, MADEIRA ISLAND

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Abstract:

Green building strategies are commonly framed through energy performance, materials, indoor comfort and certification systems. In territories exposed to short concentration times, steep catchments and rapid urban runoff, however, the environmental performance of buildings also depends on their relationship with drainage networks, river corridors and land-use dynamics. This paper develops a conference-oriented synthesis centred on Madeira Island, with Machico and Ribeira Brava as principal territorial references. The objective is to connect green building principles with hydraulic resilience, blue-green infrastructure and water-sensitive planning in insular urban territories. The methodological approach is based on a structured review and reinterpretation of recent peer-reviewed studies on land-use change, flood hazard assessment, hydraulic planning, riverbed roughness and strategic urban rehabilitation in Madeira. To improve coherence with established terminology, blue-green infrastructure is treated as a planned network of natural, semi-natural and engineered elements that supports stormwater retention, infiltration, conveyance and urban resilience. The synthesis identifies three critical interfaces: land-use change, soil sealing and surface runoff; detention, infiltration and channel roughness management; and the integration of building-scale design with catchment-scale hydraulic performance. Machico and Ribeira Brava provide complementary lessons: Machico illustrates how urban form, rehabilitation strategies and river-course occupation influence vulnerability, while Ribeira Brava demonstrates the operational value of hydraulic modelling, detention basin sizing and drainage-capacity assessment. The paper proposes a catchment-to-building framework in which green building is treated as part of a territorial water-resilience system, particularly relevant for island regions where steep topography, limited land availability and intense rainfall demand integrated criteria across buildings, public space and hydraulic infrastructure.

Key words: *blue-green infrastructure, flood management, green building, hydraulic resilience, Madeira Island*

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1. INTRODUCTION

The transition toward greener built environments requires more than the optimisation of individual buildings. In climate-exposed territories, the performance of buildings is inseparable from the behaviour of the urban catchment in which they are located. Extreme precipitation, rapid runoff concentration, soil sealing and the progressive occupation of natural drainage corridors can compromise the environmental quality, operational safety and long-term functionality of built assets. This broader interpretation is aligned with international climate-risk assessments, which emphasize that adaptation depends on reducing exposure and vulnerability across infrastructure systems, settlements and land-use practices [1].

The Green Building 2026 thematic framework explicitly links architecture, urban planning, civil engineering, hydraulic engineering, water management and climate adaptation. This scope is particularly appropriate for island territories, where the relationship between buildings, slopes, streams and coastal outlets is direct and often critical. Madeira Island provides an instructive case because its steep morphology, narrow valleys and concentrated urban occupation create short hydrological response times and strong dependence on hydraulic infrastructure. In such settings, a green building strategy limited to envelope performance, energy efficiency or material selection would remain incomplete unless it also addressed drainage, permeability, water retention and river corridor management [2].

This paper therefore develops a synthesis centred on two Madeiran references: Machico and Ribeira Brava. Machico is used to explore the relation between land-use evolution, urban structure, strategic rehabilitation and flood hazard along an insular watercourse. Ribeira Brava is used to illustrate the hydraulic planning dimension, including drainage capacity, detention basin sizing, riverbed roughness and hydrological modelling. The contribution of the paper is not the presentation of a new field campaign; rather, it is a structured reinterpretation of recent research outputs in order to position hydraulic resilience as a necessary component of green building and climate-adapted urban design in insular territories [5-12].

2. BACKGROUND: GREEN BUILDING AND HYDRAULIC RESILIENCE

Green building discourse has traditionally emphasized building-level variables such as energy demand, passive design, resource efficiency, material circularity, indoor environmental quality and life-cycle impacts. These criteria remain essential, but they do not fully capture the environmental performance of buildings located in flood-prone urban basins. In dense or morphologically constrained settlements, the building plot becomes part of a distributed hydraulic system: roofs, pavements, basements, retaining walls, access roads and public spaces collectively affect the generation, concentration and conveyance of stormwater [2].

The framework adopted in this paper is consistent with wider literature on sustainable drainage systems, water-sensitive urban design, low-impact development and sponge-city approaches. Although these traditions use different terms, they share a

common planning principle: stormwater should be managed close to its source through a connected network of permeable, vegetated, retentive and conveyance elements, rather than transferred rapidly to downstream channels. This interpretation also aligns with the European concept of green infrastructure as a strategically planned network that delivers multiple ecosystem services, including flood regulation, water management and urban climate adaptation [3,4].

Hydraulic resilience can be understood as the capacity of a territorial system to absorb, convey, temporarily store and recover from hydrometeorological events without unacceptable social, economic or structural damage. At the scale of green building, this implies attention to permeable surfaces, roof drainage, rainwater harvesting, detention and infiltration systems, safe overland flow paths and the avoidance of construction practices that increase runoff or obstruct natural channels. At the urban scale, the same principle requires coordinated land-use planning, green corridors, detention basins, maintenance of channel capacity and monitoring of hydraulic bottlenecks [7-9].

The Madeira case is relevant because previous studies demonstrate the strong interaction between land occupation and hydrological response. Research on Ribeira Brava showed that land-use change and urban expansion in an insular municipality must be interpreted together with flood susceptibility and planning constraints [6]. Complementary hydraulic studies demonstrated that mitigation measures such as detention basin sizing and adjustment of the roughness coefficient can improve system performance when adapted to local basin characteristics [7-9]. In Machico, land-use evolution and flood hazard studies have likewise pointed to the importance of river-course occupation, urban rehabilitation and channel-management criteria [5,9-12].

3. MATERIALS AND METHODS

The paper uses a qualitative and analytical synthesis method. The work was developed in four steps: (1) screening of recent peer-reviewed publications on Madeira Island dealing with Machico, Ribeira Brava, land-use change, hydraulic planning and flood mitigation; (2) grouping of the methodological components into territorial dynamics, hydrological-hydraulic response and green-building implications; (3) reinterpretation of the evidence through the thematic lens of Green Building 2026, especially water, environment, blue-green infrastructure, climate-adapted cities and resilient planning; and (4) conversion of the synthesis into practical design criteria linking catchment-scale planning to building-scale requirements.

The selected references include studies based on CORINE Land Cover analysis, Geographic Information Systems, morphometric characterization, hydrological estimation, flood propensity assessment, detention basin sizing, drainage-capacity analysis, riverbed roughness evaluation and urban rehabilitation planning. These methods are not reproduced numerically in full; instead, they are used to identify transferable design principles and quantitative anchors relevant to green-building practice, such as the 1990-2018 land-use interval, the use of a 100-year return period in

hydraulic capacity assessment and the consideration of detention basins and roughness adjustment as mitigation measures [5-9].

The two main territorial units were selected because they represent complementary dimensions of the same problem. Machico illustrates the interaction between urban form, historical land occupation, strategic rehabilitation and flood exposure. Ribeira Brava illustrates how hydraulic modelling and intervention design can be used to reduce flood propensity in steep insular basins. Together, they provide a basis for discussing the integration of green building, urban hydrology and hydraulic infrastructure without presenting the conference paper as a substitute for the original empirical studies.

4. CASE-STUDY SYNTHESIS: MACHICO AND RIBEIRA BRAVA

The location of the two reference municipalities is shown in Figure 1. Both are coastal settlements on Madeira Island, but they represent different spatial relations between urban occupation, valley morphology and drainage infrastructure. This territorial framing is necessary because the proposed framework depends on the interaction between building plots, public space, upstream catchment response and downstream hydraulic constraints.

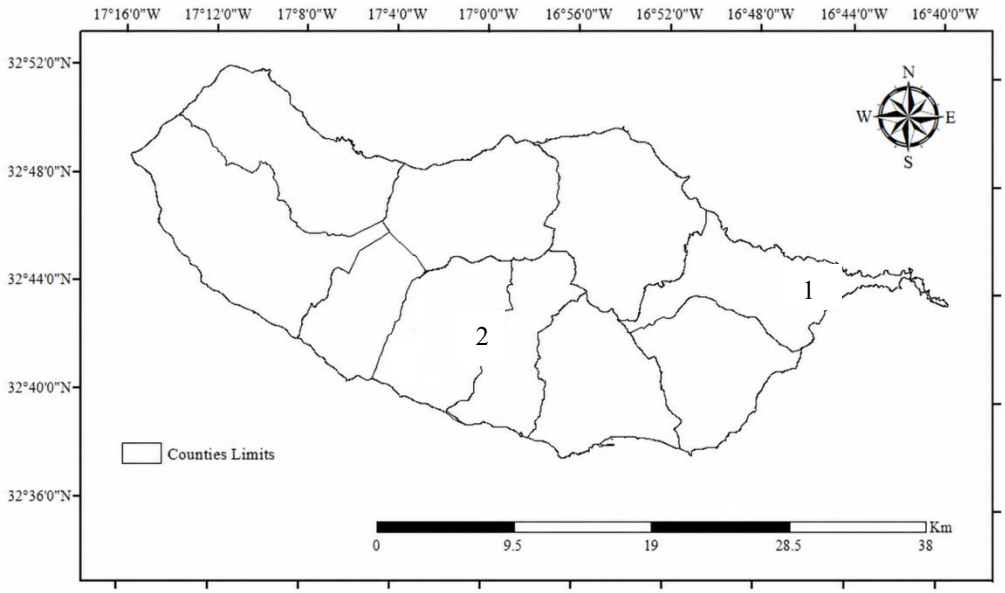


Figure 1. Study area map identifying Madeira Island, Machico (1) and Ribeira Brava (2). Source: authors.

Machico is a relevant case because it combines historical urban settlement, coastal exposure, valley occupation and a watercourse whose hydraulic behaviour is sensitive to land-use decisions. Recent research on Machico analysed land-use evolution from 1990 to 2018 using GIS and CORINE Land Cover data, showing that urban stagnation, agricultural change and vegetation transformation must be interpreted as planning variables rather than as merely descriptive land-cover categories [5]. The same

territorial logic is reinforced by studies on strategic urban rehabilitation, which argue that rehabilitation instruments can support sustainable municipal development when they are connected to spatial planning, housing and infrastructure objectives [11,12].

From the perspective of green building, Machico shows that the sustainability of buildings depends on the surrounding public-space and drainage context. Redevelopment or rehabilitation in flood-influenced areas should therefore include plot permeability, stormwater retention, safe discharge points, avoidance of basement vulnerability, protection of riparian corridors and the compatibility of built form with emergency drainage routes. The relevance of channel roughness is also evident in research on the Ribeira de Machico, where flood phenomena are linked to hydraulic resistance and the condition of the riverbed [9,10]. In practical terms, green building in Machico should be treated as a spatially distributed hydraulic intervention, not simply as a set of isolated building specifications.

Ribeira Brava provides a second perspective. Earlier work on land-use changes in Ribeira Brava demonstrated that retrospective analysis from 1990 to 2018 can inform sustainable development by revealing the spatial consequences of urbanisation, agricultural change and territorial transformation [6]. Hydraulic planning research on Ribeira Brava showed the importance of analysing flood propensity and proposing mitigation methodologies, including detention basin sizing and riverbed roughness adjustment [7]. The later Tabua study deepened this approach by examining drainage capacity under a 100-year return period and by identifying the need to compare estimated flood flows with river-mouth discharge capacity under extreme-event assumptions [8].

The lesson for green building is clear: building sustainability in Ribeira Brava cannot be dissociated from catchment response. Buildings, roads and paved platforms increase runoff when they replace permeable surfaces. Conversely, site-level infiltration, distributed detention, green roofs, permeable paving and controlled discharge can reduce the pressure imposed on downstream hydraulic infrastructure. The territorial scale and the building scale are therefore coupled. This coupling is particularly important in steep basins, where even small increases in imperviousness can contribute to accelerated runoff and reduced opportunity for local storage.

5. RESULTS: INTEGRATED DESIGN CRITERIA

The synthesis produced five design criteria for integrating hydraulic resilience into green building strategies in Madeira Island: catchment awareness, permeability preservation, controlled runoff release, compatibility with river-corridor maintenance and monitoring/adaptive management. The criteria are derived from the cross-reading of land-use studies, hydraulic-planning studies and urban-rehabilitation studies rather than from a new empirical campaign. This title was therefore revised from “Results” to “Proposed design criteria and quantitative evidence” to avoid suggesting that the paper presents independent field results.

Several quantitative elements from the cited studies are retained as decision anchors. First, the land-use analyses for Machico and Ribeira Brava are based on a

three-decade observation window from 1990 to 2018, which is long enough to relate urban transformation to planning pressure [5,6]. Second, the hydraulic-planning studies consider flood propensity and drainage capacity under extreme-event logic, including a 100-year return period in the Tabua drainage-capacity assessment [8]. Third, the mitigation logic combines detention basin sizing and roughness-coefficient adjustment, which are operational hydraulic variables that can be translated into planning and design criteria [7-9].

Table 1 separates the evidence base, hydraulic interpretation and design implication to improve readability and avoid mixing territorial diagnosis with project recommendations. It is intended as a screening matrix for early-stage planning, architectural design and municipal decision-making, not as a replacement for detailed hydrological and hydraulic calculation.

Table 1. Synthesis matrix linking Madeira Island evidence to green-building and hydraulic-resilience criteria.

Evidence source	Quantitative or methodological anchor	Hydraulic interpretation	Green-building / planning implication
Machico land-use evolution	CORINE Land Cover / GIS, 1990-2018	Land-cover transformation changes runoff generation and exposure conditions	Require plot-level permeability, retention and drainage compatibility
Machico flood hazard and river corridor	Flood-hazard assessment and roughness analysis	Channel condition and hydraulic resistance influence flood behaviour	Preserve maintenance access, channel capacity and safe overland flow routes
Ribeira Brava land-use change	Retrospective territorial analysis, 1990-2018	Urban expansion modifies catchment response and cumulative runoff	Compensate imperviousness through infiltration, rainwater reuse and delayed discharge
Ribeira Brava hydraulic planning	Detention basin sizing and roughness-coefficient adjustment	Structural and semi-structural measures can improve downstream performance	Link building permits to catchment-level hydraulic constraints
Tabua drainage-capacity study	100-year return period and river-mouth capacity assessment	Downstream discharge capacity may limit the effectiveness of isolated local measures	Combine source control with downstream capacity verification

As illustrated in Figure 2, the proposed catchment-to-building framework positions blue-green infrastructure as a planned and continuous stormwater-management system rather than as a decorative environmental feature. In Machico, the priority is to connect urban rehabilitation and land-use control with drainage-sensitive design. In Ribeira Brava, the priority is to combine source control with structural and semi-structural hydraulic measures. In both cases, the building is one component of a wider retention, conveyance and resilience system.

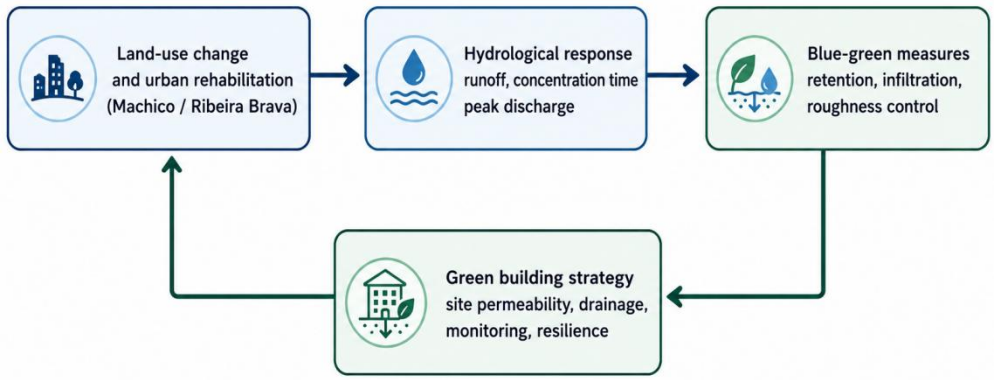


Figure 2. Catchment-to-building hydraulic resilience framework for Madeira Island case studies. Source: authors.

6. DISCUSSION

The main implication of the synthesis is that green building in insular territories should be evaluated through a broader territorial metabolism. Energy-efficient buildings may still contribute to risk if they accelerate runoff, increase soil sealing or occupy areas required for hydraulic functioning. Conversely, ordinary buildings can support climate adaptation when they incorporate permeable surfaces, delayed discharge, rainwater reuse and compatibility with drainage corridors. This shift is especially important in Madeira, where urban valleys and steep watersheds create a direct connection between land-use decisions and flood response.

Machico and Ribeira Brava also show that hydraulic resilience is not only a technical matter. It is a governance and planning issue. Strategic urban rehabilitation, housing policy, land-use monitoring and maintenance of watercourses all influence the degree to which the built environment can coexist with intense rainfall. This means that green-building guidelines should be coordinated with municipal master plans, rehabilitation programmes, flood-risk mapping and civil-protection requirements. The synthesis therefore supports a more cautious and operational link between architectural sustainability, hydraulic engineering, urban planning and territorial management.

The terminology of blue-green infrastructure is used here in a restricted and established sense: a strategically planned network of natural, semi-natural and engineered spaces that can provide stormwater regulation, ecological connectivity, thermal moderation and other ecosystem services. Within the scope of this paper, only the water-management function is developed in detail. Examples relevant to the Madeiran cases include green roofs, vegetated swales, detention basins, infiltration trenches, permeable pavements, riparian buffers, controlled discharge systems and maintained riverbeds. In compact island settlements, these elements should be designed as a network because individual measures may be insufficient when downstream capacity is limited.

A further point concerns monitoring. Several Madeiran basins are sensitive to short-duration rainfall, sediment transport, vegetation blockage and rapid changes in channel condition. Green-building strategies should therefore include post-occupancy and post-

construction hydraulic monitoring, particularly for larger developments or rehabilitation areas. Monitoring can connect rainfall, water level, flow, soil moisture and drainage performance, making it possible to adjust maintenance and design standards over time. This adaptive dimension is consistent with contemporary resilience thinking and with the need to move from static compliance to performance-based management [1,12].

7. RECOMMENDATIONS FOR GREEN BUILDING PRACTICE IN MADEIRA

Based on the synthesis developed in the previous sections, the following practical recommendations are proposed for future building and urban rehabilitation projects in Machico, Ribeira Brava and comparable insular municipalities:

1. Include a drainage statement in relevant building or rehabilitation projects, identifying pre-development and post-development runoff conditions.
2. Minimize or compensate impervious surfaces through retention, infiltration, delayed discharge or rainwater reuse.
3. Preserve emergency overland flow routes and avoid barriers across natural or artificial drainage lines.
4. Protect basement levels, access ramps and underground parking where local flood exposure justifies additional design measures.
5. Design public space as part of the storage and conveyance system, rather than merely transferring runoff to downstream networks.

At municipal level, planning instruments should require that green-building certification or sustainability assessment includes water-resilience criteria. These criteria should be adapted to island morphology and should not be copied mechanically from flat continental contexts. In steep catchments, the decisive issue is often the speed of concentration and the limited space available for detention. Therefore, distributed source control is essential, but it must be complemented by downstream capacity analysis, maintenance plans and emergency routing. Ribeira Brava demonstrates the relevance of detention basin sizing and roughness adjustment, while Machico demonstrates the importance of land-use control and rehabilitation strategies [5,7,8,10].

Table 2 presents a concise design-oriented checklist that can be used in early project appraisal. It is intentionally simple, because conference papers should provide transferable criteria that can be operationalised by architects, civil engineers, municipal planners and infrastructure managers.

Table 2. Green-building and hydraulic-resilience checklist for insular urban territories.

Scale	Recommended criterion	Expected resilience contribution
Building plot	Limit imperviousness and include retention or infiltration	Reduces peak runoff generated at source
Building envelope	Use roof drainage, green roofs or rainwater reuse where feasible	Delays discharge and supports resource efficiency
Public space	Use permeable pavements, swales and safe overland flow paths	Improves storage and emergency conveyance

Scale	Recommended criterion	Expected resilience contribution
River corridor	Preserve access, roughness control and channel maintenance	Maintains hydraulic capacity during intense rainfall
Municipal planning	Link permits to catchment-scale hydraulic constraints	Prevents cumulative risk from isolated developments
Monitoring	Install rainfall, flow or water-level monitoring in critical basins	Supports adaptive maintenance and evidence-based design

8. CONCLUSIONS

This paper developed a synthesis linking green building strategies with hydraulic resilience in Madeira Island, using Machico and Ribeira Brava as principal references. The analysis shows that, in insular urban territories, the sustainability of buildings depends on their hydrological and hydraulic integration with the surrounding catchment. Green building should therefore be interpreted not only as a building-performance agenda, but also as a territorial water-management strategy.

Machico highlights the importance of land-use evolution, urban rehabilitation, river-course occupation and hydraulic roughness in shaping flood vulnerability. Ribeira Brava highlights the value of morphometric analysis, detention basin sizing, drainage-capacity assessment and mitigation through hydraulic planning. Together, the two cases demonstrate that building-scale measures and catchment-scale interventions must be designed as a coherent system.

The main contribution of the paper is the proposed catchment-to-building framework. It places permeability, retention, controlled discharge, river-corridor maintenance and monitoring at the centre of green-building practice in island regions. This framework is especially relevant for territories with steep slopes, limited land availability, intense rainfall and rapid runoff response. Future work should develop quantitative performance indicators for applying this framework to municipal licensing, rehabilitation programmes and building-sustainability assessment in Madeira and comparable ultraperipheral regions.

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Research paper

RESERVOIR SEDIMENTATION AS A GREEN-DAM PERFORMANCE INDICATOR: BOVAN CASE STUDY

Milica Marković[1], Jelena Marković Branković[2], Mladen Milanović[3]

Abstract *Existing dams are usually assessed through structural safety, operation and maintenance, while the long-term performance of their reservoirs is often treated as a secondary issue. This paper places the reservoir at the centre of green-dam assessment and uses storage-capacity loss, storage-zone depletion and proximity to functional thresholds as complementary performance and risk indicators. Bovan Reservoir is analysed as the main case study and quantitatively compared with Bresnica and Rastovnica Reservoirs. The comparison shows that absolute sediment volume alone is not sufficient, because the consequences of sedimentation depend on reservoir size, useful storage, dead storage, intake elevation and operating rules. Bovan exhibits a substantial long-term reduction in storage, while Bresnica illustrates rapid depletion of dead storage and Rastovnica shows a sedimentation trend affecting the intake-related lower storage zone. Initial and updated storage-capacity curves are used to visualise these differences and demonstrate why repeatable bathymetric surveys are essential for reservoir management. A low-resource green/smart framework is proposed, prioritising updated reservoir geometry, reliable monitoring, data continuity, sediment-aware operation, catchment erosion-control measures and appropriate outlet management before advanced digital modelling is introduced. The results indicate that storage loss and reservoir sedimentation can serve as practical indicators of long-term reservoir performance when interpreted relative to reservoir size, storage zones and functional thresholds.*

Key words: *reservoir sedimentation, storage-capacity curve, reservoir sustainability, green-dam, smart monitoring*

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1. INTRODUCTION

Existing dams are commonly assessed through structural safety, operation and maintenance, but the long-term performance of their reservoirs is often treated as secondary. Reservoirs are the functional storage component of dam systems: they support water supply, flood attenuation, low-flow augmentation, irrigation and energy production. Sedimentation progressively modifies reservoir geometry and the elevation-storage relationship, reducing usable volume and, in smaller reservoirs, moving sediment toward dead-storage, intake and outlet elevations. Storage loss is therefore both an infrastructure-performance issue and a loss of climate-adaptation capacity.

Dam-safety guidance emphasises surveillance and structured operation [1]. Recent studies address uncertainty in bathymetric reconstruction [2] and demonstrate the use of updated elevation–area–capacity relationships for assessing reservoir-capacity loss [3]. Sustainable service-life extension and sediment-management strategies remain central reservoir-management objectives [4,5]. Long-term storage dynamics and repeat monitoring are further emphasised in recent global and technical studies [6,7], while global assessments confirm that sediment-related storage loss is a widespread problem [8].

This paper applies a reservoir-focused perspective to Bovan and quantitatively compares it with Bresnica and Rastovnica [9-12]. The aim is to compare harmonised storage-loss trends, functional thresholds and monitoring needs across reservoirs of very different size. Existing approaches, however, rarely combine storage-capacity loss, functional storage thresholds and monitoring readiness into a single low-resource assessment framework for existing reservoirs. The contribution is an indicator framework that separates storage performance, functional risk, monitoring reliability and management response, and links them to capacity-curve change and reservoir-specific thresholds.

2. GREEN-DAM CONCEPT FOR EXISTING RESERVOIRS

In this paper, the term green-dam does not denote a formal regulatory classification or an internationally standardised sustainability label. It is used as an author-proposed, reservoir-centred conceptual framework for assessing how storage preservation, monitoring reliability and operational response contribute to the long-term sustainability and climate resilience of existing dam–reservoir systems. The framework complements, but does not replace, established dam-safety and reservoir-management procedures. The green-dam concept used here is reservoir-centred: an existing reservoir should continue to deliver its intended services without avoidable loss of storage, excessive intervention or unmanaged risk. For multipurpose systems, this means preserving useful storage, dead-storage protection, flood-reception space and access to intake and outlet elevations. The smart component is pragmatic: measurements must be functional, traceable, quality-checked and connected to decisions before advanced analytics are introduced. Reservoir sedimentation is a

suitable indicator because it integrates catchment erosion, inflow conditions, geometry and operation into an observable change in storage. Repeated elevation-storage curves show whether the reservoir is retaining its functional buffer or moving toward a critical threshold. Four indicator groups are distinguished. Performance indicators quantify loss of reservoir service; risk indicators describe proximity to physical limits; monitoring indicators describe the reliability and timeliness of evidence; and management indicators describe the operator's capacity to respond through level control, outlet operation and catchment measures.

Table 1. Reservoir-focused indicator framework used in this study.

Indicator group	Indicator	Unit	What it measures	Screening / physical trigger
Storage performance	Relative storage loss, L_v	%	Loss of capacity at a common within-reservoir reference elevation	Management review at $L_v \geq 10\%$ (screening)
Storage-zone risk	Dead-storage depletion, L_D	%	Share of the original sediment-buffer volume consumed	Management review at $L_D \geq 50\%$; physical limit at 100%
Intake risk	Vertical intake buffer, B_i	m	Separation between the sediment surface and intake elevation	Detailed local survey at $B_i \leq 2$ m; physical limit at $B_i \leq 0$
Flood-space performance	Flood-space loss, L_F	%	Reduction in designated flood-reception capacity	Operating-rule review at $L_F \geq 10\%$ (screening)
Monitoring reliability	Survey gap, G_s	yr	Time since the last compatible bathymetric survey	New survey when G_s exceeds the planned or risk-based interval

In this study, L_v is calculated for Bovan, Bresnica and Rastovnica, while L_D is calculated for Bresnica and Rastovnica. The indicators B_i, L_F and G_s remain proposed framework components because compatible data were unavailable. The author-defined screening thresholds are not regulatory limits: 10% denotes a double-digit loss of service capacity, 50% denotes consumption of half of the designated sediment buffer, and 2 m represents an early-warning intake buffer. All thresholds require site-specific calibration.

3. METHODOLOGY: RESERVOIR-FOCUSED ASSESSMENT

The methodology is a semi-quantitative reservoir assessment for cases with incomplete digital archives but available technical reports, bathymetric surveys and observation records. The required inputs are initial and updated elevation-storage data, survey intervals, storage-zone limits, intake and outlet elevations, water-level operation and monitoring status. Five steps are used: (1) define reservoir functions and storage zones; (2) reconstruct and compare capacity curves; (3) evaluate physical and management thresholds; (4) assess operational and sedimentation-monitoring readiness; and (5) translate the observed trend into management priorities. A physical threshold is the point at which function is directly affected, while a management threshold is an earlier trigger for a survey, operating adjustment or intervention.

3.1. Quantitative reservoir indicators

All inter-reservoir values were calculated from initial and updated elevation-storage ordinates. Source documents were used as measurement data sets; their published annual rates were not adopted because their reference volumes and calculation bases were not fully harmonised.

$$\Delta V_r = V_{0,r} - V_{t,r} \quad (1)$$

$$L_{V,r} = \frac{\Delta V_r}{V_{0,r}} \times 100 \quad (2)$$

$$r_V = \frac{L_{V,r}}{\Delta t} \quad (3)$$

$$L_X = \frac{X_0 - X_t}{X_0} \times 100 \quad (4)$$

$$B_I = z_I - z_{b,max} \quad (5)$$

In Equations (1)-(5), V_o and V_t denote storage at the same reference elevation z_r; Δt is the survey interval; X represents useful (U), dead (D) or flood-control (F) storage; z_i is intake elevation; and $z_{\beta,max}$ is the highest measured bed or sediment elevation in the intake zone. The annualised rate r_v is a linear average. For each reservoir, $V_o(z_r)$ and $V_t(z_r)$ were evaluated at the same elevation by linear interpolation between tabulated ordinates. B_i was not calculated where reliable intake-zone sediment elevation was unavailable. Bovan uses current observation evidence and the detailed sedimentation survey [9,10]; Bresnica and Rastovnica provide the quantitative comparison [11,12]. The technical reports cited as references [9]–[12] are non-open institutional documents. Access to the complete reports is subject to permission from the report owner and the responsible institution and may be requested through the corresponding author.

4. CASE STUDY: BOVAN RESERVOIR

Bovan Reservoir is formed on the Moravica River near Aleksinac, Serbia, by a rockfill dam with a central clay core [9,10]. The reservoir extends for about 6.5 km and is operated as a multipurpose regional water-storage system. Its total design volume is approximately 60 hm³ and its useful volume approximately 41 hm³. The reported values of approximately 60 hm³ total storage and 41 hm³ useful storage are nominal design values assigned to project-defined reservoir storage zones. They were used only as general reservoir descriptors and were not used in the capacity-loss calculation. The reconstructed elevation–storage curves represent cumulative storage below each tabulated elevation. At the selected reference elevation of 252.50 m a.s.l., the initial and updated curves give cumulative volumes of 30.100 hm³ and 24.410 hm³, respectively. The nominal design-zone volumes and the curve-derived cumulative volumes therefore represent different storage definitions and should not be compared directly. The capacity-curve analysis uses 252.50 m a.s.l. as the normal-pool reference elevation; the minimum operating level is 243.00 m a.s.l. and the spillway crest is at 258.50 m a.s.l. Because water supply, flood protection, low-flow augmentation, irrigation and energy-related functions share the same storage resource, long-term reduction of the elevation-storage curve reduces operational flexibility across several

services at once. Bovan is therefore suitable for a reservoir-focused green-dam case study in which the main questions are how much capacity has been lost, where the loss is located, and whether monitoring and operation can detect and respond to further change.

5. RESULTS: RESERVOIR STORAGE CHANGE AND SEDIMENTATION

5.1. Bovan reservoir operation and monitoring context

The reviewed technical observation data show that Bovan Reservoir operated within a relatively narrow water-level band (251.01-253.72 m a.s.l.) compared with the available operating range [9]. This matters because water-level persistence affects flood-reception capacity, sediment residence time and the elevation zones in which material is deposited. The reservoir-monitoring chain is broad but incomplete. Available evidence identifies interruptions in SCADA/data transfer, non-functional or damaged instruments and missing sedimentation measurements relative to the intended survey rhythm [9]. Operational monitoring and sedimentation monitoring must be distinguished: SCADA can provide water levels, inflows, outflows, precipitation and outlet-operation records, whereas direct change in reservoir geometry still requires compatible bathymetric or profile surveys. Their integration is necessary, but SCADA alone cannot quantify sediment deposition.

5.2. Comparative reservoir sedimentation and storage-capacity change

At the selected reference elevation of 252.50 m a.s.l., the reconstructed Bovan capacity curves give V_0 = 30.100 hm³ and V_t = 24.410 hm³.

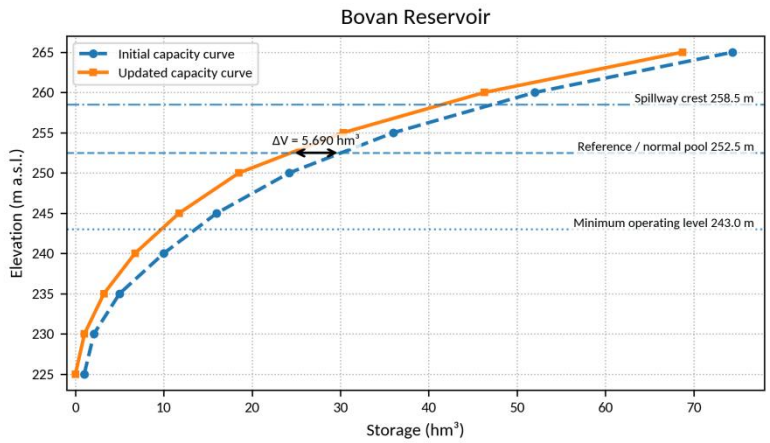


Figure 1a. Bovan capacity curves with ΔV at z_r = 252.50 m a.s.l. and selected operating elevations

The comparison of the elevation–storage relationships indicates a capacity reduction of 5.690 hm³ at the selected reference elevation. This corresponds to a relative storage loss of L_v = 18.90% and an average annualised relative loss of r_v = 0.73%/yr over the adopted 1984–2010 interval. Bresnica Reservoir, in the Prokuplje

area, has a reported total storage of approximately 1.344 hm³ and supports water supply, flood protection, sediment retention and low-flow augmentation. Rastovnica Reservoir, also near Prokuplje, has a reported total storage of approximately 0.468 hm³ and supports water supply, flood protection and sediment retention [11,12].

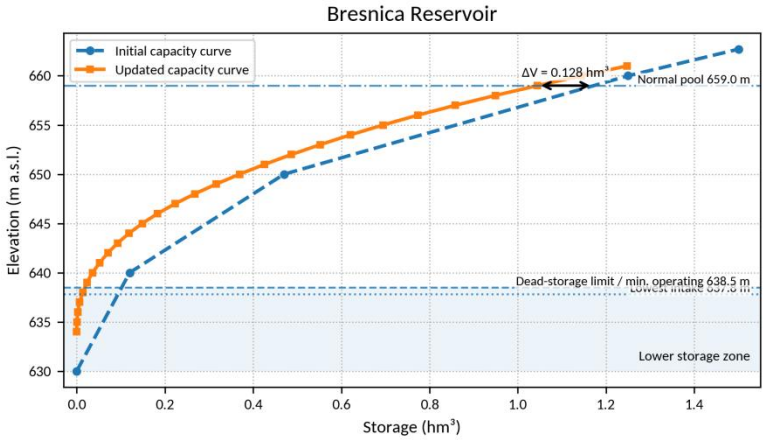


Figure 1b. Bresnica capacity curves with ΔV at z_r = 659.00 m a.s.l., the lower-storage boundary and lowest intake

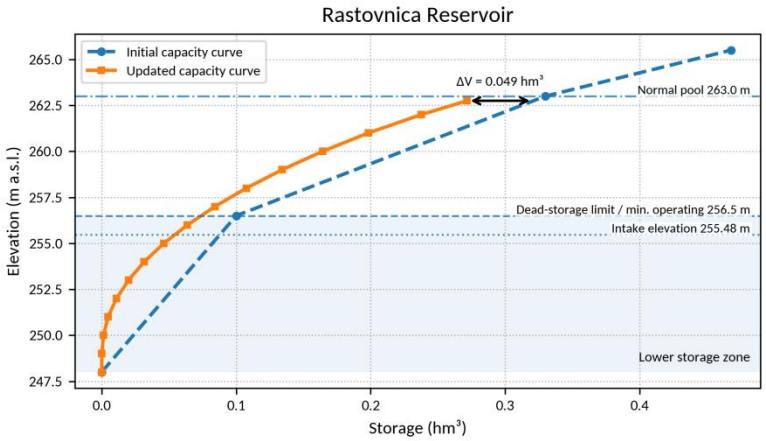


Figure 1c. Rastovnica capacity curves with ΔV at z_r = 262.75 m a.s.l., the lower-storage boundary and intake elevation

For Bresnica Reservoir, the common reference elevation is the normal pool at 659.00 m a.s.l. The calculated values are V_o = 1.172 hm³ and V_t = 1.044 hm³, giving ΔV = 0.128 hm³, L_v = 10.89% and r_v = 0.38%/yr over 29 years. The lower zone is more critical than the overall rate: at the dead-storage limit of 638.50 m a.s.l., the remaining volume is approximately 0.018 hm³ compared with an initial 0.090 hm³, which corresponds to L_D = 79.65%. For Rastovnica Reservoir, 262.75 m a.s.l. was selected because it is the highest common elevation supported by the updated curve. The calculated values are V_o = 0.321 hm³ and V_t = 0.272 hm³, giving ΔV = 0.049 hm³, L_v = 15.40% and r_v = 0.81%/yr over 19 years. At the 256.50 m a.s.l. lower-storage boundary, approximately 0.074 hm³ remains from an initial 0.100 hm³, corresponding to L_D =

25.97%. The intake elevation of 255.48 m a.s.l. is therefore a physical threshold that warrants focused local bathymetric control.

Figures 1a-1c were reconstructed from the tabulated elevation-storage ordinates in the available surveys. They are used for trend comparison rather than high-resolution sediment-volume modelling. The displacement between the curves quantifies capacity loss at a common elevation, while the horizontal reference lines show how the same loss acquires different functional meaning in the lower, useful and flood-related storage zones. The harmonised comparison confirms that absolute loss alone is insufficient. Bovan has the largest absolute and relative capacity reduction at the selected reference elevation, Rastovnica has the largest annualised relative loss among the smaller reservoirs, and Bresnica has the most advanced depletion of the designated dead-storage zone.

Table 2. Harmonised storage-capacity indicators.

Reservoir	z_r (m a.s.l.)	Δt (yr)	V_o (hm^3)	V_t (hm^3)	ΔV (hm^3)	L_v (%)	r_v (%/yr)
Bovan	252.50	26 (1984-2010)	30.100	24.410	5.690	18.90	0.73
Bresnica	659.00	29 (1983-2012)	1.172	1.044	0.128	10.89	0.38
Rastovnica	262.75	19 (1992-2011)	0.321	0.272	0.049	15.40	0.81

All values were calculated with the same procedure at a common elevation within each reservoir. r_v is a linear annualised average. The reference elevation differs among reservoirs because each initial and updated curve is compared at the same physically meaningful elevation within that reservoir. Inter-reservoir comparability is achieved through the normalised indicator L_v, not using a common absolute elevation. For Rastovnica, the baseline capacity information originates from the earlier zero-survey documentation, whereas the adopted 19-year sedimentation interval corresponds to reservoir operation from 1992 to the 2011 survey.

5.3. Interpretation of reservoir trends

The normalised results demonstrate that reservoir size changes the meaning of sedimentation. Bovan has the largest absolute loss (5.690 hm^3) and the largest relative loss at the selected reference elevation (18.90%). Rastovnica loses only 0.049 hm^3, but its annualised relative loss is 0.81%/yr, while the intake elevation represents an important physical threshold requiring local bathymetric control. Bresnica has the lowest annualised total-capacity loss, yet 79.65% of its initial dead-storage volume has already been depleted. These are different expressions of the same reservoir-sustainability problem. A physical threshold is reached when reservoir function is directly affected, for example when dead storage is fully consumed or the sediment surface reaches an intake elevation. A management threshold is set earlier to trigger a new survey, operational adjustment or intervention. In this screening framework, $L_v \geq 10\%$, $L_D \geq 50\%$, $B_i \leq 2$ m or an exceeded survey interval justify management review, while $L_D = 100\%$ and $B_i \leq 0$ represent physical limits.

6. RESERVOIR-FOCUSED GREEN/SMART UPGRADE PRIORITIES

For Bovan, the priority is a traceable reservoir baseline: verified capacity curves, reference elevations, survey geometry and an explicit schedule for repeat bathymetry. The second priority is continuous operational monitoring through water-level, inflow, outflow, precipitation and outlet-operation records. The third priority is to integrate these operational data with direct sedimentation surveys so that capacity changes can be interpreted in relation to hydrological events and reservoir operation. SCADA should therefore be treated as the operational-monitoring component of an integrated system, not as a substitute for bathymetry. SCADA explains when and under which operating conditions sedimentation pressure occurs; repeat bathymetric surveys show where reservoir geometry and capacity have changed. This reservoir-centred pathway is consistent with sustainable sediment-management literature, which emphasises repeat monitoring, sediment routing, outlet operation and catchment measures selected according to reservoir geometry and functional objectives [5-7]. For Bovan, these measures should be evaluated as coordinated storage-preservation actions rather than isolated maintenance tasks [9,10]. The practical assessment-to-action sequence consists of baseline verification, integrated monitoring, indicator updating, threshold review and reservoir-management response.

Table 3. Proposed reservoir-focused assessment-to-action sequence for Bovan Reservoir.

Step	Assessment-to-action stage	Recommended action	Expected green/smart benefit
1	Baseline verification	Verify reference elevations, capacity curves, survey intervals and threshold definitions.	Creates an auditable basis for storage-loss assessment.
2	Operational monitoring	Restore SCADA/telemetry for levels, inflows, outflows, precipitation and outlet operation.	Links reservoir operation to sediment-sensitive hydrological events.
3	Sedimentation monitoring	Repeat compatible bathymetric/profile surveys on a risk-based cycle.	Directly measures geometry change and capacity loss.
4	Capacity and threshold update	Recalculate capacity curves, L_v, $r_v$and storage-zone indicators after each survey.	Tracks approach to dead-storage, intake and flood-space thresholds.
5	Sediment-aware operation	Review dispatch rules and use low-level outlets where technically and environmentally appropriate.	Reduces deposition in critical zones and preserves operating flexibility.
6	Catchment and maintenance response	Combine erosion-control measures with access, vegetation and instrument maintenance.	Addresses sediment production and keeps the monitoring system functional.

7. DISCUSSION

The Bovan case shows that the green value of an existing dam is inseparable from the condition of its reservoir. A structurally serviceable dam cannot maintain water-security, flood-management and low-flow functions if the storage space that supports those services is progressively lost. Preserving capacity should therefore be treated as a core performance objective alongside structural safety. Potential sustainability benefits

of preserving existing capacity include delaying the need for replacement storage, avoiding part of the material and land-use impacts associated with new construction, retaining existing water-security services and reducing additional development pressure on the catchment. These are potential benefits of storage preservation; they were not quantified through a life-cycle assessment in this study.

The comparison with Bresnica and Rastovnica shows why a universal sediment-volume threshold is inappropriate. Large reservoirs require attention to absolute loss and multipurpose operating flexibility, whereas small reservoirs may reach dead-storage or intake thresholds after much smaller absolute deposition. Capacity curves and functional elevations provide the common basis needed to compare those different situations. The main limitation is data heterogeneity. The surveys differ in reference elevations, measurement intervals, profile density and reporting detail. The present analysis reduces this problem by recalculating all comparison values at a common elevation within each reservoir and by using the same equations, but it does not constitute a fully normalised sediment-yield model. The calculated rates are long-term linear averages and should not be interpreted as evidence of constant annual deposition. The resulting hierarchy is practical: establish a reliable capacity baseline; maintain compatible bathymetric surveys; connect storage loss with physical and management thresholds; integrate operational monitoring; and only then introduce predictive modelling or digital-twin tools. This sequence keeps reservoir function, rather than technology, at the centre of decision-making.

8. CONCLUSIONS

This paper proposed a reservoir-focused low-resource framework for evaluating existing dams as green and smart infrastructure. The results indicate that reservoir sedimentation can serve as a practical indicator of long-term reservoir performance when it is expressed through harmonised storage loss, capacity-curve change and proximity to functional thresholds. For Bovan Reservoir, the calculated comparison at 252.50 m a.s.l. gives a capacity loss of 5.690 hm^3, or 18.90%, and an average annualised relative loss of 0.73%/yr over 26 years. The priority is to reconnect compatible bathymetric surveys, capacity-curve updating, operational monitoring, dispatch rules and outlet management so that the remaining useful and flood-related storage can be preserved. Bresnica and Rastovnica demonstrate that smaller reservoirs may become functionally vulnerable even when absolute losses are modest. Bresnica has lost 79.65% of its initial dead-storage volume, while Rastovnica combines a 15.40% relative loss at the selected reference elevation with an intake-related lower-storage constraint. These results support the use of reservoir-specific physical and management thresholds. The comparison should be interpreted as a reservoir-management screening framework rather than a fully normalised sediment-yield assessment. Its main contribution is a transparent procedure that separates measurement data, calculations, functional thresholds and management responses. Once those elements are maintained consistently, more advanced digital tools can be introduced on a sound technical basis.

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TOPIC 06

SMART & CLIMATE-ADAPTED CITIES

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

LOCAL AND NATIONAL RESPONSIBILITIES FOR CLIMATE CHANGE ADAPTATION MEASURES IN SERBIA'S PUBLIC HEALTH SECTOR

Sonja Novak[1], Borislava Blagojević[2], Maja Nikolić[3]

Abstract

This article presents a typology of public health measures for climate change adaptation based on the Handbook for Climate Change Adaptation Planning in Local Communities in Serbia. A major issue addressed in the paper is the lack of clarity in the Handbook regarding which measures fall under national responsibility, local self-government, or require joint implementation. By structurally analyzing 24 key public health measures listed in the Handbook, the research challenges the traditional notion that protecting public health from climate extremes is solely the domain of a centralized healthcare system. Instead, it demonstrates that effective climate adaptation in Serbia depends on vertical coordination: the national level establishes the legislative and informational framework, while local governments act as the frontline operational defense through autonomous, context-specific measures. The paper also discusses measures that professionals in urban planning, architecture, and related civil engineering disciplines can realistically plan and execute as vital, non-pharmacological epidemiological tools in addressing 21st-century public health challenges. The proposed typology and matrix provide a practical guide for local self-government units in Serbia to implement climate adaptation strategies effectively. This framework supports future research aimed at empirically quantifying the health and economic benefits of local adaptation measures as multisectoral, built-environment-based interventions that jointly contribute to climate resilience and public health protection.

Key words: *public health, climate change adaptation measures, local level, national level*

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1. INTRODUCTION

By the end of the 21st century, climate change is no longer viewed exclusively as an environmental or economic challenge, but rather as one of the greatest contemporary threats to public health (PH) [1]. Global trends within the "Healthy Cities" concept and the sustainable development agenda emphasize that, among other factors, urban design, green spaces, transport systems, and building design can determine population health outcomes [2]. Under conditions of pronounced climate anomalies, phenomena such as urban heat islands (UHI) dramatically increase cardiovascular and respiratory morbidity and mortality, particularly among vulnerable population categories. Consequently, the "Health in All Policies" approach is increasingly gaining traction worldwide, requiring medical prevention and epidemiological surveillance measures to be integrated into all aspects of settlement/city planning and design—ranging from urban planning and architecture to communal infrastructure and the way public spaces are constructed and maintained.

The Republic of Serbia is located in the Southeast Europe region, which has been identified as a global climate "hotspot" with a warming rate that exceeds the global average [3]. Extreme heatwaves, prolonged periods of drought, and the emergence of new vector-borne infectious diseases (such as West Nile fever) have become a regular epidemiological reality in the country [4]. Following global and European regulatory pathways, Serbia made a significant stride forward by adopting the umbrella Law on Climate Change [5], which formally obligates both national and local authorities to adopt programs and action plans for adaptation to changed climate conditions.

However, despite a solid legislative foundation, a gap remains in the operational implementation of PH measures on the ground [6]. While strategic documents and early warning systems are designed at the national level, actual implementation and the direct protection of citizens fall upon local self-government units (LSGUs). To facilitate this process, the Handbook for Climate Change Adaptation Planning in Local Communities in Serbia [7] was developed (herein referred to as "Handbook"). It outlines a methodological five-phases cycle for local adaptation and includes a catalog of measures across various sectors. Nevertheless, the stated measures relating to the PH sector frequently remain declarative or insufficiently elaborated regarding competencies and financing.

The primary objective of this paper is to establish a meaningful typology and operationalization matrix for 24 key PH measures listed in [7], to carry out a clear differentiation of levels of responsibility. The paper intention is to distinguish between measures within the autonomous competence of local self-governments and those dependent on higher, national authorities, providing an applicable roadmap for decision-makers when drafting local adaptation plans. The secondary paper objective is to identify PH measures falling in the broad ‘’green building’’ context. Previous analyses of spatial-epidemiological risks and the role of blue-green infrastructure in Serbia indicated a need to view local adaptation measures as actionable, built-environment-oriented PH interventions aligned with the principles of the green building concept [8].

2. METHODOLOGY

This paper applies the methodology of qualitative content analysis and the structural classification of public policies. The primary data sources used include umbrella legislative acts of the Republic of Serbia [5, 9], strategic reports from relevant institutions [1, 2, 3, 4], as well as the official Handbook [7].

The research was conducted through four successive analytical phases, combining document analysis, conceptual mapping, and competence-based classification.

1. Identification and Extraction of Measures

A total of 24 adaptation measures were extracted from the Handbook [7]. Measures were included if they directly or indirectly linked climate change impacts with PH outcomes or addressed vulnerabilities in the built environment. Extraction was performed separately by two researchers using a standardized template (ID, measure name, description, proposed level of competence). The final classification was reviewed jointly by both researchers and cross-checked against the relevant legal and institutional framework governing PH and local self-government competencies in Serbia.

2. Built-Environment Orientation Screening

Each measure was then assessed to determine whether it was built-environment-oriented, defined as involving: a) spatial or infrastructural interventions, b) building standards or construction practices, c) urban planning or design solutions, or d) technical competencies typically held by architects, urban planners, civil/environmental engineers, or PH professionals working on environmental determinants of health. Measures meeting these criteria were flagged for separate discussions, regardless of their governance level.

3. Conceptual Mapping to the Governance Structure

All measures were analyzed in relation to the vertical organization of public administration and the health system in Serbia, with attention to: a) legal mandates, b) institutional responsibilities, c) financing mechanisms, and d) operational capacities at national and local levels. This step provided the conceptual basis for competence classification.

4. Competence-Based Categorization (Typology)

Each measure was classified into one of three competence categories using a legal–financial test: 1) National - implementation requires legislative change, national-level regulation, or central financing; 2) Local - implementation is feasible within the autonomous competencies, budgets, and services of local self-government units; 3) Shared - implementation requires coordinated action, co-financing, or joint regulatory/operational responsibility between national and local actors.

This typology enabled a structured overview of adaptation measures relevant to PH and the built environment at the local level.

There are two limitations of applied methodology: 1) Qualitative extraction carries a risk of subjectivity; quantitative validation (e.g., surveying local services) is recommended for future studies; 2) The categorization of competencies does not account for variations in LSGU capacities (financial and human resources), which may affect the practical applicability of the measures.

3. RESULTS

The central result of this research is a structured Matrix of PH Measures and Levels of Operational Responsibility (Table 1), which directly links the proposed PH interventions and climate adaptation instruments with administrative execution levels in the Republic of Serbia.

Table 1. Matrix of Public Health (PH) Measures and Levels of Operational Responsibility

Measure ID	Measure Name	Description and Objective of the Measure	Primary Competence / Level of Application
PH1	Increasing investment in PH	Investing in PH is essential for preserving population health and preventing risk factors. Without adequate investments, future treatment costs for climate change consequences will be multiple times higher.	National level (Republic Budget, National Health Insurance Fund (NHIF), Ministry of Health)
PH9	Home care programs	During the summer, visits to elderly and lonely individuals should be intensified to monitor their health. Cooperation with social services helps mitigate the problem of social isolation during climate disasters.	Local level (LSGU home treatment services and local NGOs)
PH10	Helplines	Establishing info-lines enables citizens to quickly receive advice on protection against heatwaves. These services help streamline emergency cases toward appropriate healthcare centers.	Local level (Local institutes of PH / primary health centers)
PH11	Room cooling in institutions	It is necessary to install sun protection and thermal insulation in hospitals to protect both patients and staff. Utilizing plants for shade and adequate air conditioning are standards for preventing heat-related illnesses within buildings.	Shared level (Funds from republic/local capital projects)
PH12	Additional training for healthcare workers	Healthcare employees must learn to quickly recognize and manage symptoms of heat strain. Education is crucial for adapting clinical care to specific risks brought by the climate.	National level (CME - Continuous Medical Education, Medical Chamber)
PH13	Evacuation	It is necessary to draw up plans for relocating the most vulnerable groups in the event of extremely high temperatures. This measure requires coordination with civil protection services as a last resort for life protection.	Local level (Local emergency situations headquarters of the LSGU)
PH14	Ensuring stockpiles of medical resources	The system must maintain stable supplies of medications and materials for chronic patients following natural disasters. Efficient distribution of these resources is a priority for caring for the affected population.	National level (Central commodity reserves / NHIF liquidity)

Measure ID	Measure Name	Description and Objective of the Measure	Primary Competence / Level of Application
PH15	Early detection of infectious diseases	Efficient epidemiological surveillance enables timely risk identification and outbreak prevention. Systematic information gathering serves to plan emergency actions and mitigate health risks.	National level (Network of institutes led by the "Batut" Institute)
PH16	Sentinel epidemiolo-gical surveillance	This surveillance monitors disease trends within a specific segment of the population to assess the situation across the entire territory. A typical example is influenza monitoring, which aids in the early identification of climate-induced anomalies.	National level (Epidemiological protocols at the state level)
PH17	Syndromic surveillance	This method focuses on symptoms before an accurate diagnosis is established, enabling a faster systemic response. Although results can be non-specific, modern algorithms allow for quality early detection of disease clusters.	National level (Integrated Health Information System - IZIS)
PH18	Health vulnerability mapping	Utilizing GIS technologies helps visualize territories and groups most at risk. Mapping enables directing resources where community resilience deficiencies are greatest.	Local level (Drafting local geographical and demographic vulnerability maps)
PH19	Heatwave Early Warning System (HEWS)	HEWS serves to notify decision-makers and the public in time about upcoming dangerous temperatures. The system's goal is providing advice to the population to avoid fatal health outcomes.	Shared level (Republic Hydro Meteorological Service of Serbia - RHMSS data at the national level / Alerting and media at the local level)
PH20	Early warning system for natural hazards	This system monitors and predicts occurrences such as floods, storms, and droughts to protect lives. Timely information dissemination precedes the decision-making process regarding evacuation or other protective measures.	Shared level (RHMSS, Sector for Emergency Management of the Ministry of Interior / Alerting and media at the local level)
PH21	Warning system for vector-borne and waterborne diseases	Mathematical models utilize meteorological data to predict the occurrence of diseases like Lyme disease or foodborne infections. Forecasting helps in carefully selecting intervention strategies before mass morbidity occurs.	National level (Scientific institutes, veterinary and medical chambers)
PH22	Public awareness development	Informing citizens about climate risks to health is carried out through campaigns and communication strategies. Raising awareness helps individuals take self-protective measures in crisis situations.	Shared level (National TV campaigns / Local forums and flyers)

Measure ID	Measure Name	Description and Objective of the Measure	Primary Competence / Level of Application
PH23	Development of scientific and professional capacities	Multidisciplinary research is required to better understand and monitor climate effects on health. Generating reliable data is the first step in formulating successful national adaptation policies.	National level (Ministry of Science, universities, and project funding funds)
PH24	Community empower-ment	An active and organized community can significantly reduce risks and save lives during disasters. The goal is integrating adaptation measures into local development plans and ecosystem management.	Local level (Local communities/*Mesne zajednice*, local eco-initiatives, civil sector)

The quantitative distribution of the identified measures within the proposed matrix (Table 1) reveals a specific structure of institutional responsibility in the Republic of Serbia. Out of the 24 analyzed PH measures, the largest share of 45.8% (11 measures) falls under the primary and exclusive competence of the National level. On the other hand, 29.2% (7 measures) are located exclusively at the Local level as an autonomous competence of LSGUs, while the remaining 25% (6 measures) require a hybrid, i.e., Shared level of action. These data clearly point to a high centralization of surveillance instruments and financing, whereas operational implementation on the front line of defense is necessarily divided between local actors and shared platforms.

4. DISCUSSION

The obtained results of the quantitative distribution of competencies (45.8% national, 29.2% local, 25% shared level) indicate a structural challenge in managing climate risks adaptation in the Republic of Serbia. While legislative and epidemiological surveillance is highly centralized, population exposure and vulnerability are fundamentally localized phenomena. This fragmentation creates an operational vacuum that directly impacts the efficacy of preventive PH interventions.

Building upon the spatial concept of blue-green infrastructure and accompanying epidemiological risks [8], the results of this research point to the necessity of vertical synergy between national and local government levels in the Republic of Serbia so that the formal legal framework and methodological handbooks for climate adaptation can be operationally translated into concrete local health interventions.

Our three-tiered division of competencies from the results explains this problem:

National measures (PH1, PH2, PH5, PH6, PH12, PH14–PH17, PH21, PH23) depend entirely on central institutions (for instance, the Ministry of Health, Institute of Public Health of Serbia). Surveillance systems and the introduction of integrated information systems (IZIS) can be designed exclusively from the top of the management hierarchy.

Shared levels (PH3, PH4, PH11, PH19, PH20, PH22) represent the greatest operational challenge. For example, the Heatwave Early Warning System (HEWS, measure PH19) primarily utilizes data from the RHMSS, but its epidemiological

efficiency is insignificant unless the local self-government possesses a developed network for media alerting and cooling shelters.

Local autonomous measures (PH7–PH10, PH13, PH18, PH24) represent the first line of defense from climate treats. Identifying vulnerable groups through GIS mapping (PH18) and home care programs (PH9) fall under the exclusive competence of primary health centers and local centers for social work.

These patterns confirm that climate adaptation in PH cannot be fully understood through governance levels alone. A distinct analytical lens is needed for built-environment-oriented measures, whose implementation relies on spatial, infrastructural, and design-based interventions and therefore demands a separate examination of their feasibility and current practice in Serbia.

4.1. System Fragmentation and Challenges of the HEWS System (Measure PH19)

Although the adoption of the Law on Climate Change established the legal framework [5], the operational reactivity of the Heatwave Early Warning System (HEWS – measure PH19) is limited by a lack of horizontal and vertical integration at the local level. Meteorological warnings from the RHMSS are not automatically translated into specific epidemiological actions at the level of local self-government units [7]. For HEWS to have a real function in mortality reduction, data must be integrated with local health profiles and urban plans [1]. The absence of clear protocols for activating local media, the civil sector, and temporary "cooling stations" in urban areas neutralizes the predictive value of advanced models [10], i.e., without spatially targeted PH action, the information alone cannot reduce the rate of emergency hospitalizations among vulnerable groups [11].

4.2. Building Codes and Thermal Stress in Institutions (Measures PH4 and PH11)

Shared competence over infrastructure resilience (PH4) and room cooling (PH11) highlights the need to adapt building standards to rising summer temperatures. Domestic practice and energy efficiency regulations in Serbia traditionally focus on winter heat retention, while summer overheating is mostly addressed via energy-intensive active air conditioning [8]. From a PH perspective, heavy reliance on active cooling can worsen the urban heat island (UHI) effect through anthropogenic heat emissions and strain the power grid [2]. In addition to building-scale interventions, the immediate micro- urban environment of healthcare facilities - such as courtyards, tree canopies, permeable surfaces, and blue- green infrastructure - can further reduce thermal stress and complement passive cooling strategies [8, 14]. Therefore, incorporating bioclimatic parameters and passive cooling strategies into national building regulations represents a key systemic preventive measure. Empirical data shows that passive architectural interventions can reduce indoor temperatures by 2°C to 4°C [12], directly mitigating thermal stress for vulnerable patients in healthcare and gerontological facilities.

4.3. Spatial-Epidemiological Paradigm and GIS Mapping (Measure PH18)

Identifying health vulnerability through GIS technologies (PH18) represents a crucial bridge between urban planning and preventive medicine, but its application in Serbia at the LSGU level is sporadic and technically uncoordinated. Systematic mapping and analysis of urban heat islands in the territory of the City of Niš represent the starting baseline for defining specific local adaptation measures, which include the planned increase in the share of green and blue infrastructure elements within the urban fabric to mitigate heat stress and protect the health of the most vulnerable population groups [13]. The highest urban heat island risk typically emerges in areas with the greatest population density, where older adults and chronically ill residents are often concentrated. Yet, despite this spatial overlap of thermal exposure and vulnerability, local self-governments rarely cross-reference satellite thermal imagery with demographic data regarding the density of the population older than 65 and chronic patients [10]. Although classified as a local-level competence, in practice vulnerability mapping relies on nationally generated geospatial datasets and standardized frameworks, highlighting technical interdependence between national and local levels [10, 13].

Without precise local vulnerability maps, resource allocation (such as installing public drinking fountains, temporary water tankers, or planting tree lines) is carried out haphazardly, instead of being directed toward spaces with the highest heat stress index [7]. Clinical studies suggest that the spatial correlation of high land surface temperature and socio-economic isolation represents the most reliable predictor of the spatial distribution of cardiovascular mortality during summer months [14].

4.4. Blue-Green Infrastructure as a Non-Pharmacological Intervention (Measure PH24)

When community engagement (PH24) is integrated with Nature-based Solutions (NbS), blue-green infrastructure (BGI) shifts from a predominantly aesthetic urban element to a functional non-pharmacological PH intervention. Measures reflecting concepts such as green building, and blue-green infrastructure are particularly well represented in the Handbook [7], especially within the catalog dedicated to the urban environments sector. From the PH perspective, increasing the share of public green spaces and the revitalization of urban watercourses act as a primary, non-pharmacological preventive measure [8]. Trees and green areas perform evapotranspiration and provide shade, thereby effectively lowering ambient air temperatures by 3°C to 7°C within their radius of influence, dramatically reducing the risk of heat exhaustion [15]. According to PubMed data, increasing the normalized difference vegetation index (NDVI) in urban zones by 10% correlates with a statistically significant drop in all-cause mortality during extreme heatwaves, confirming that investing in urban greenery is a more economically justified measure than the secondary mitigation of health consequences [16, 17].

Finally, the synergy of the health and construction sectors at the local level should move beyond reactive crisis response and become a proactive framework in which

urban plans are recognized as core public-health tools. In this light, the classification offered here distinguishes the measures that rely on built-environment expertise from those that do not, defining the appropriate boundaries of professional responsibility.

5. CONCLUSION

This paper examined the role of public health measures in climate change adaptation in the Republic of Serbia through a structural analysis of 24 key measures, with particular emphasis on the interaction between the healthcare sector, local self-government units, and spatial planning instruments. The analysis assessed the institutional and operational mechanisms that support the protection of public health from climate-related hazards.

Based on the conducted analysis, the following conclusions can be drawn:

1. The results challenge the traditional perception that protection of public health from climate extremes is solely the responsibility of a centralized healthcare system. Effective adaptation requires coordinated action across multiple sectors and governance levels.

2. The success of climate change adaptation in Serbia largely depends on efficient vertical coordination. While the national level provides the legislative, strategic, and informational framework, local self-government units constitute the primary operational level responsible for implementing adaptation measures and responding to local climate-related risks.

3. Concepts such as green building, bioclimatic design, and blue-green infrastructure should be recognized not only as tools for improving energy efficiency, but also as important non-pharmacological public health interventions that can reduce climate-related health risks and strengthen community resilience.

The proposed matrix provides a practical framework for local self-government units in Serbia to support the implementation of the Adaptation Planning Handbook and the integration of health considerations into climate adaptation policies. Future research should focus on the empirical assessment of the health, social, and economic benefits of ecologically conscious urban and spatial planning solutions, thereby providing a stronger evidence base for policy development and implementation.

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Research paper

AN APPROACH TO SMART DAYLIGHT CONTROL IN MEMBRANE-COVERED SPORTS FACILITIES

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Abstract

The importance of daylight for occupant health and well-being and requirements for reduction of energy consumption has led to the development of innovative and sustainable solutions. In recent years, membrane structures have become increasingly popular for covering sports halls, and various other facilities due to their high daylight transmittance, fast construction, and lightweight. Unlike conventional roofs (which are generally solid and opaque), membrane envelopes, particularly those made of high-performance membrane materials, offer the possibility of using natural daylight as a primary light source during building operation . However, unwanted daylight penetration can also cause visual discomfort, glare, and an increased load on the cooling system if not managed appropriately. Accordingly, integrating smart daylight control strategies with membrane-covered structures represents a promising approach to energy-efficient and sustainable sports facilities. Based on the literature, intelligent daylight management systems could be a promising solution for improving the performance of membrane-covered sports halls. The integration of real-time environmental monitoring with adaptive lighting control can enhance visual comfort, optimize daylight utilization, and reduce energy consumption. Studies indicate that smart daylighting strategies applied in membrane facilities provides significant potential for improving indoor environmental quality and promoting the sustainable design of sports facilities. Given that numerous membrane-covered sports facilities have become popular in the last two decades, it is necessary to become familiar with innovative possibilities for controlling the optimal use of daylight and consequently optimal energy consumption. In this context, the present study aims to provide a methodological foundation for the implementation and quantitative validation of intelligent lighting control strategies, based on sensing occupancy detection and lighting control, in both existing and newly constructed sports facilities with membrane roofing systems.

Key words: *Daylight control, Membrane facilities, Smart lighting, Energy efficiency*

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1. INTRODUCTION

It is well established that light influences the behavior well-being, and visual performance of occupants. It enables the perception of space, shapes, and colors and provides the visual conditions necessary for performing a wide range of visual tasks. The benefits of using daylight include energy savings, reduced CO_2 emissions (CO_2 footprint) and health-related reasons [1-3]. Daylight distribution in facilities is mostly determined by structural and envelope characteristics, and daylighting design is a complex multidisciplinary task which requires balancing visual comfort, energy performance, and well-being of occupants [4,5]. Although natural daylight represents the most efficient and environmentally friendly light source, there are some disadvantages. Namely, its availability of daylight constantly changes across seasons, times of day, and weather conditions, making fixed lighting strategies insufficiently efficient. Also, excessive daylight may produce glare, non-uniform illuminance, overheating, and increased cooling loads, especially during summer periods. Design of daylight in sports halls therefore requires a balance between natural and artificial light, with particular attention to glare control, uniform illuminance, and solar heat gains [6].

On the other hand, the concept of smart building exists for several decades. It was created due to the growing need for improved occupant comfort, resource efficiency, and more effective building operation [7,8]. A key objective is the rational use of energy and other resources, which has become increasingly important because of rising energy demand and environmental concerns [9]. Buildings account for a substantial share of global energy consumption, while lighting represents an important component of electricity demand. Sports facilities are particularly demanding because they require appropriate illuminance levels over large indoor spaces and may operate from early morning until late evening [10,11]. Consequently, reducing electricity consumption associated with artificial lighting has become an important objective of sustainable building design [12].

The emergence of membrane structures represents a significant innovation, opening up new possibilities for the use of daylight. Given that these structures combine architectural flexibility with lightweight construction, they can be widely applied to various sports facilities. Unlike conventional opaque roofs, membrane envelopes transmit a considerable portion of visible light while maintaining structural efficiency [13]. These envelopes, particularly those made of high-performance membrane materials such as polytetrafluoroethylene (PTFE) or ethylene tetrafluoroethylene (ETFE), offer the possibility of using natural daylight as the primary light source during the operation of building. ETFE cushions may achieve visible light transmittance exceeding 90%, as it is presented in Figure 1 [14], whereas PTFE-coated fiberglass membranes typically provide diffuse transmission between 10% and 40%, depending on material composition and coating characteristics [14-16]. Despite these advantages, membrane-covered facilities present specific lighting and thermal challenges. Consequently, modern membrane-covered sports facilities increasingly integrate intelligent lighting systems, that enable the dynamically balancing natural and artificial lighting according to actual environmental conditions.

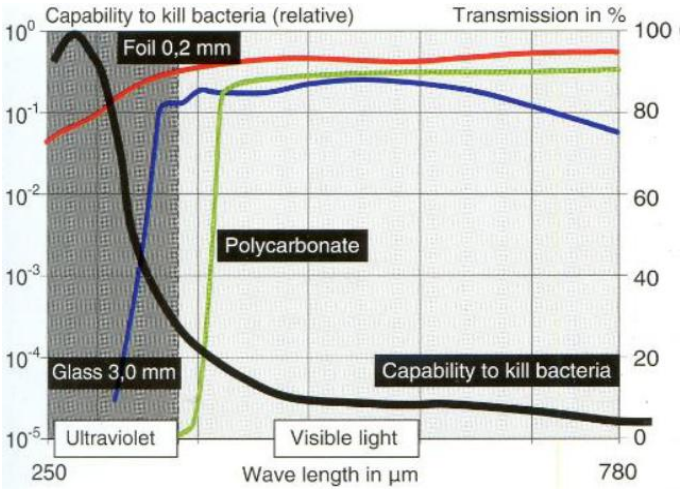


Figure 1. Light Transmittance of ETFE and Other Transparent Materials [14]

It should be emphasized that recent advances in sensing technologies, used for Internet of Things (IoT) devices, wireless communication, and Building Management Systems (BMS) have enabled the development of smart daylight control systems [17,18]. These systems can continuously monitor indoor illuminance, occupancy, weather conditions, and solar radiation and automatically adjust artificial lighting to maintain the required illumination levels while reducing unnecessary electricity consumption [17-21].

The application of daylight-control technologies is also influenced by geographical conditions, building use, user requirements, and applicable standards [11, 12]. Therefore, this paper focuses on the potential application of smart daylight control to membrane-covered sports facilities under real-world operating conditions. The study first reviews the principal characteristics of membrane sports facilities and relevant daylight-control technologies and then synthesizes these findings into a conceptual framework for integrating membrane architecture with intelligent lighting technologies. The proposed framework is intended as a conceptual basis for future implementation and quantitative validation rather than as an experimentally validated control system.

It should be emphasized that this study uses a focused narrative literature-review approach to identify and synthesize knowledge relevant to daylight control in membrane-covered sports facilities. Practically, the literature was organized into four thematic groups: (i) daylight, visual comfort, and human well-being; (ii) daylighting performance and membrane materials, with particular attention to ETFE and PTFE systems; (iii) intelligent lighting, occupancy sensing, IoT, and BMS-based control; and (iv) adaptive building-envelope and daylight-control technologies. Sources were selected according to their direct relevance to daylight performance, sports-facility lighting, membrane-envelope behavior, or intelligent control. The reviewed findings were compared qualitatively and then used to identify the functional components and information flows required for a conceptual smart daylight-control strategy.

2. MEMBRANE-COVERED SPORTS FACILITIES

In addition to computational structural analysis and fabrication technologies, improvements in polymer materials enabled significant development of membrane structures during the last three decades. The most frequently applied membrane materials include ETFE foil cushions, multi-layer pneumatic membrane systems, PTFE-coated fiberglass fabrics and PVC-coated polyester fabrics. The properties of ETFE make it mostly suitable for sports facilities requiring natural lighting [13,16,19]. This material is well suited due to its high optical transparency, low weight, chemical resistance, and long service life. ETFE cushions weigh less than 1% of equivalent glass surfaces while transmitting more than 90% of visible daylight.

However, the transmitted light depends not only on membrane material properties but also on solar altitude, curvature, orientation, contamination, aging, environment and surrounding reflections [13,19].

It should be mentioned that PTFE membranes typically produce highly diffuse illumination, reducing direct glare but transmitting less daylight overall. On the other hand, ETFE cushions allow considerably higher daylight penetration while maintaining excellent transparency. This property makes ETFE particularly attractive for large stadium roofs and enclosed arenas where maximizing natural lighting is desirable. Nevertheless, maximizing daylight transmission alone is not sufficient. High daylight availability may result in excessive illuminance levels exceeding recommendations specified in EN 12193 (also SRPS EN 12193:2019) for sports lighting, especially during clear summer days [12].

To overcome solar heat gains, modern membrane systems increasingly employ advanced solutions. Recent studies have investigated climate-adaptive ETFE facades. It is demonstrated that switchable ETFE systems can dynamically modify daylight transmission according to solar conditions, thereby simultaneously improving daylight availability and reducing glare [22]. Such adaptive envelope technologies represent an important step toward intelligent building envelopes capable of actively interacting with environmental conditions rather than functioning as passive structural elements.

3. SMART DAYLIGHT CONTROL SYSTEMS FOR MEMBRANE-COVERED SPORTS FACILITIES

The primary purpose of a smart daylight management system is to maximize the use of available natural daylight and also ensure that the illuminance required for different sports activities remains within the prescribed range. Unlike conventional lighting systems, which may operate at a constant output regardless of environmental conditions, an intelligent daylight-control system adjusts the artificial-light contribution according to measured indoor daylight, occupancy, and relevant environmental conditions [22-24]. This approach has been made possible by the development of IoT technologies, wireless sensor networks, and BMS systems, which enable (support) continuous monitoring of environmental parameters, rapid data processing, and automatic lighting adjustment without continuous user intervention [22-24].

In membrane-covered sports facilities, daylight availability is highly dynamic because membrane transmittance and solar exposure allow substantial changes in indoor illuminance. Consequently, intelligent lighting control can be particularly beneficial. A typical smart daylight-control system consists of four principal components: (a) a daylight-sensing subsystem, (b) occupancy monitoring, (c) an intelligent control algorithm, and (d) a dimmable LED lighting system, as presented in Figure 2.

Within the smart daylight-control system, indoor daylight sensors continuously measure horizontal illuminance on the playing surface or at representative measurement points. The measured daylight illuminance is transmitted to the lighting controller, which determines the required level of artificial lighting to maintain the illuminance specified for the relevant sports activity. If daylight is sufficient to meet the target, artificial lighting can be reduced to its minimum operating level or switched off when appropriate. During cloudy conditions or evening hours, the controller increases LED output to compensate lack of daylight.

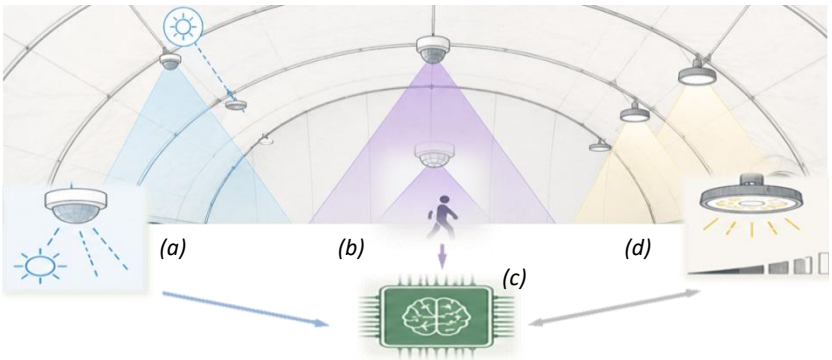


Figure 2. Typical smart daylight control system consists of four principal components: (a) daylight sensing subsystem, (b) occupancy monitoring, (c) intelligent control algorithm, (d) dimmable LED lighting system

Unlike conventional on/off control, continuous dimming allows for gradual transitions between lighting levels, preventing sudden changes that could distract athletes or spectators. It is evident that the use of a smart daylight control system can significantly reduce electricity consumption for lighting. However, the potential reduction in electricity consumption depends on climate, building orientation, membrane optical properties, occupancy, operating schedules, and the characteristics of the lighting system. Therefore, a specific percentage of savings should not be assumed without quantitative validation.

Another important fact is that sports halls are rarely in continuous use throughout the day. Instead, their operation generally involves alternating periods of intensive activity, maintenance, training, and the complete absence of users. Therefore, occupancy sensors represent another essential element of intelligent lighting systems which provide an additional control input. Commonly used technologies include: passive infrared (PIR) sensors, ultrasonic detectors, microwave sensors, camera-based occupancy estimation, and image-processing systems using artificial intelligence, as presented in Figure 3. When no occupancy is detected, the lighting system can reduce

its output to a predefined standby level or switch artificial lighting off, provided that the remaining illumination is appropriate for the intended activity.

It is important to mention that the really fast development of LED technology has fundamentally transformed sports lighting during the last two decades. Compared with metal-halide sources previously used in many sports facilities, LED systems offer high luminous efficacy, rapid switching, dimming capability, long service life, lower maintenance requirements, improved color rendering, and high operational reliability.

For daylight-control applications, one of the most significant advantages of LED technology is continuous dimming rather than operation only at full power. Modern dimmable LED luminaires equipped with appropriate electronic drivers can regulate luminous flux over a wide range [25]. Consequently, artificial lighting can supplement only the portion of the required illuminance that is not provided by daylight. In the proposed framework, the required artificial lighting contribution can be conceptually expressed as $E_{art} = E_{req} - E_{dl}$, where E_{req} is required illuminance, while E_{dl} is measured value of illuminance provided by daylight. Obviously, according to this mathematical expression, the smallest value of E_{art} is 0, because artificial lighting cannot have a negative value if the daytime brightness is higher than required. On the other hand, the normalized LED dimming command can be represented as E_{art} / E_{LEDmax} , where E_{LEDmax} represents the maximum illuminance that can be provided by the artificial lighting system. These relationships represent the control principle, but their coefficients and calibration would need to be determined experimentally for a particular sports hall.



(a) *(b)* *(c)* *(d)* *(e)*

Figure 3. Element of intelligent lighting systems: (a) passive infrared (PIR) sensors, (b) ultrasonic detectors, (c) microwave sensors, (d) camera-based occupancy estimation, and (e) image-processing systems using artificial intelligence

4. PROPOSED CONCEPTUAL SMART DAYLIGHT CONTROL STRATEGY

It is obvious that the introduction of innovative approaches in the control of daylighting in membrane-covered sports facilities has the potential to improve the utilization of natural light and reduce unnecessary operation of artificial lighting. Such a strategy could be incorporated during the design of new facilities and, subject to

compatibility with the existing electrical and BMS infrastructure, could also be introduced progressively into existing structures. The concept may therefore be relevant to existing school sports facilities, such as the physical education facility at the "Ivan Goran Kovačić" Elementary School (Figure 4) in the Nikola Tesla suburb of Niš.



(a) (b)

Figure 4. View of the physical education sport facility (a) exterior and (b) interior

Based on the reviewed literature, a conceptual smart daylight control strategy suitable for membrane-covered sports facilities is proposed. The framework integrates four information sources: indoor daylight sensors, an outdoor weather station, an occupancy monitoring system, and the BMS. The controller uses these inputs to determine whether the hall is occupied, estimate the available daylight, identify relevant environmental conditions, and adjust the artificial-light contribution accordingly.

The proposed control architecture is shown in Figure 5. An outdoor weather station can provide global solar irradiance, solar position, cloud-cover information, and outdoor temperature. Simultaneously, indoor sensors designed for continuous operation can measure horizontal illuminance on the playing surface or at representative points within the sports hall. Occupancy information determines whether the hall is in active use. The BMS provides operating schedules and interfaces with the lighting system. All sensor data are transmitted to a central controller, where the daylight-control algorithm calculates the required artificial-light contribution.

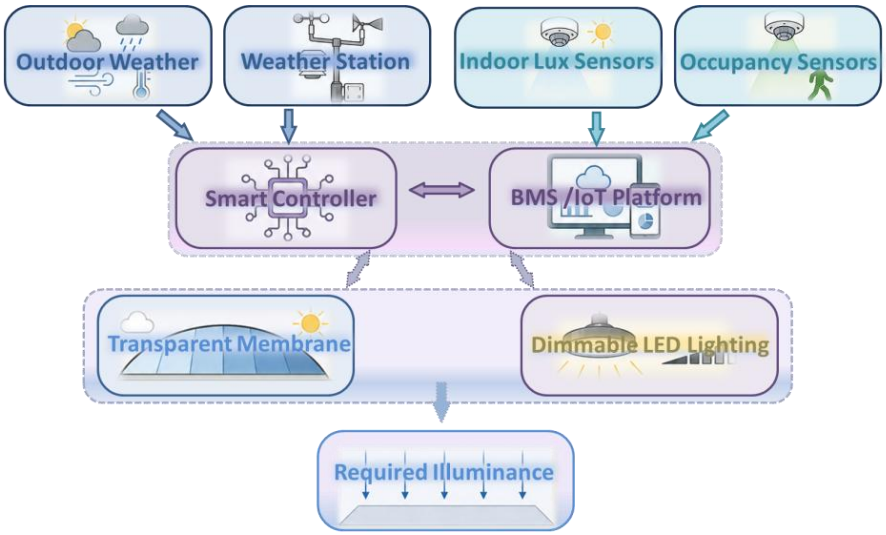


Figure 5. Conceptual smart daylight control strategy suitable for membrane-covered sports facilities

For occupied periods, the controller compares measured daylight with the target illuminance specified for the relevant sport or activity and adjusts the dimmable LED system accordingly. A short time delay or hysteresis should be incorporated to prevent rapid switching or oscillation caused by temporary fluctuations in daylight.

Furthermore, future implementations could utilize artificial intelligence algorithms capable of predicting daylight availability some time in advance, using weather forecasts and environmental data. Such predictive control may further improve the coordination of natural and artificial lighting, but its performance would need to be assessed experimentally and compared with simpler control strategies.

Although the proposed framework has not yet been quantitatively validated as a complete control system, in the future investigation it would be usefull to providesimultaneous long-term measurements of indoor illuminance, occupancy, and electrical lighting consumption under controlled comparison conditions. In addition, it would be useful to present calibrated simulations that quantify annual energy savings or improvements in visual comfort. Consequently, the potential benefits of the proposed strategy should be interpreted as a conceptual assessment based on the reviewed literature rather than as experimentally demonstrated performance. Quantitative validation should include multi-point illuminance measurements on the playing surface, outdoor solar irradiance and weather data, occupancy schedules, LED electrical power, and indicators of visual comfort such as illuminance uniformity and glare. Measurements should be conducted under representative seasonal and weather conditions and compared with a baseline operating mode without daylight-responsive control. Calibrated daylight and energy simulations could be used to extend th e assessment to annual performance and to test alternative membrane properties, sensor locations, control thresholds, and operating schedules.

5. CONCLUSION

Membrane-covered sports facilities have become an increasingly attractive architectural and structural solution because of their lightweight construction, rapid creation, and potential for extensive daylight diffusion. However, effective utilization of daylight requires control strategies capable of responding to continuously changing environmental and occupancy conditions. In this paper, an intensive literature review was used to recognize the principal requirements and technologies relevant to smart daylight management in membrane-covered sports facilities. Based on the studied indication, a conceptual control framework was developed that integrates indoor daylight sensors, occupancy detection, outdoor weather monitoring, dimmable LED luminaires, and BMS integration. The proposed conceptual strategy for smart daylight management defines a control principle for dynamically balancing natural and artificial lighting based on target illuminance levels and occupant presence. Future experimental and simulation-based validation is required to quantify energy performance, illuminance uniformity, visual comfort, and the influence of membrane optical properties. The framework can potentially be applied to both new and existing sports facilities as a basis for improving daylight utilization and lighting energy efficiency.

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Research paper

TOWARDS A SMART CITY: A FRAMEWORK FOR SMART FLOOD MANAGEMENT IN SARAJEVO

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Abstract

Rapid urban development and increasing hydro-meteorological variability are creating new challenges for flood risk management in urban areas. In this context, the concept of a smart city offers opportunities to improve the understanding, prediction, prevention, and management of flood events through the integration of environmental monitoring, digital technologies, data, modelling, and decision-support systems. However, becoming a "smart city" in terms of flood management requires more than the introduction of individual technological solutions. This paper explores what Sarajevo would need to develop an effective smart flood management system. The analysis considers the key components required for such a system, including reliable and spatially distributed meteorological and hydrological monitoring, real-time data acquisition and transmission, integration of heterogeneous data sources, high-resolution geospatial databases, hydraulic and hydrological modelling, flood forecasting and early warning, and decision-support tools for emergency response. Particular attention is given to the integration of existing monitoring and information systems and to the interoperability of data generated by different institutions and infrastructure systems. The paper further considers the importance of defining clear institutional responsibilities, data-sharing mechanisms, communication channels, and procedures for translating technical information into timely decisions. Rather than proposing a single technological solution, the paper identifies the essential components and their interconnections that should form the basis for Sarajevo's transition towards smart flood risk management. The proposed framework can serve as a basis for assessing the current level of preparedness and identifying priorities for future investments in monitoring, modelling, digital infrastructure, institutional capacity, data exchange, and warning communication.

Key words: *Smart city, Sarajevo, Flood Management, Smart Flood Management Framework*

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1. INTRODUCTION

Urban flooding is a growing challenge for cities, where urbanization and climate change can amplify impacts on concentrated populations, infrastructure and economic activities. Urban areas may be affected by interacting flood mechanisms, including fluvial flooding caused by river overflow, pluvial flooding resulting from intense rainfall and inadequate drainage capacity, and rapidly developing flash floods associated with intense rainfall and rapid runoff [1].

Sarajevo, the capital of Bosnia and Herzegovina (BiH), is located within a basin surrounded by mountainous terrain of the Dinaric system. Its wider urban area extends beyond four city municipalities, and is characterized by spatial variability in topography, land use and urban development. These conditions, combined with the local precipitation regime, dense urbanization and river network, contribute to its susceptibility to flooding [2, 3].

The main watercourses relevant to flood hazard in the Sarajevo urban area include the Miljacka, Željeznica, Dobrinja and Bosna rivers. Previous studies have documented riverine flood hazard and risk in the wider Sarajevo area, and demonstrated the importance of hydrological and hydraulic modelling for flood assessment [4, 5]. Densely urbanized and low-lying areas are also susceptible to surface runoff accumulation when urban drainage capacity is exceeded. Flood risk in Sarajevo therefore results from both fluvial and pluvial processes, highlighting the need for an integrated approach combining river flows, urban drainage, monitoring and spatial planning.

Smart-city technologies offer opportunities to integrate flood risk management with monitoring, data management, urban planning and decision-support systems. Smart flood management should therefore be understood not as the application of individual technologies, but as an integrated approach combining monitoring, data, modelling, infrastructure and decision-making [6, 7]. This is particularly relevant for cities exposed to multiple and interacting water-related hazards [7].

Against this background, this study addresses the following research question: What information, technological and institutional components are required to develop a smart flood management system for Sarajevo?

2. MATERIAL AND METHODS

This study used a structured desk-based assessment to examine what Sarajevo needs to develop a smart flood management approach. The assessment brought together scientific literature, publicly available institutional information and data, technical reports, existing flood hazard and risk assessments, monitoring and forecasting systems, and available data on management platforms relevant to Sarajevo.

For the purposes of this study, Sarajevo is considered as an urban flood-management area rather than a single administrative unit. The spatial scope therefore refers to the Sarajevo urban area affected by the main watercourses, urban drainage processes and flood-related infrastructure considered in the study. This functional definition is used because flood monitoring, forecasting, water management, urban

drainage and emergency response involve institutions operating at different administrative and spatial levels.

The review covered several types of sources. First, it included scientific studies on urban flood risk, smart-city solutions, hydrological and hydraulic modelling, early warning systems, and flood-risk management. Second, the study examined publicly available information and data from key institutions. Third, available flood hazard and flood risk maps, modelling studies, and technical reports were reviewed. Finally, the assessment considered the existing hydrometeorological monitoring network, forecasting and warning systems, and data-sharing arrangements.

2. SMART FLOOD MANAGEMENT CONCEPT

The technological foundation of smart urban water management includes the integration of monitoring systems, digital data, GIS, remote sensing (RS), Internet of Things (IoT), modelling and other digital technologies. Their combined use can improve real-time information availability and support more efficient decision-making in urban water management [8, 9]. Examples from European cities demonstrate that the value of these technologies lies in their integration into a coherent management system capable of transforming continuously collected data into actionable information [10]. This principle is directly applicable to flood management, where the integration of monitoring, data processing, modelling, forecasting and decision support is essential for moving from conventional to smart flood risk management. Early warning systems (EWS) are already widely established as an important component of conventional flood management [11].

Table 1 shows the key elements of a smart flood management system addressing pluvial floods caused by intense rainfall, fluvial floods resulting from river overflow, and flash floods.

Table 1. Key elements of smart flood management system

Element	Description
Monitoring	Sensors placed around rivers, drainage systems, and urban areas continuously collecting real-time water level and rainfall data.
Data Integration	A central hub where diverse data streams—from weather stations, river gauges, and IoT devices—are combined for comprehensive analysis
GIS/RS	Maps overlaying flood risk zones, rainfall advancement – spatial patterns, and topography to visually represent vulnerable areas
IoT	Networked smart devices such as weather sensors, water flow meters, and alert systems interconnected for seamless communication
Hydrologic/hydra-ulic modelling	Simulations illustrating flood dynamics and water movement through urban and river environments for better understanding flood behavior
Forecasting and EWS	Predictive models projecting flood events combined with automated alerts to inform authorities and citizens
Decision Support	A control center interface where data-driven insights are used to guide flood response, emergency actions, and urban planning for enhanced resilience
Public communication and preparedness	Communication channels and digital tools for disseminating warnings, preparedness information and guidance to citizens.

3. CURRENT SITUATION AND REQUIREMENTS FOR SMART FLOOD MANAGEMENT IN SARAJEVO

3.1. Existing monitoring

Hydrological and meteorological monitoring in the Sarajevo urban area is primarily provided through the observation network operated by the Federal Hydrometeorological Institute of BiH (FHMZ). The spatial distribution of the relevant stations is shown in Figure 1.

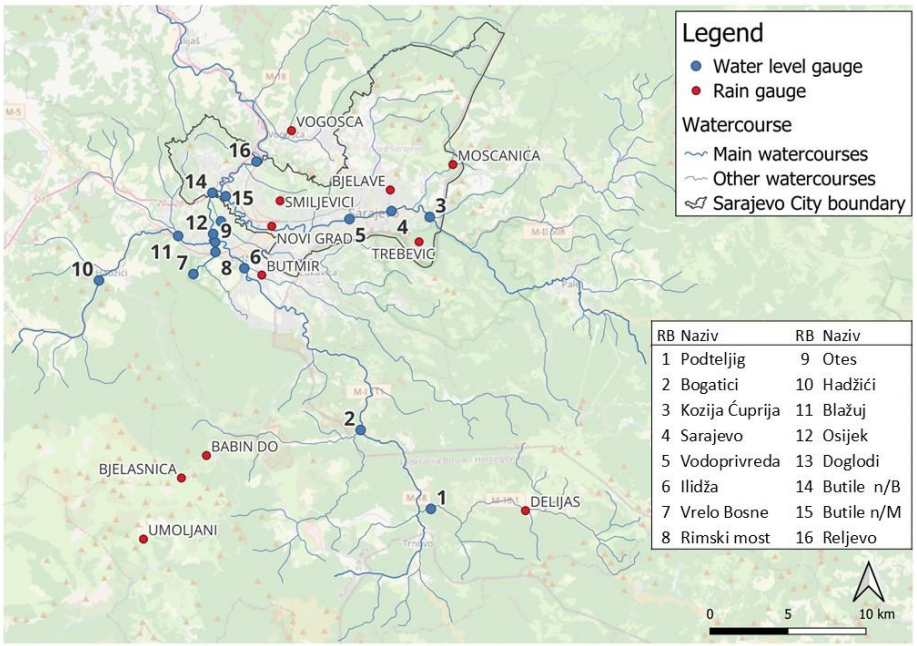


Figure 1. Locations of hydrological (water level gauge) and precipitation (rain gauge) monitoring stations in the Sarajevo urban area. Data source: FHMZ and AVP Sava; map prepared by the Authors.

For pluvial flood management, information relevant to monitoring is primarily associated with the urban stormwater drainage system and its main hydraulic components, including collectors, pumping stations and outfalls. However, unlike the hydrometeorological monitoring network used for river flooding, a dedicated and publicly documented monitoring system specifically designed for real-time observation of intense rainfall, surface-water accumulation and drainage-system performance has not been identified for the Sarajevo urban area. This limits the availability of spatially distributed real-time information required for pluvial flood forecasting and early warning.

3.2. Available data

A range of data relevant to flood risk management is available for the Sarajevo urban area from existing monitoring networks, information systems and previous studies. Precipitation observations, river water levels and discharge data are provided

through the FHMZ monitoring network. Hydrological observations from FHMZ stations are exchanged through the International Sava River Basin Commission (ISRBC) and are available in near real time through the Sava HIS information system [12], while selected real-time observations are also published by FHMZ [13].

Ground-based observations can be complemented by satellite-based precipitation products. For example, the NASA GPM IMERG product provides near-real-time precipitation estimates at a spatial resolution of 0.1° × 0.1° and a temporal resolution of 30 minutes [14]. Although its spatial resolution is relatively coarse for detailed urban flood analysis, it can provide useful supplementary information on the spatial and temporal distribution of precipitation, particularly where ground observations are limited.

In addition to monitoring data, previous flood hazard and risk assessment studies have produced important spatial datasets for the Sarajevo area, including flood hazard and flood risk maps. These maps are publicly available through the Agency for the Sava River Basin District (AVP Sava) [15] and provide an important existing information base for flood risk assessment and the development of future smart flood management applications.

3.3. Institutions

Flood management in Sarajevo involves institutions operating at different administrative and spatial levels, from local utility companies and civil protection to cantonal, federal and river-basin institutions. Their main roles and the information systems relevant to flood management are summarized in Table 2.

Table 2. Key institutions and systems relevant to smart flood management in Sarajevo

Component	Key institutions/systems
Information & data	Federal Hydrometeorological Institute of BiH (FHMZ); Agency for the Sava River Basin District (AVP Sava); the International Sava River Basin Commission (ISRBC) /Sava HIS; Public Utility Company “Water Supply and Sewerage” Sarajevo (KJKP ViK Sarajevo)
Monitoring, modelling & forecasting	FHMZ; Sava FFWS; AVP Sava
Urban drainage information	KJKP ViK Sarajevo
Flood risk assessment & mapping	AVP Sava; FHMZ; relevant technical/research institutions (University of Sarajevo, Hydraulic Engineering Institute (HEIS), Institute for Water Management Sarajevo — IWM Sarajevo, etc.)
Data exchange	FHMZ - AVP Sava - ISRBC/Sava HIS
Flood warning & emergency response	FHMZ; Federal Administration of Civil Protection (FUCZ); Cantonal/local Civil Protection
Water-management policy & coordination	Federal Ministry of Agriculture, Water Management and Forestry (FMAWM); AVP Sava
Operational flood protection	AVP Sava; civil protection authorities; local authorities; relevant water-management/utility organisations

3.4. Modelling

Existing flood hazard maps for the Sarajevo area indicate that both hydrological and hydraulic modelling has already been applied to support flood hazard assessment [15]. These modelling activities provide an important basis for simulating flood flows and inundation under different hydrological scenarios and have resulted in spatially distributed information on flood hazard that can be used for further risk assessment and decision-making. In addition to modelling undertaken for official flood hazard mapping, research-oriented hydrological and hydraulic modelling has also been applied in the Sarajevo area. For example, Binesh et al. [5] used a coupled hydrological–hydraulic modelling approach to simulate river-flood scenarios and assess their implications for urban areas and critical infrastructure. Hadžić et al. [4] likewise demonstrated the application of flood hazard and risk mapping for the Zujevina River within the wider Sarajevo area. Together, these examples indicate that relevant modelling experience and datasets already exist, but they remain fragmented across different applications and are not yet integrated within a common operational smart flood management framework.

3.5. Forecasting and Early Warning System

Following the severe floods of 2014, AVP Sava initiated the development of a real-time flood forecasting system for the Sava River basin in the Federation of BiH. By mid-2021, operational systems integrating real-time hydrometeorological observations, meteorological forecasts and hydrological–hydraulic models covered the major sub-basins, including the Bosna River basin relevant to Sarajevo [16, 17].

At the regional level, additional forecasting and early warning capacity is provided through the Sava Flood Forecasting and Warning System (Sava FFWS), based on the Delft-FEWS platform and involving FHMZ and AVP Sava [18]. An effective EWS integrates risk knowledge, hazard detection and forecasting, warning communication and response preparedness [19]. For Sarajevo, these elements should be linked with local response arrangements, particularly for rapidly developing pluvial and flash-flood events.

3.6. Data sharing and interoperability

Data sharing and interoperability are already established at the river-basin level through cooperation among FHMZ, AVP Sava, and the ISRBC. The Sava HIS [12] provides a common framework for the exchange and harmonisation of hydrological data, while the Sava FFWS integrates data, models and forecasts from national institutions through the Delft-FEWS platform. However, the existing interoperability framework is primarily organised at the national and basin levels, while direct operational links with institutions responsible for urban drainage and local flood management in Sarajevo are less clearly established. This indicates a need to strengthen the integration of basin-scale information with local urban data and decision-making, particularly regarding drainage-system information and rapidly developing urban flood events.

3.7. Identified gaps

A fundamental requirement for the development of a smart flood management system is the availability of reliable and sufficiently detailed hydrological and spatial data. In BiH, however, the development and application of flood hazard and risk assessment methodologies are constrained by the availability, spatial distribution and quality of hydrological data and supporting hydro-meteorological information. Recent analyses of the state of hydrological data in BiH have highlighted the need to improve the data sources used for flood hazard mapping and related risk-management activities [20]. This issue is particularly relevant for Sarajevo, where effective flood management requires not only the availability of hydrological observations, spatial datasets, rainfall information and hydraulic modelling, but also their integration into a consistent and continuously updated information framework.

4. PROPOSED FRAMEWORK FOR SMART FLOOD MANAGEMENT IN SARAJEVO

Based on the analysis of the existing monitoring, data, modelling, forecasting and institutional capacities, a framework for smart flood management in Sarajevo is proposed. The framework is structured around three complementary aspects: (i) information and data, (ii) technology, and (iii) institutional arrangements. The proposed approach builds on existing national and basin-level capacities and connects them with local urban flood management, particularly for pluvial and flash-flood events. The proposed framework, including existing capacities and further requirements, is summarized in Figure 2.

The proposed framework is primarily intended to support real-time monitoring and forecasting, together with emergency preparedness and response. The information generated through the system can also be used for longer-term flood risk prevention and spatial and urban planning. In this way, planning is seen as a secondary use of the system outputs, for example in identifying flood-prone areas, assessing exposure, and supporting future urban development decisions.

Information and data. The first component comprises the establishment of an integrated information base for flood risk management. This should combine observed precipitation, river water levels and discharges from the FHMZ monitoring network with spatial information on the urban drainage system, including stormwater collectors, critical hydraulic structures, outfalls and areas susceptible to surface-water accumulation. Existing flood hazard and risk maps, modelling results, historical flood records and exposure data should be incorporated into the same spatial framework. Real-time data should be complemented by high-resolution rainfall estimates from radar, satellite and other sources, particularly where rain gauges cannot adequately represent intense convective rainfall. The resulting information base should be continuously updated and made accessible to the institutions responsible for assessment, forecasting and emergency response.

Technological components. The second component should transform heterogeneous observations and spatial information into timely flood intelligence. The existing FHMZ monitoring network, the forecasting platform operated by AVP Sava and the Sava FFWS provide an important foundation for flood forecasting and should be complemented by an urban-scale monitoring system focused on intense rainfall, surface-water accumulation and the performance of the stormwater drainage network. A GIS-based data platform should integrate real-time observations, historical records, terrain and land-use data, drainage infrastructure and flood hazard information. Hydrological and hydraulic models should be linked to this platform to support both fluvial and urban pluvial flood forecasting, while high-resolution rainfall nowcasting should improve the prediction of rapidly developing events. The technological framework should also include automated data exchange, alert generation, visualization and decision-support functions, allowing relevant information to be transformed into operational warnings and response actions.

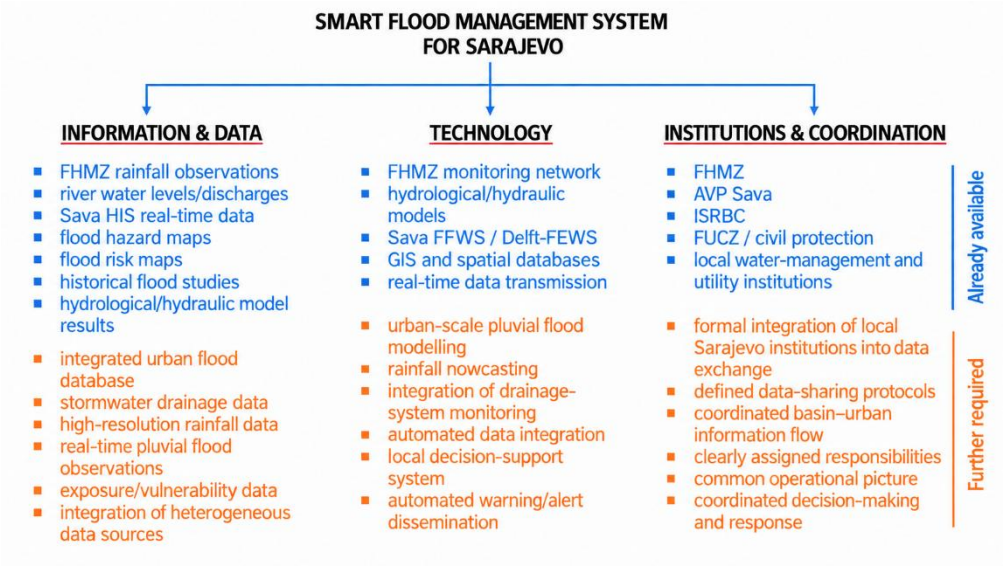


Figure 2. Proposed framework for a smart flood management system in Sarajevo. Source: Authors.

Institutional arrangements. The third component concerns the institutional organization required to ensure that data and technologies are effectively used for decision-making. The existing roles of FHMZ, AVP Sava and ISRBC in monitoring, data exchange, flood forecasting and basin-level management should be connected with the institutions responsible for urban drainage, local water management, spatial planning and civil protection in Sarajevo. Systematic data exchange between basin-level systems and local institutions should include urban drainage and local flood-impact information, with clear responsibilities for data provision, modelling, forecasting, warning dissemination, public communication and emergency response. A coordinated institutional framework would therefore enable information generated at different administrative and spatial scales to be transformed into a common operational picture and shared basis for decision-making.

The three components are interdependent and should not be developed as separate systems. Information provides the evidence, technology transforms information into actionable intelligence, and institutional arrangements ensure that this intelligence reaches the right decision-makers and results in coordinated action. The proposed framework therefore represents a transition from existing but partly fragmented monitoring and flood-management activities towards an integrated smart flood management system for Sarajevo, capable of addressing both riverine flooding and rapidly developing urban pluvial and flash-flood events.

5. CONCLUSION

This study briefly reviewed the existing information and data sources, monitoring infrastructure, hydrological and hydraulic modelling, flood forecasting and early warning capacities, and institutional arrangements relevant to flood risk management in Sarajevo. All these aspects were reviewed with the aim of identifying the key gaps that currently separate Sarajevo from a smart flood management system. Particular attention was given to the availability and integration of data, existing technological solutions, and the links between basin-level and local urban flood management. Based on this assessment, the following conclusions are drawn:

1. Sarajevo already has significant flood-management capacities, including hydrometeorological monitoring, flood hazard and risk maps, hydrological and hydraulic models, and basin-level flood forecasting through AVP Sava forecasting systems and the Sava FFWS.
2. Despite remaining gaps in data availability and quality, the main systemic challenge is their integration, particularly the connection of basin-scale systems with local urban information on rainfall, drainage infrastructure and pluvial flooding.
3. A smart flood management system requires three interconnected components: integrated information and data, interoperable technologies for monitoring, modelling, forecasting and information exchange, and coordinated institutional arrangements.
4. For Sarajevo, priority should be given to linking existing capacities with local urban flood management, with particular attention to high-resolution rainfall monitoring, pluvial and flash-flood forecasting, data sharing, and coordinated decision-making.

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Research paper

ADVANCING CLIMATE-ADAPTIVE URBAN INTELLIGENCE: MACHINE LEARNING PREDICTION OF $PM_{2.5}$ DYNAMICS ACROSS THE BELGRADE METROPOLITAN AREA

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Abstract

This study analyses the seasonal and spatial dynamics of fine particulate matter ($PM_{2.5}$) across 13 low-cost sensor monitoring sites in the Belgrade metropolitan area over a 12-month period (15 April 2025 - 14 April 2026), divided into a non-heating season (NHS; 15 April - 14 October 2025) and a heating season (HS; 15 October 2025 - 14 April 2026). The area-averaged HS mean (32.5 ± 25.6 µg/m³) was 2.7 times higher than the NHS mean (11.9 ± 8.9 µg/m³), with December 2025 recording the peak monthly average of 43.4 µg/m³. The WHO 2021 daily $PM_{2.5}$ guideline (15 µg/m³) was exceeded on 75.5% of HS monitoring days. Strong spatial gradients were identified: Ritopek (42.5 µg/m³) and Zemun (41.8 µg/m³) recorded the highest HS means, while Beli Potok (23.6 µg/m³) was the least polluted site. Temperature was the strongest meteorological driver (Pearson r = −0.57 during HS). Four machine learning models were evaluated for $PM_{2.5}$ prediction; the best model, Random Forest augmented with site identity and autoregressive lag features, achieved R^2 = 0.680 (MAE = 7.24 µg/m³), a substantial improvement over meteorology-only approaches (R^2 = 0.552). *The implications for smart city air quality monitoring, climate-adapted urban planning and PM-rated ventilation in green buildings are discussed.*

Key words $PM_{2.5}$; machine learning; WHO exceedance; heating season; smart cities; green buildings

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1. INTRODUCTION

Fine particulate matter ($PM_{2.5}$) is the leading environmental risk factor for human health globally, responsible for approximately 6.7 million premature deaths annually [1]. The WHO 2021 Air Quality Guidelines set an annual $PM_{2.5}$ target of 5 $\mu g/m^3$ [2], yet concentrations in Central and Eastern European (CEE) cities routinely exceed this threshold by factors of three to ten during winter months, driven primarily by residential solid-fuel combustion [3]. Serbia and the Western Balkans rank among the highest $PM_{2.5}$ burden areas in Europe, and Belgrade, with ~1.7 million inhabitants, complex orography and a large legacy thermal power plant, represents a particularly challenging urban air quality context [4].

The proliferation of low-cost IoT sensor networks, exemplified by the Klimerko open-data platform, now enables neighbourhood-scale continuous PM monitoring inaccessible to sparse regulatory networks [5, 6]. Combined with machine learning (ML) algorithms, these datasets support data-driven $PM_{2.5}$ prediction models that can serve as the algorithmic backbone of smart building ventilation control and real-time urban air quality management [7, 8]. Ensemble ML methods (Random Forest, Gradient Boosting) consistently outperform linear models for PM-meteorology relationships, and incorporating autoregressive lag features and site identity further improves predictive accuracy [9, 10].

This study pursues three objectives: (i) characterise seasonal and spatial $PM_{2.5}$ dynamics across 13 Belgrade sites over a full annual cycle; (ii) quantify WHO guideline exceedance frequency; and (iii) develop and compare ML models for $PM_{2.5}$ prediction, with implications for Smart and Climate-Adapted Cities (T06) and Green Buildings and Energy Efficiency (T02).

2. MATERIALS AND METHODS

2.1. Study Area and Air Quality Data

Belgrade (44.8°N, 20.5°E; 3,234 km^2) lies at the Sava–Danube confluence in north-central Serbia. Thirteen monitoring sites within the city's administrative boundaries were selected from the Klimerko network [5] based on data completeness (>150 valid daily records per seasonal sub-period): Beograd, Zemun, Batajnica, Barajevo, Obrenovac, Mladenovac, Jajinci, Kaluđerica, Ripanj, Ritopek, Beli Potok, Sremčica and Čukarica. Klimerko sensors (Plantower PMS7003 optical particle counters) report daily mean $PM_{2.5}$ under an open-data licence. The study period spans 15 April 2025 - 14 April 2026, divided into the NHS (183 days) and HS (182 days).

No formal cross-calibration of the Klimerko PMS7003 sensors against co-located reference-grade instruments was performed in this study, as verified SEPA reference data for the study period are not yet publicly available for download. Previous independent studies in Serbian urban environments have demonstrated strong correlation between Klimerko sensors and co-located SEPA Grimm EDM180 reference monitors (R^2 = 0.879 for PM2.5 in Belgrade [2]), though uncalibrated devices are known

to overestimate PM2.5 at relative humidity above 70% due to hygroscopic aerosol growth [11]. Stojanović et al. [12] reported acceptable agreement between sensors of the same type and SEPA stations across 15 Serbian municipalities after co-location calibration (PM2.5 RMSE = 6.50 μg/m³). In the present study, data were used without correction; absolute PM2.5 values should therefore be interpreted with caution, while relative spatial and temporal patterns remain robust.

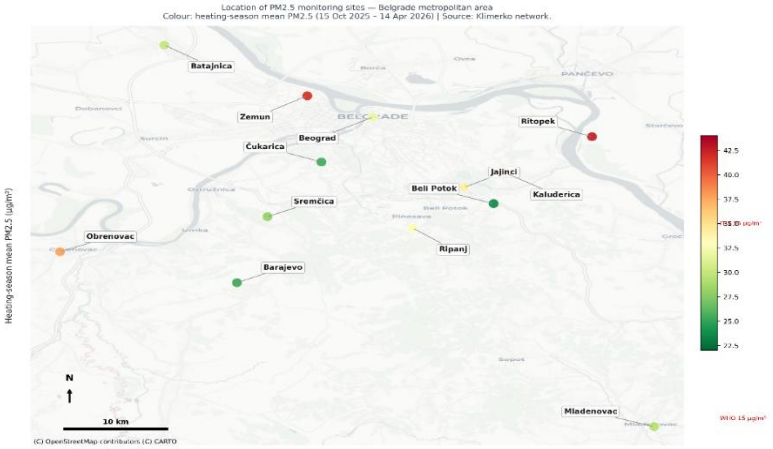


Figure 1. Map of $PM_{2.5}$ monitoring sites in the Belgrade metropolitan area

2.2. Meteorological Data

Daily meteorological observations for 13 sites were obtained from the Visual Crossing Weather API: temperature (°C), relative humidity (%), wind speed (km/h), sea-level pressure (hPa), cloud cover (%), precipitation (mm), dew point (°C), visibility (km) and solar radiation (W/m²). Merged $PM_{2.5}$–meteorology records yielded 4,588 site-days after quality screening.

2.3. Statistical and Machine Learning Analysis

Bivariate $PM_{2.5}$-meteorology relationships were assessed using the Pearson correlation coefficient computed separately for each season. WHO exceedance frequency was calculated as the percentage of site-days with $PM_{2.5} > 15$ μg/m³ [2]. Four supervised regression models were trained for $PM_{2.5}$ prediction: (i) Linear Regression, (ii) Ridge Regression (α = 1.0), (iii) Random Forest (RF; 200 trees, depth 12) and (iv) Gradient Boosting (GB; 200 estimators, LR = 0.05). Three progressive feature sets were evaluated: (a) 12 meteorological + temporal features; (b) adding a site identity encoding; and (c) additionally adding three autoregressive lag features ($PM_{2.5}$ at t−1, t−2, t−3) and a 7-day rolling mean. All models were evaluated by 5-fold cross-validation (R^2, MAE, RMSE). Analyses used Python 3.12 / scikit-learn 1.8 [13]. Pairwise Pearson correlations among meteorological predictors revealed several strong associations (temperature–dew point: r = 0.880; temperature–solar radiation: r = 0.809; relative humidity–solar radiation: r = −0.749), reflecting the physical co-occurrence of these variables during winter anticyclonic episodes. For the ensemble methods, predictor multicollinearity does not bias predictions but may distribute feature importance across correlated variables [14].

3. RESULTS AND DISCUSSIONS

3.1. Seasonal and Spatial PM2.5 Dynamics

The monthly time series (Figure 2a) reveals a sharp seasonal cycle across all 13 sites. During the NHS, area-mean $PM_{2.5}$ remained stable and low (10.1–13.2 μg/m³), near or below the WHO 2021 annual guideline. An abrupt transition occurred in October 2025 (18.9 μg/m³), with concentrations escalating to peak monthly averages of 43.4 and 42.6 μg/m³ in December 2025 and January 2026, respectively, nearly threefold exceedance of the WHO guideline. The HS mean (32.5 ± 25.6 μg/m³) was 2.7 times higher than the NHS mean (11.9 ± 8.9 μg/m³). The large HS standard deviation reflects day-to-day variability driven by synoptic patterns: anticyclonic blocking events with temperature inversions produce multi-day $PM_{2.5}$ episodes up to 250 μg/m³, while cyclonic conditions temporarily reset concentrations. This seasonal amplification is consistent with observations in similar CEE cities (Sofia, Bucharest, Warsaw) [3, 15, 16].

Considerable spatial heterogeneity was observed (Figure 2b). During the HS, site means ranged from 23.6 μg/m³ (Beli Potok) to 42.5 μg/m³ (Ritopek), a near-twofold intra-urban gradient. Ritopek's elevated values reflect its position in a narrow Danube valley that promotes nocturnal cold-air drainage and temperature inversions trapping combustion products. Zemun and Kaluđerica rank second and third, driven by dense low-rise residential heating in peri-urban settlements. Obrenovac records the highest NHS mean (25.5 μg/m³) attributable to the year-round operation of the Nikola Tesla thermal power plant (TENT A+B), the largest coal-fired facility in the Western Balkans (~3–7 km from the sensor).

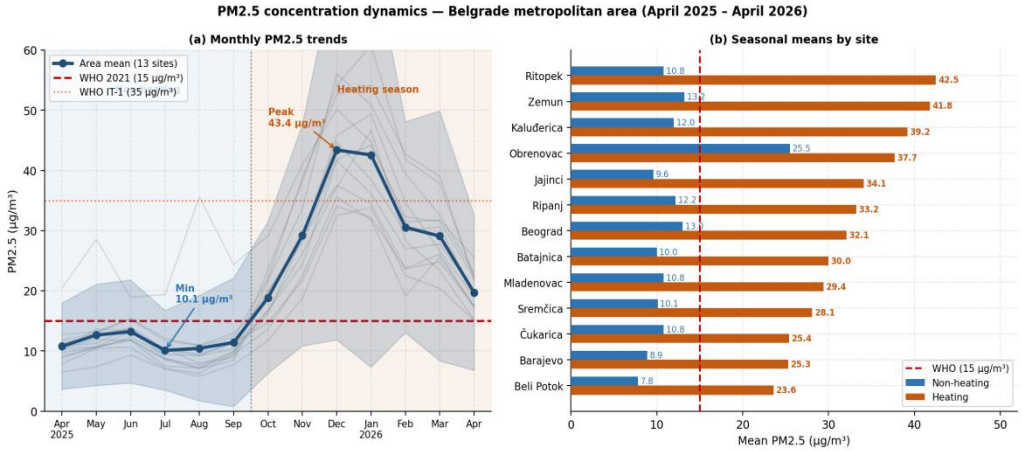


Figure 2. (a) Monthly $PM_{2.5}$ trends: grey lines = individual sites; dark line = 13-site area mean ±1 SD (shaded). Dashed red: WHO 2021 annual guideline (15 μg/m³); dotted orange: WHO IT-1 (35 μg/m³). (b) Seasonal mean PM2.5 by site, sorted by heating-season mean

3.2. WHO Guideline Exceedances

The WHO 2021 $PM_{2.5}$ guideline (15 μg/m³) was exceeded on 24.9% of NHS site-days but on 75.5% of HS site-days. The spatio-temporal exceedance pattern (Figure 3b)

reveals near-universal guideline violation during December 2025 and January 2026: most sites recorded >90% of days above the threshold, with Ritopek, Zemun and Kaluđerica reaching 100% in December. By contrast, July and August 2025 showed exceedance rates below 10% at the majority of sites, a window of relative compliance. The HS exceedance rate of 75.5% is broadly comparable to Bucharest (~70%) and Warsaw (65–70%), but substantially lower than Kraków (>85%), where basin topography compounds the coal-heating effect [16, 17]. It far exceeds London (<5%) and Munich (<8%), illustrating the scale of the regulatory gap between CEE and Western European cities [3].

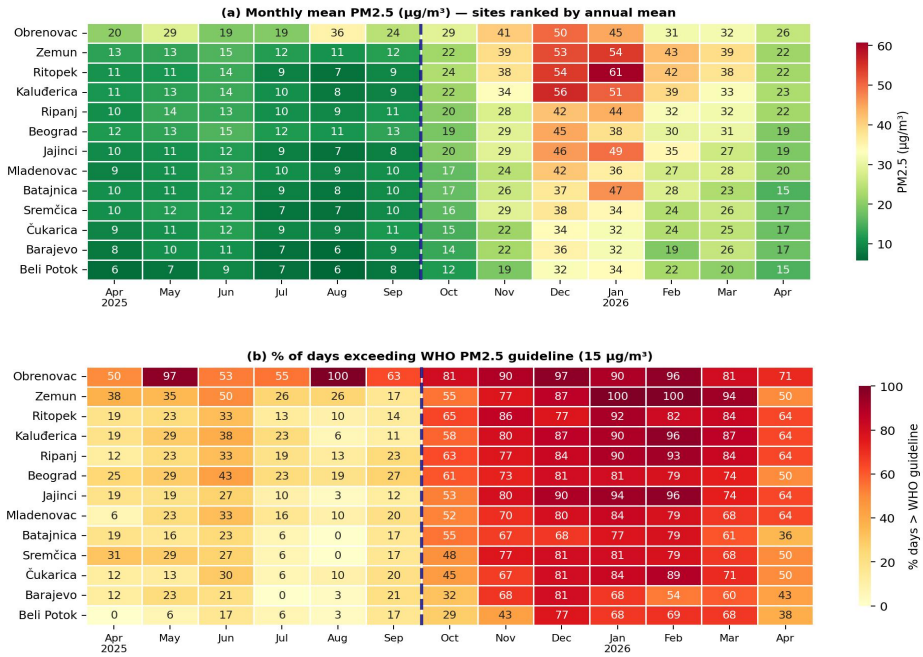


Figure 3. (a) Monthly mean $PM_{2.5}$ (µg/m³) by site and month. Sites ranked by annual mean (descending). Colour: green (low) → red (high). (b) Percentage of days exceeding the WHO $PM_{2.5}$ guideline (15 µg/m³) by site and month. Dashed blue line separates the two seasons

3.3. Meteorological Drivers of PM2.5

Pearson correlation analysis (Figure 4a) confirms temperature as the dominant negative driver of $PM_{2.5}$ during the HS (r = −0.57), reflecting the non-linear coupling between ambient temperature, residential heating demand and atmospheric stability. Solar radiation (r = −0.50) acts as a proxy for mixing layer development. Sea-level pressure (r = +0.29) and relative humidity (r = +0.31) show positive HS correlations consistent with anticyclonic blocking and hygroscopic aerosol growth, respectively [18]. Wind speed (r = −0.27) reflects dilution by ventilation. These meteorological archetypes, low temperature, high pressure, low wind, high humidity, constitute the dominant synoptic configuration for severe $PM_{2.5}$ episodes in the Sava-Danube basin [18], and are particularly frequent from December to February.

3.4. Machine Learning Prediction of PM2.5

3.4.1. Model performance

The 5-fold cross-validation results (Table 1, Figure 4b) demonstrate a clear hierarchy of model complexity and performance. Linear and Ridge Regression (R^2 = 0.369) capture only the linear components of $PM_{2.5}$–meteorology relationships. Adding site identity as a categorical encoding (RF + site ID) raises R^2 to 0.611, confirming that baseline spatial differences in $PM_{2.5}$ levels, spanning nearly 19 µg/m³ between sites during the HS, constitute a substantial predictable signal absent from the original feature set. The addition of autoregressive lag features (PM2.5 at t−1, t−2, t−3, and a 7-day rolling mean) further improves performance to R^2 = 0.680 (MAE = 7.24 µg/m³, RMSE = 12.30 µg/m³) - a 23% gain over the meteorology-only baseline. The lag features encode the autocorrelation of multi-day pollution episodes driven by persistent anticyclonic weather. Gradient Boosting with the same feature set achieves R^2 = 0.671, marginally below Random Forest; the latter is therefore selected as the preferred model. These R^2 values are consistent with literature on meteorology-only ML models for CEE urban $PM_{2.5}$: Kim et al. [10] reported R^2 = 0.48–0.56 for Seoul, while Zamani Joharestani et al. [9] obtained R^2 = 0.60–0.73 with additional satellite aerosol optical depth inputs.

Table 1. Predictive performance of ML models for daily $PM_{2.5}$ (5-fold cross-validation)

Models	Feature set	R^2	±SD	MAE (µg/m³)	RMSE (µg/m³)
Linear Regression	Meteo+time	0.379	0.024	11.28	17.17
Ridge Regression	Meteo+time	0.379	0.024	11.28	17.17
Random Forest	Meteo+time	0.552	0.032	8.33	14.59
Random Forest	+ site ID	0.621	0.028	7.89	13.44
Random Forest ✓ best	+ site ID + lags	0.680	0.045	7.24	12.30
Gradient Boosting	+ site ID + lags	0.671	0.044	7.50	12.48

MAE = Mean Absolute Error; RMSE = Root Mean Square Error. Green row = best model

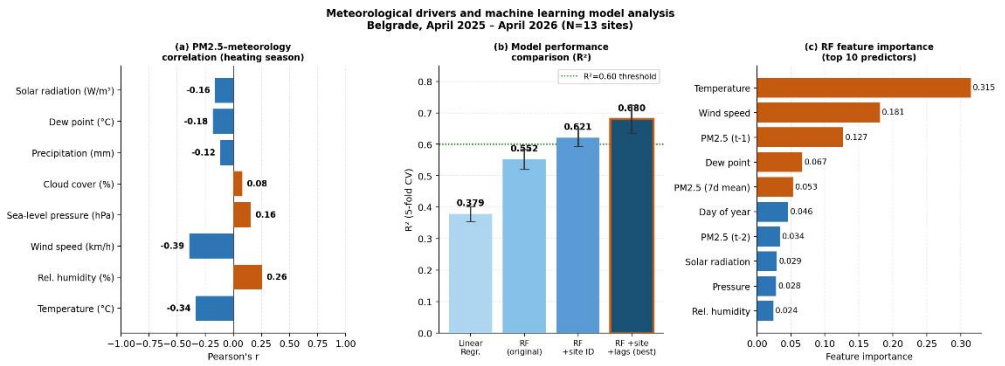


Figure 4. (a) $PM_{2.5}$–meteorology Pearson correlations during the heating season. (b) R^2 progression across model configurations (error bars: CV SD; orange outline: best model). (c) Top-10 feature importances for the best RF model

3.4.2. Feature importance and prediction quality

Feature importance analysis (Figure 4c) reveals that temperature (0.245) and wind speed (0.174) are the leading meteorological predictors, followed closely by the previous-day $PM_{2.5}$ lag (0.174), confirming that episode persistence is as informative as instantaneous meteorological state. The 7-day rolling mean $PM_{2.5}$ (0.084) captures the multi-day accumulation dynamics of anticyclonic episodes. Month and day-of-year together contribute ~15%, encoding the seasonal heating cycle. Site identity, while modest in raw importance, is essential for capturing baseline spatial differences in exposure levels. It should be noted that strong correlations among meteorological predictors (temperature–solar radiation: r = 0.809; relative humidity–solar radiation: r = −0.749) may cause the model to distribute importance scores across correlated features; the combined contribution of the thermal-radiative predictor cluster to $PM_{2.5}$ prediction therefore likely exceeds what individual importance values suggest [14].

Figure 5 (left) presents the scatter of observed versus predicted $PM_{2.5}$ on the 20% holdout test set (R^2 = 0.735, MAE = 6.36 μg/m³). The model tracks the time-series dynamics of the heating season peak well (Figure 5, right), capturing week-to-week fluctuations between anticyclonic accumulation episodes and cyclonic clearance events. Systematic underestimation occurs at the most extreme concentrations (>150 μg/m³), a known limitation of ensemble averaging methods [9]. Future integration of boundary-layer height observations and traffic intensity data could address the remaining residual variance.

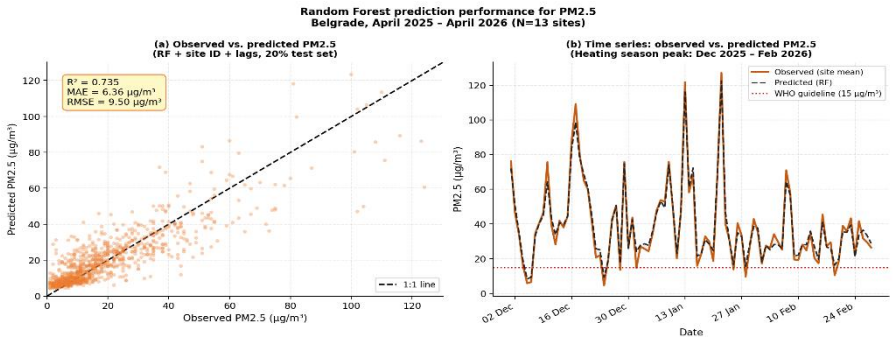


Figure 5. (a) Observed vs. predicted PM2.5 on the independent test set (Random Forest + site ID + lags; N ≈ 918 site-days, 13 sites). (b) Time-series comparison for the heating season peak (December 2025 – February 2026). Shaded area: residuals; dotted red: WHO guideline (15 μg/m³)

3.5. Implications for Smart Cities and Green Buildings

The findings carry direct and actionable implications across three thematic domains of Green Building 2026. (i) Smart Cities and Real-Time Management: the Klimerko sensor layer, combined with the RF prediction model developed here, constitutes the infrastructure backbone for real-time $PM_{2.5}$ dashboards and 24–72 h pollution episode forecasting using publicly available meteorological products (ECMWF, ALADIN). Such forecasts could trigger pre-emptive interventions, temporary traffic restrictions, adaptive public transport provision, heating fuel transition advisories, consistent with

smart city digital twin frameworks [7]. (ii) Climate Adaptation: the 2.7-fold HS amplification of $PM_{2.5}$ documents the air quality co-penalty of solid-fuel space heating. Replacing coal and wood combustion with heat pumps or district heating is projected to reduce residential $PM_{2.5}$ contributions by 60–80% [3], simultaneously advancing climate decarbonisation targets under the EU Green Deal. Continuous monitoring networks such as Klimerko will be essential for evaluating actual air quality co-benefits as building energy renovation programmes scale up. (iii) Green Building Ventilation: the sustained HS exceedance rate (75.5% of days above 15 μg/m³) establishes a robust empirical basis for mandatory mechanical ventilation with PM-rated filtration (ISO e$PM_{2.5}$ ≥60%, EN ISO 16890) in new and renovated buildings in Belgrade. Current Serbian building regulations do not explicitly require PM-class filtration, a gap increasingly at odds with EN 16798-3 and ASHRAE 62.1-2022. Given indoor/outdoor $PM_{2.5}$ penetration efficiencies of 50–80% in unfiltered buildings [19], residents in high-exceedance zones (Ritopek, Zemun) face annual indoor $PM_{2.5}$ exposures of 20–34 μg/m³, four to seven times the WHO annual guideline. The spatial exceedance maps developed here should be incorporated into site environmental assessments within BREEAM and LEED certification processes for Belgrade.

4. CONCLUSION

One full annual cycle of $PM_{2.5}$ monitoring across 13 sites in the Belgrade metropolitan area reveals a city operating in two fundamentally different air quality regimes. During the non-heating season, concentrations remain close to or below the WHO 2021 annual guideline of 15 μg/m³, confirming that the warm-season baseline $PM_{2.5}$ burden in Belgrade is broadly manageable and comparable to moderately polluted mid-sized European cities. The heating season tells a starkly different story: a near-instantaneous transition in October, a 2.7-fold amplification of the area mean to 32.5 μg/m³, and peak monthly averages approaching 43 μg/m³ in December and January. On three out of every four heating-season days, the WHO guideline was exceeded across the entire monitoring network. These are not marginal violations, they represent a structurally embedded public health problem rooted in the building sector's dependence on solid-fuel combustion.

The spatial analysis adds an important dimension to this picture. Even within a single city, $PM_{2.5}$ exposure during the heating season varies by nearly a factor of two between monitoring sites, shaped by topographic channelling of cold air (Ritopek, Kaluđerica), the density of low-rise residential heating in peri-urban districts (Zemun), and the year-round industrial signature of the Nikola Tesla thermal power plant in Obrenovac, which uniquely elevates non-heating-season concentrations and demands source-specific rather than seasonally uniform policy responses. This intra-urban heterogeneity has direct consequences for building design: a ventilation standard appropriate for Beli Potok is wholly inadequate for Ritopek or Zemun.

The meteorological analysis confirms that the most severe pollution episodes are the product of synoptic convergence, low temperature and wind speed, elevated pressure and humidity acting simultaneously to suppress the atmospheric boundary

layer and concentrate combustion emissions. This meteorological fingerprint is highly predictable, and it is precisely this predictability that the machine learning framework developed here exploits. By incorporating site identity and autoregressive lag features alongside meteorological predictors, the Random Forest model captures the day-to-day dynamics of multi-day accumulation episodes with sufficient fidelity for operational deployment in smart city air quality management systems.

Taken together, these results frame Belgrade's $PM_{2.5}$ challenge as simultaneously a climate problem, a building energy problem and a smart city governance problem. The heating-season pollution regime documented here will not be resolved by monitoring or modelling alone, it requires accelerated fuel switching and deep energy renovation of the residential building stock, transitioning households away from solid fuels toward electrified heating supplied by decarbonised grids. The air quality co-benefits of such a transition, projected at 60–80% reductions in residential $PM_{2.5}$ contributions [3], would transform the exceedance maps presented in this study and bring Belgrade's winter air quality within reach of WHO guideline compliance. Until that transition is complete, the findings presented here provide the empirical foundation for two complementary near-term interventions: mandatory PM-rated mechanical ventilation (EN ISO 16890, $ePM_{2.5}$ ≥60%) in new and renovated buildings across all high-exceedance zones, and deployment of the ML prediction model as a real-time forecasting layer within Belgrade's emerging smart city digital infrastructure, enabling pre-emptive building management responses, citizen exposure alerts and data-driven policy decisions triggered by forecast pollution episodes.

Future work should extend this framework in two directions: upward, through integration with mesoscale atmospheric models and satellite aerosol retrievals to improve episode prediction at extreme concentrations; and downward, through hourly temporal resolution and expanded sensor coverage to resolve the diurnal heating and traffic cycles that drive within-day exposure variability and inform the next generation of building ventilation control standards.

ACKNOWLEDGMENT

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Research paper

MITIGATING URBAN HEAT ISLANDS IN INHERITED INDUSTRIAL SPACES – CASE STUDY OF NIŠ, SERBIA

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Abstract

Historic industrial areas represent some of the most thermally vulnerable urban environments due to extensive impervious surfaces, limited vegetation, and large structures that contribute to the formation of Surface Urban Heat Islands (SUHI). At the same time, many of these sites possess historical and cultural values, requiring mitigation strategies that are compatible with heritage conservation policies. This study investigates the relationship between historic industrial areas and SUHI formation in the city of Niš, Serbia, with the aim of identifying priority locations for UHI mitigation while supporting the sustainable regeneration of industrial heritage. The proposed methodology integrates Geographic Information Systems (GIS), remote sensing, and spatial analysis by combining Landsat-derived Land Surface Temperature (LST), the Normalized Difference Vegetation Index (NDVI), urban morphology, and heritage assessment. A total of 53 historic industrial sites were identified, while 18 representative case study areas were selected for detailed thermal assessment using daytime and morning satellite observations. The results indicate that industrial areas exhibit substantially higher land surface temperatures than surrounding suburban and rural environments, with temperature differences exceeding 10 ^{o}C. Several of the identified thermal hotspots also represent registered industrial heritage cultural goods, demonstrating that priority climate adaptation areas frequently are related to locations of cultural significance. The findings highlight the need for heritage-sensitive mitigation strategies in critical hotspots.

Key words: *Urban Heat Islands, Cultural Heritage, Industrial Heritage, Climate Adaptation, Mitigation*

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1. INTRODUCTION

Historic industrial areas represent some of the most thermally vulnerable urban landscapes. Designed to accommodate manufacturing processes, storage, heavy transport, and large-scale infrastructure [1], these sites are typically characterized by extensive impervious surfaces, large building footprints, sparse vegetation, and significant exposure to solar radiation. As a result, industrial areas can develop thermal hotspots with elevated land surface temperatures compared with their surrounding environments [2]. These characteristics make historic industrial spaces relevant to the study of urban heat accumulation and the creation of Surface Urban Heat Islands.

The Urban Heat Islands (UHI) is a phenomenon whereby urban areas experience higher temperatures than their surrounding rural environments, driven by urbanization, which replaces natural landscapes with concrete, asphalt, and other impervious materials [2]. As urban populations continue to grow, UHI has become an increasingly significant challenge for sustainable urban development [3]. UHI is commonly classified into two types: the Atmospheric Urban Heat Island (AUHI), which measures near-surface air temperature, and the Surface Urban Heat Island (SUHI), derived from remotely sensed Land Surface Temperature (LST) and widely applied in urban studies due to its consistent spatial coverage [4]. Materials with low albedo and high thermal capacity absorb and store large amounts of solar radiation, while the loss of vegetation reduces cooling through shading and evapotranspiration. The UHI effect contributes to increased energy consumption, air pollution, heat-related health risks, and reduced thermal comfort [5]. UHI mitigation and climate adaptation are closely related but refer to different objectives, and it is important to highlight their terminological distinction. UHI mitigation focuses primarily on reducing excessive urban heat and the physical conditions that contribute to heat accumulation [6]. Climate adaptation aims to reduce the effects of increasing temperatures on people, buildings, infrastructure, and urban systems. Some interventions can contribute to both objectives. For example, increasing vegetation can reduce surface temperatures while also providing shade and improving outdoor thermal conditions. In this context, the present study primarily focuses on the mitigation of surface urban heat in inherited industrial spaces, while recognizing that such interventions can also contribute to broader climate adaptation. It is also important to clearly explain the distinguishment between a thermal hotspot and SUHI. A thermal hotspot refers to a location characterized by relatively high surface temperatures, whereas SUHI describes the difference in surface temperature between urban and surrounding non-urban or reference environments [7][8]. Therefore, the identification of a thermally hot location does not, by itself, indicate the level of heat-related risk. Heat-related risk depends not only on the thermal hazard but also on the population, infrastructure, or other elements exposed to heat and their vulnerability. Since the present study does not explicitly assess population exposure or vulnerability, the identified priority locations should be understood as areas of elevated thermal hazard and potential priority for UHI mitigation, rather than as areas of highest heat-related risk.

Mitigation challenges are especially complex in historic urban environments [9][10], and studies have shown that inherited industrial spaces, contribute to the formation of

UHI [11][12]. At the same time, many historic industrial sites possess values that qualify them as industrial heritage. Their regeneration therefore involves a dual challenge: mitigating overheating and improving environmental performance while preserving the spatial character and cultural significance of inherited industrial structures. Beyond assigning a new function, regeneration must also enhance spatial quality to ensure a comfortable environment for users. In this context, outdoor thermal comfort emerges as a critical aspect. This parameter largely depends on local climatic conditions, as well as spatial morphology [13]. Thus, the process of urban renewal should not focus solely on the functional and aesthetic transformation, but also on the integration of Nature-based Solutions (NbS) and promotion of urban resilience of historic cities through the enhancement of well-being [13]. When revitalizing historic industrial sites, this task becomes even more significant, particularly because these areas are characterized by low-rise, large-footprint buildings, accompanied by vast asphalt surfaces [14][15].

This paper examines outdoor thermal comfort within inherited industrial sites in the city of Niš – which was selected as one of the most prominent historical industrial hubs in Serbia. More specifically, the paper focuses on analyzing the occurrence of SUHI. By conducting a Geographic Information Systems (GIS) based methodology, the purpose of this research is to identify critical spots where heritage-sensitive mitigation measures may be relevant.

2. RESEARCH METHODOLOGY

This research adopts a case study approach that combines remote sensing, GIS, and spatial analysis to investigate the relationship between historic industrial areas and the formation of SUHI in the city of Niš, Serbia – which was selected as a principal case study as it represents one of Serbia's largest historical production centers, where numerous inherited industrial sites still stand despite industrial decline. Moreover, the city exhibits a wide range of historical industrial typologies, and different heritage statuses – including ones with legal protection, and others that are officially taken into consideration for protection. The methodological framework integrates environmental indicators with heritage assessment in order to identify climate adaptation measures capable of reducing surface temperatures while supporting the sustainable conservation of industrial heritage areas.

Firstly, industrial areas in Niš were identified and mapped using GIS analysis, existing literature, archival documentation, and field surveys. The authors have relied on the industrial heritage classification conducted by The International Committee for the Conservation of the Industrial Heritage [16] and the European Route of Industrial Heritage [17], which recognizes factories, plants, infrastrucure, and historic military buildings as industry-related heritage. Furthermore, the authors reviewed academic research [18][19], on-site analysis, and land-use plugins in QGIS, such as OpenStreetMap data-extraction plugins in QGIS (QuickOSM) – used to retrieve land-use and infrastructure layers. Based on the combined methodology, a total of 53 historical industrial sites were identified in Niš.

Second, Landsat 9 OLI/TIRS Collection 2 Level-2 imagery acquired on 16 August 2024 was obtained from the USGS EarthExplorer platform and used to derive daytime Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI). The selected scene corresponds to WRS-2 path 185 and row 030. The Level-2 Surface Temperature (ST_B10) product was used for LST analysis. Unlike an LST value calculated manually from the original thermal band, the ST_B10 product provides surface temperature derived through the USGS Landsat Surface Temperature Algorithm, based on the TIRS Band 10 data. The thermal information has a native sensor resolution of approximately 100 m, while the Level-2 product is provided on a 30 m spatial grid, which represents a limitation of this research. The ST_B10 values were converted from digital numbers to Kelvin using the scale factor and additive offset specified for Landsat Collection 2 Level-2 Surface Temperature products, and converted to degrees Celsius for analysis. The resulting LST represents the estimated LST at the time of the Landsat acquisition and should not be interpreted as near-surface air temperature.

NDVI was calculated from the Landsat 9 red and near-infrared surface reflectance bands. The resulting 30 m NDVI raster was used to characterize the spatial distribution of vegetation within the study area and to examine its relationship with surface temperature. NDVI was calculated from Band 5 (near-infrared) and Band 4 (red). Areas with NDVI values above 0.2 were classified as vegetated for the spatial analysis.

To complement the daytime Landsat observations, morning LST values were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra satellite. The MODIS observations represent different observation timeframes and spatial resolution from the Landsat data and were treated as a complementary morning surface-temperature observation rather than a directly equivalent measurement [20].

Third, the results were compared with the locations of the previously identified and mapped industrial sites in QGIS. This overlay analysis enabled the detection of industrial areas that coincide with elevated surface temperatures and limited vegetation cover. For each industrial site, the daytime–morning temperature difference was calculated as the difference between the mean daytime Landsat LST and the corresponding mean morning MODIS/Terra LST. For the site-level thermal analysis, the boundaries of the 18 selected industrial sites were manually drawn in QGIS based on the identified spatial extent of each site and available cartographic and satellite data. The resulting polygons were used as spatial units for the extraction of LST values. The mean LST for each industrial site was calculated using the Zonal Statistics tool in QGIS. The calculated mean therefore represents the average LST of the raster cells located within each site boundary. No buffer was applied around the polygons. Therefore, this value represents the difference between the two satellite-derived surface-temperature observations at different times of day. It is interpreted as a measure of the observed diurnal surface-temperature contrast rather than as a direct measure of SUHI intensity.

Finally, the environmental indicators were synthesized with spatial and heritage-related analyses to identify critical spots. This stage focused on determining where mitigation measures may be required and assessing whether such interventions can be implemented in registered industrial heritage areas. The resulting prioritization is based

primarily on thermal hazard, represented by elevated land surface temperatures and temperature differences relative to surrounding suburban and rural areas. Surface temperature is treated as an indicator of thermal hazard, reflecting the intensity of surface overheating within the investigated areas. Rather than applying categorical thermal-favorability thresholds, the present study uses the observed LST values and their differences from suburban and rural reference areas as quantitative indicators of surface thermal hazard. However, surface temperature alone does not represent heat-related risk, which would additionally require consideration of population or asset exposure and vulnerability. Therefore, the thermal assessment is used to identify areas of elevated thermal hazard rather than to classify heat-related risk. Heritage status and current use are considered as contextual criteria for interpreting the suitability and sensitivity of potential mitigation interventions. However, population exposure and vulnerability are not explicitly assessed in this research.

3. QUANTITATIVE ANALYSIS

To investigate the relationship between industrial heritage of Niš and urban heat accumulation, the spatial distribution of SUHI and vegetation cover was analyzed using NDVI datasets (Figure 1) and Landsat-derived LST (Figure 2).

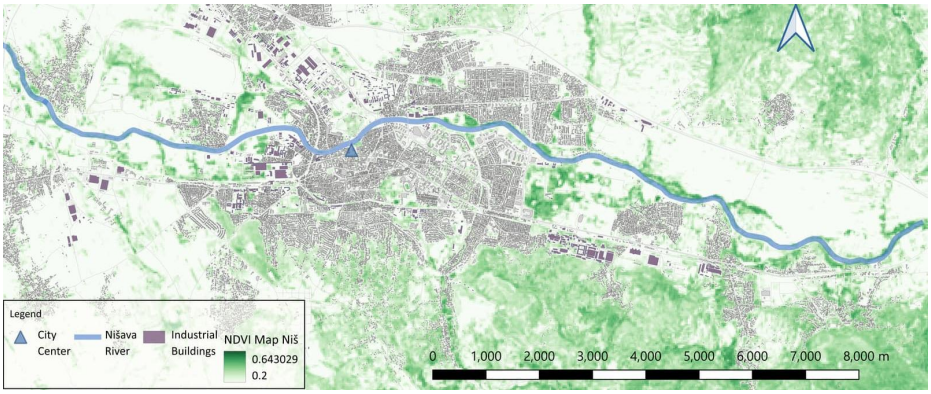


Figure 1. NDVI in the city of Niš, Serbia, obtained from Landsat 9 OLI/TIRS Collection 2 Level-2 imagery recorded on 16 August 2024 (Source: https://earthexplorer.usgs.gov/; edited in QGIS).

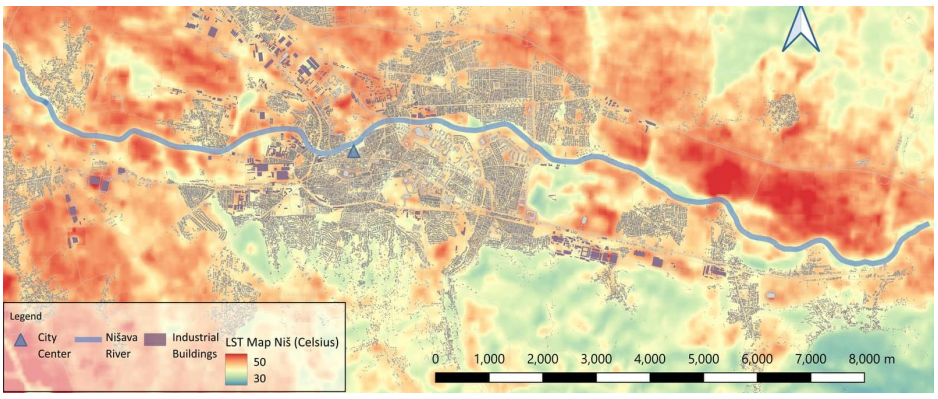


Figure 2. LST in the city of Niš, Serbia, obtained from Landsat 9 OLI/TIRS Collection 2 Level-2 imagery recorded on 16 August 2024 (Source: https://earthexplorer.usgs.gov/; edited in QGIS).

Eighteen industrial sites across the city were selected as case study areas. The selected sites encompass both urban and suburban locations, a range of current uses, and different heritage statuses, providing a representative sample of industrial areas undergoing various stages of transformation and regeneration (Table 1).

Table 1. Case study areas (source: Google Earth, authors)

Case study area	Location	Current use	Heritage status
1. New Brick Factory	Suburban	Abandoned	No
2. City Water Utility Site	Suburban	Infrastructure	No
3. Tobacco Industry Niš	Suburban	Industry	Yes
4. "Niteks" Textile Industry	Urban	Abandoned	No
5. Mechanical Industry – upper	Urban	Mixed-use	No
6. Mechanical Industry – greenery	Suburban	Abandoned	No
7. "Žitopek" Baking Industry Site	Suburban	Abandoned	No
8. "Bubanjski Heroji" Barracks	Urban	Abandoned	No
9. "Filip Kljajić" Barracks	Urban	Adaptive reuse	Yes
10. "Jastrebac" Pump Industry	Suburban	Abandoned	No
11. Mechanical Industry – Foundry	Suburban	Industry	No
12. Electronic Industry	Suburban	Mixed-use	Yes
13. Niš Brewery	Urban	Industry	No
14. City Heating Plant	Urban	Infrastructure	No
15. "Knez Mihailo" Barracks	Urban/Suburban	Military industry	No
16. "Pomoravlje" Industrial Site	Suburban	Business	No
17. "Old Monopoly" Industrial Site	Urban	Mixed-use	No
18. "Old Vulkan" Industrial Site	Urban	Abandoned	Yes

Their spatial distribution was subsequently compared with the city's LST map, revealing that the selected sites coincide with some of the most thermally intensive industrial zones (Figure 3).

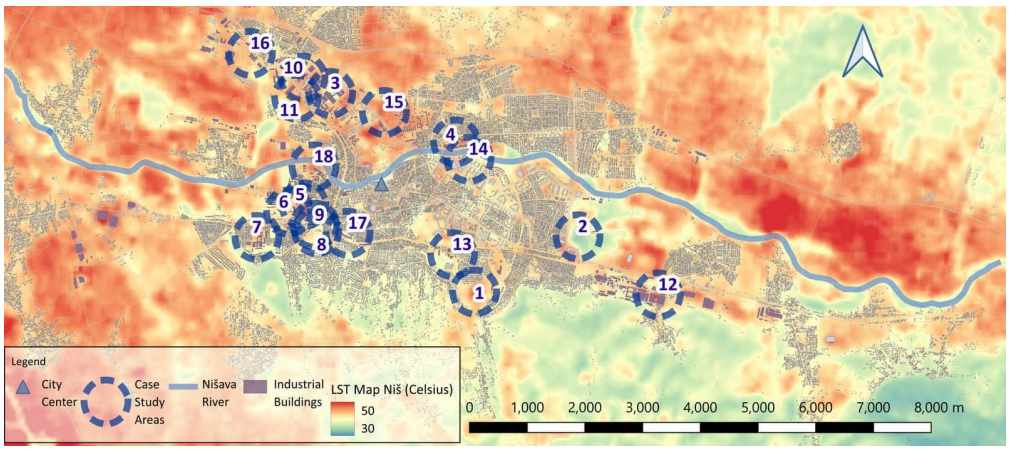


Figure 3. Identified areas with elevated surface heat in industrial spaces in Niš, Serbia, obtained from Landsat 9 OLI/TIRS Collection 2 Level-2 imagery recorded on 16 August 2024 (Source: https://earthexplorer.usgs.gov/; edited in QGIS).

4. RESULTS AND DISCUSSION

For each selected location, two LST values were considered: daytime LST derived from Landsat imagery and morning LST derived from MODIS/Terra imagery. The temperature difference was calculated as the daytime LST minus the morning LST and was used to describe the diurnal change in surface temperature. The average LST represents the arithmetic mean of the daytime and morning LST values and was calculated to provide a descriptive indicator of the thermal conditions at each location. Five additional suburban and rural locations were included as reference areas to provide a comparative thermal context for the investigated sites. These locations do not represent immediate surroundings of individual industrial sites; rather, they were selected to represent non-industrial suburban and rural environments within and around the wider study area. Their LST values were used to establish a comparative reference against which the thermal conditions of the industrial sites could be interpreted (Table 2).

Table 2. Daytime and morning LST, observed LST difference, and thermal favorability classification for the selected industrial sites and suburban/rural reference areas on August 16, 2024 (Source: Landsat satellite and NASA's MODIS satellite sensor)

Location	Daytime LST	Morning LST	Average LST	Difference LST
SUBJECT AREAS				
1. New Brick Factory	47,5 °C	26,8 °C	37,1 °C	20,7 °C
2. City Water Utility Site	34,2 °C	26,3 °C	30,3 °C	7,9 °C
3. Tobacco Industry Niš	37,0 °C	27,5 °C	32,3 °C	9,5 °C
4. "Niteks" Textile Industry	45,4 °C	28,2 °C	36,8 °C	17,2 °C
5. Mechanical Industry – upper	45,3 °C	28,1 °C	36,7 °C	17,2 °C
6. Mechanical Industry – greenery	41,5 °C	27,4 °C	34,4 °C	14,1 °C
7. "Žitopek" Baking Industry Site	44,6 °C	27,4 °C	36,0 °C	17,2 °C
8. "Bubanjski Heroji" Barracks	40,6 °C	28,3 °C	34,4 °C	12,3 °C
9. "Filip Kljajić" Barracks	39,7 °C	28,3 °C	34,0 °C	11,4 °C
10. "Jastrebac" Pump Industry	46,3 °C	28,2 °C	37,3 °C	18,1 °C
11. Mechanical Industry – Foundry	45,4 °C	27,2 °C	36,3 °C	18,2 °C
12. Electronic Industry	47,8 °C	25,2 °C	36,5 °C	22,6 °C
13. Niš Brewery	42,6 °C	27,8 °C	35,2 °C	14,8 °C
14. City Heating Plant	41,3 °C	28,2 °C	34,7 °C	13,1 °C
15. "Knez Mihailo" Barracks	46,8 °C	28,2 °C	37,5 °C	18,6 °C
16. "Pomoravlje" Industrial Site	44,3 °C	27,1 °C	35,7 °C	17,2 °C
17. "Old Monopoly" Industrial Site	42,0 °C	28,4 °C	35,2 °C	13,6 °C
18. "Old Vulkan" Industrial Site	46,6 °C	28,1 °C	37,3 °C	18,5 °C
Average (subject sites)	43,0 °C	27,6 °C	35,4 °C	
SUBURBAN (SU) AND RURAL (R) AREAS				
1. Memorial park „Bubanj" (SU)	35,8 °C	26,5 °C	31,1 °C	9,3 °C
2. Former FK Sinđelić site (SU)	35,9 °C	28,0 °C	32,0 °C	7,9 °C
3. Vinik settlment (R)	35,8 °C	26,4 °C	31,1 °C	9,4 °C
4. Koritnjak (R)	33,6 °C	26,2 °C	29,9 °C	7,4 °C
5. Mramor (R)	37,3 °C	24,9 °C	31,1 °C	12,4 °C
Average (suburban and rural areas)	34,0 °C	26,0 °C	30,0 °C	

Overall, industrial areas exhibited considerably high daytime surface temperatures than the surrounding suburban and rural environments. The average daytime LST of the investigated industrial sites reached 47.8 °C, while the mean daytime LST across the industrial sites was approximately 9 °C higher than that of the suburban and rural reference areas. Similarly, the average diurnal temperature increase was substantially greater within industrial areas than in the surrounding landscapes, confirming the contribution of industrial land use to local heat accumulation.

The highest daytime temperatures and temperature differences were recorded at the No. 12 and No. 1, exceeding over 20 °C of temperature difference between daytime and morning LST. These locations are characterized by extensive impervious surfaces, large building footprints, and exposed roofing materials – promoting rapid heat absorption and storage during the day. Conversely, lower temperature differences were observed at sites containing larger green areas, such as No. 2 and No. 3.

Of particular importance is the fact that several of the identified hotspots represent registered and institutionally protected industrial heritage assets. No. 12 and No. 18 are temporarily protected as Cultural Goods Under Previous Protection [21][22], while No. 3 and No. 9 are protected as a Spatial Cultural and Historical Unit and Cultural Monument, respectively [23]. In these cases, mitigation strategies and any other type of intervention need to align with conservation requirements, integrating heritage-sensitive interventions that preserve the historical character of these spaces. This finding demonstrates that areas requiring priority mitigation measures frequently coincide with locations of cultural significance. Spaces deprived of formal heritage protection could have more flexible regeneration approaches, as those sites lack formal conservation requirements. Mitigation strategies could include the alteration of the original fabric. Nevertheless, they should not endanger the authenticity and potential heritage values that are yet to be determined.

The spatial distribution of the identified hotspots provides a basis for prioritizing future mitigation challenges, as well as climate adaptation interventions. This integrated assessment demonstrates how remote sensing can support evidence-based decision-making in balancing climate resilience with appropriate industrial heritage conservation.

5. CONCLUSION

The results of this research demonstrated that historic industrial areas are spaces with significant elevation of surface heat. The principal contribution of this research lies in the development of an integrated GIS-based methodological framework that combines LST analysis, vegetation assessment through NDVI, urban morphology, and heritage evaluation to identify climate-vulnerable industrial sites. The proposed approach demonstrates how environmental indicators can be integrated with heritage conservation principles to support evidence-based decision-making in the regeneration of historic industrial areas.

The findings also provide several practical implications. The identified thermal hotspots establish priorities for implementing climate adaptation strategies that

simultaneously improve environmental performance and preserve industrial heritage values. The integration of previously defined measures into adaptive reuse projects can contribute to mitigating surface overheating while maintaining the authenticity and cultural significance of historic industrial sites. Consequently, the proposed methodology may serve as a practical decision-support tool for planners, conservation authorities, and local governments involved in the sustainable regeneration of former industrial areas.

Despite these contributions, several limitations should be acknowledged. The thermal analysis was based on satellite observations acquired on a single summer date and therefore does not capture seasonal or long-term temporal variability. In addition, the study relied primarily on remotely sensed LST rather than in-situ microclimatic measurements or human thermal comfort indices. Future research should incorporate multi-temporal satellite datasets, field measurements, and microclimate simulations to evaluate the effectiveness of specific mitigation strategies. Furthermore, applying the proposed methodology to other (post)industrial cities would enable comparative analyses and support the development of broader guidelines for climate-resilient regeneration of industrial heritage.

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This research contributes to SDG 11 – Sustainable Cities and Communities and SDG 13 – Climate Action by supporting climate-resilient urban regeneration, industrial heritage conservation, and evidence-based urban heat mitigation and adaptation.

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TOPIC 07

DIGITAL TECHNOLOGIES (BIM & DATA)

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

DOI: **10.5937/greenb26062S**
Research paper

DIGITAL TRANSFORMATION OF THE ARCHITECTURAL SECTOR IN SOUTHEAST EUROPE: BENEFITS AND CHALLENGES

Martina Stoyanova[1], Orlin Davchev [2]

Abstract

This study examines the process of digital transformation within the Architecture, Engineering, and Construction (AEC) sector in Southeast Europe. The primary focus is placed on the role of Building Information Modeling (BIM) as an integrated methodology for information management and project coordination. The research analyzes the levels of BIM implementation and maturity across the region, while highlighting the role of OpenBIM standards in enhancing interoperability among stakeholders in the construction and investment process. The study explores the specific characteristics of the regional digital transition, characterized by fragmented design workflows, limited institutional integration, and uneven levels of digital maturity. Furthermore, it evaluates national digitalization policies, BIM adoption in both public and private sectors, and the role of higher education in architecture and engineering across selected Southeast European countries. The paper identifies the key benefits of BIM, such as improved coordination, design optimization, and more efficient building lifecycle management. Additionally, it addresses significant implementation challenges, including the lack of standardization, limited investment, and resistance to organizational change. Finally, future trends in BIM development are outlined, emphasizing the integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin technologies, as well as the growing significance of digital ecosystems for the sustainable development of the construction industry.

Key words: *Building Information Modeling (BIM), Digital Transformation, OpenBIM, Digital Twin, Artificial Intelligence (AI)*

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1. INTRODUCTION

Over the past two decades, the Architecture, Engineering, and Construction (AEC) sector has undergone an intensive digital transformation. The primary drivers of this process have been advancements in information technology and the increasing need for more efficient data management throughout the design and construction lifecycle. In this context, Building Information Modeling (BIM) has emerged as an integrated methodology for the creation, coordination, and management of information throughout a building's entire lifecycle [1]. BIM facilitates more effective interdisciplinary coordination, the optimization of design processes, and improved sustainability within architectural practice.

The growing importance of BIM is closely linked to the evolution of the OpenBIM approach, the adoption of international information management standards, and the integration of technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin systems [2]. In many developed European countries, BIM serves as the foundation for building integrated digital ecosystems and smart data management.

Against this backdrop, the countries of Southeast Europe present a unique context for digital transformation. The region is characterized by an uneven level of digitalization, limited institutional integration, and fragmented design processes [3]. This is further influenced by disparities in educational frameworks, management models, and the level of digital maturity. Consequently, the adoption of BIM in the region is progressing at varying speeds, remaining concentrated primarily within large design firms and public-sector projects.

The relevance of this study stems from the need to analyze digitalization processes and the extent of BIM implementation across Southeast Europe. The primary objective is to evaluate the current status, level of adoption, and future development prospects for BIM practices within a regional context.

2. LEVELS OF BIM IMPLEMENTATION AND MATURITY OF BIM PROCESSES. ANALYSIS OF SOUTHEAST EUROPE.

2.1. BIM Maturity Levels 0–3

The concept of BIM Maturity Levels describes the stages that organizations and the construction sector undergo during the implementation of digital modeling [4]. This typology serves as a framework for assessing the extent to which principles of collaboration, standardization, and information integration are applied within architectural design, as shown in Figure 1.

Level 0 (CAD environment): This stage is characterized by the use of traditional 2D CAD tools devoid of an integrated environment for information exchange or management. Data is exchanged primarily via electronic drawings; the absence of interdisciplinary coordination frequently results in inconsistencies and redundant work.

Level 1 (2D/3D CAD with a Common Data Environment): At this stage, partial standardization is introduced, alongside a Common Data Environment (CDE) for the

centralized management of files and documentation. While discipline-specific models remain separate, data exchange is conducted according to established protocols.

Level 2 (Collaborative 3D modeling and coordinated data): This level serves as the foundation for BIM as a collaborative process. Individual disciplinary models are federated into a unified information model, with data exchange facilitated through standardized formats such as IFC and COBie [5].

Level 3 (Integrated BIM – iBIM): This stage is defined by a fully integrated environment and real-time information exchange among all project stakeholders throughout the building's lifecycle. At this level, BIM evolves toward Digital Twin systems, cloud-based platforms, and automated data management leveraging Artificial Intelligence (AI) and adherence to international standards, such as ISO 19650 [6].

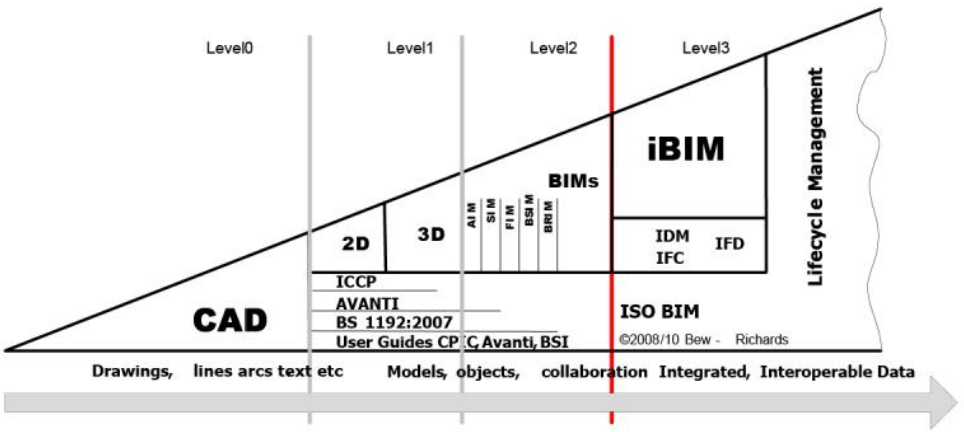


Figure 1. Bew–Richards BIM Maturity Model, Bew & Richards (2008) [4]

2.2. Analysis of Southeast Europe

Digital transformation in Southeastern Europe is characterized by uneven levels of digitalization, limited institutional integration, and varying degrees of BIM maturity across different countries and design organizations [3]. Across much of the region, clearly defined national BIM strategies and mandatory standards for public projects are still lacking, which hinders the systematic implementation of digital processes.

An additional challenge lies in the educational and professional preparation within the BIM field. In many cases, BIM training is still in the developmental stage, while professional practice remains focused primarily on traditional design methods, 3D modeling, and visualization [7].

A significant issue for the region remains the limited interoperability between various software environments and the absence of a common data environment (CDE). This fosters fragmented design practices and restricts effective coordination among stakeholders throughout the construction and investment process [5].

3. TECHNOLOGICAL TOOLS AND WORKFLOWS IN CONTEMPORARY BIM PRACTICE. OPENBIM

The current state of BIM in architectural practice is defined by the evolution of technological tools and workflows within the construction and investment process. Over the past two decades, BIM has established itself as the standard for modern design activities. The digital transformation of the architectural sector is driving the integration of various technologies into a unified information process.

Among the most widely used BIM platforms are Autodesk Revit, Graphisoft ArchiCAD, and Nemetschek Allplan. These tools enable the creation of intelligent information models containing geometric, parametric, and operational data. BIM environments are utilized not only for 3D modeling but also for project information coordination, documentation management, and tracking design changes throughout the process.

With the increasing use of diverse software platforms, the need for interoperability has become critical. It refers to the ability to achieve standardized information exchange between different BIM environments without loss of data or content. In multidisciplinary workflows, interoperability becomes a key factor for the coordination and effective management of project information.

In this context, the OpenBIM concept has gained strategic importance. Developed by buildingSMART International, it is based on the use of open standards such as IFC, BCF, and COBie [5]. These standards ensure sustainable information exchange between disparate software environments. The IFC format, in particular, is increasingly established as the primary standard for the structured description and exchange of building information [6], as illustrated in Figure 2.

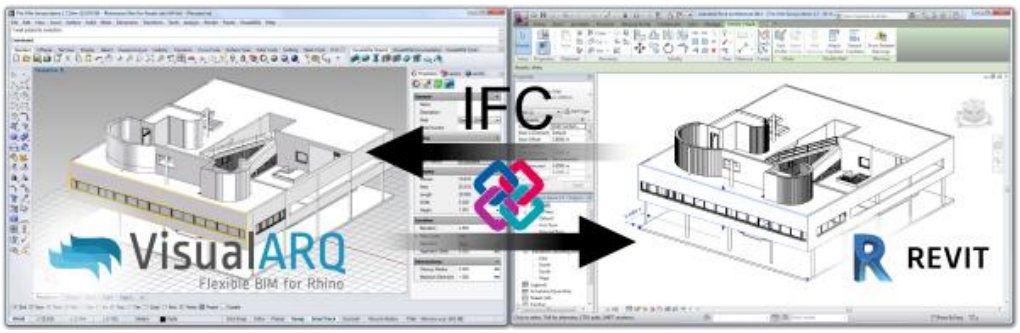


Figure 2.Exchanging models between Rhino and Revit through IFC, VisualARQ Official Website [12]

The OpenBIM approach enables more flexible collaboration among architects, engineers, investors, and contractors. At the same time, it reduces dependency on specific software vendors. This is particularly significant in the context of Southeastern Europe, where design teams often operate using various software systems and exhibit varying levels of digital maturity.

In modern architectural practice, BIM is gradually establishing itself as an integrated information environment that unifies design, coordination, and data management

throughout the entire building lifecycle [8]. In this process, OpenBIM plays a pivotal role in establishing sustainable and interoperable digital environments.

4. BENEFITS OF BIM IMPLEMENTATION IN ARCHITECTURAL PRACTICE

The implementation of BIM in architectural practice leads to significant benefits related to coordination, information management, and the optimization of design processes. In the context of Southeastern Europe, this is particularly critical due to the region's characteristic fragmented design practices and limited coordination among stakeholders in the construction and investment process. Through the creation of information models, design clashes can be identified during the design phase. This reduces the risk of errors and the necessity for subsequent changes during construction.

A key advantage of BIM is the potential for more effective exchange and management of project information among architects, engineers, investors, and contractors. Given the uneven digitalization and the use of diverse software environments, the BIM and OpenBIM approach facilitates interoperability and cross-disciplinary coordination [5]. This creates conditions for more effective communication, improved resource management, and higher traceability of project data.

BIM provides the capability for information management throughout the entire building lifecycle, from design to operation and maintenance. Of particular importance for Southeastern Europe are the opportunities for analyzing and optimizing the energy efficiency of buildings, given the challenges of high summer temperatures and the need for heating during the winter season. Through parametric modeling, energy simulations, and the monitoring of operational data, energy costs, resource efficiency, and the functional performance of buildings can be optimized [8]. This creates the prerequisites for more sustainable design and a gradual transition toward more integrated digital environments in architectural practice.

BIM further facilitates energy modeling by linking building geometry and envelope properties with performance-related parameters such as U-values, infiltration rates, thermal bridges, and solar gain coefficients, thus enabling rapid scenario testing from the early design stages. Through the connection between parametric models and energy simulation environments, it becomes possible to assess heating and cooling loads, the impact of orientation and glazing ratios, shading performance, natural ventilation potential, and daylight availability. This supports more informed decisions regarding envelope optimization, HVAC system selection, and passive design strategies, ultimately reducing operational costs and lifecycle emissions. In addition, integrated digital workflows and automated rule-based checks can support compliance with national energy performance requirements and sustainability certification frameworks, while also improving the traceability of assumptions used in the design process.

In the context of Southeastern Europe, BIM also represents a still underutilized opportunity for improving building energy performance and supporting the transition toward a decarbonized built environment. In a region marked by aging building stock, uneven renovation practices, and pressure on energy infrastructure, BIM-based workflows enable more accurate Building Performance Simulation (BPS) from the

earliest stages of design. By incorporating thermal properties, solar orientation, and envelope-related performance data into the intelligent model, architects can evaluate building behavior under both summer overheating and winter heating conditions. As a result, energy optimization is no longer treated as a late-stage verification procedure, but as an integral and generative part of the design process, contributing to more effective retrofit strategies, reduced lifecycle carbon emissions, and stronger alignment with contemporary sustainability goals.

Overall, the benefits of BIM implementation can be summarized in four main directions, as illustrated in Figure 3: quality, related to improving the quality and accuracy of project documentation; saving, including optimization of costs, resources, and process efficiency; time, focused on reducing delays and optimizing the project life cycle; and functionality, associated with improved communication, visualization, and access to project information. This demonstrates that BIM is gradually emerging as an integrated informational and methodological framework that is transforming architectural practice and supporting the broader digital and sustainable transition of the AEC sector in Southeastern Europe.

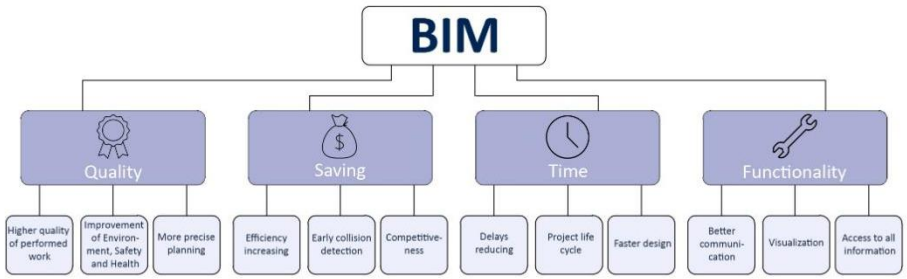


Figure 3. Main Benefits of BIM Implementation, Author's own work

5. CHALLENGES AND LIMITATIONS OF BIM IMPLEMENTATION

Despite the gradual development of BIM practices, its implementation in Southeastern Europe remains constrained by the lack of national BIM strategies, uneven digitalization, and limited institutional support. In many countries, the regulatory framework does not yet fully encompass BIM processes within the public sector, which hinders standardization and coordination among stakeholders in the construction and investment process [3].

A significant issue for the region remains the limited digital maturity of design organizations. In many cases, BIM is primarily utilized for 3D modeling and visualization, lacking established Common Data Environments (CDE) and coordinated information exchange protocols. This sustains fragmented design practices and limits effective interoperability between individual disciplines [5].

An additional challenge is the limited BIM training within architectural and engineering education. The lack of practical experience and systemic professional training often leads to partial implementation of BIM processes and inefficient management of project information.

The transition toward integrated digital processes in Southeastern Europe often proceeds at a slower pace compared to other European countries. This is attributable not only to limited institutional support and uneven digitalization but also to more conservative professional attitudes and deeply entrenched traditional working models within design practice [10].

6. CURRENT STATE OF BIM PRACTICE IN SOUTHEAST EUROPE

The development of BIM in the countries of Southeastern Europe is characterized by an uneven degree of digitalization, varying levels of institutional support, and limited regulatory integration within the public sector [3]. Although BIM has gradually established itself as part of architectural and engineering practice over the last decade, the region remains in a transitional stage between traditional design processes and the integrated digital environments characteristic of higher levels of BIM maturity.

The general trend indicates that the development of BIM in Southeastern Europe is being gradually stimulated by national digitalization policies, institutional initiatives, and the implementation of BIM in large-scale public and infrastructure projects [9]. Concurrently, there is a gradual integration of BIM into architectural and engineering education, although in most countries, training remains concentrated primarily on 3D modeling and basic coordination.

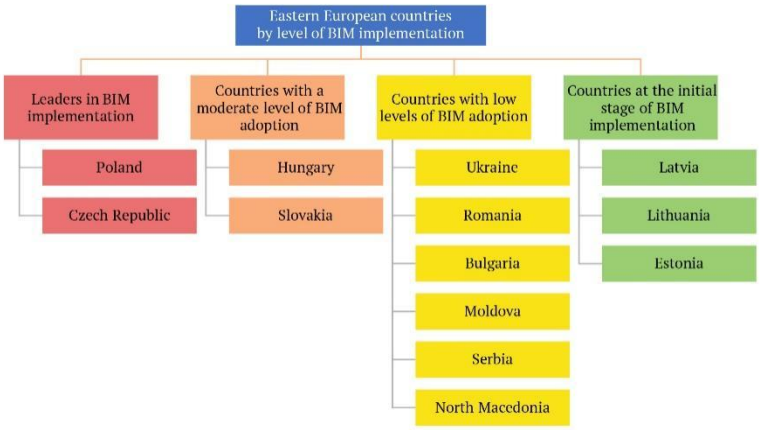


Figure 4. Classification of Eastern European countries by the level of BIM implementation, Ihor Mysak, Pavlo Mysak [3]

Figure 4 presents a summarized distribution of the countries in Eastern Europe according to their level of BIM implementation and digital integration. Although the broader comparative framework draws on Eastern Europe, the present study focuses specifically on Southeastern Europe due to the subregion's shared institutional, educational, and market-related conditions affecting BIM adoption. The majority of countries in the region are still in an early or transitional stage of BIM integration. This overall pattern highlights the uneven pace of digital transformation across the region and justifies the need for a more detailed comparative assessment. Since a significant share of the analyzed countries fall into the "Low levels of BIM adoption" category, the

next part of the research is aimed at a more in-depth analysis of selected cases. To address this gap, Table 1 presents a comprehensive comparative analysis developed by the authors, evaluating the institutional framework, private sector integration, and educational landscape across selected regional markets. The main focus of the study is divided into three key areas: state and institutional support, the level of BIM implementation in the private sector, and the integration of BIM training into architectural and engineering education.

Table 1. Comparative Analysis of BIM Adoption in Bulgaria, Romania, Croatia, Greece and Slovenia, Author's own work

Country	Public procurement frameworks and national policies	Private sector	Education
Bulgaria	The National Strategy for Digital Transformation of the Construction Sector 2030 envisages a phased implementation of BIM Level 2 in public procurement.	BIM is primarily used in large design firms, international companies, and infrastructure projects.	Limited BIM training, focused primarily on 3D modeling and basic coordination. Gradual development of BIM training, organized by EDIHs and supported by European digitalization programs.
Romania	There is a lack of mandatory national implementation. BIM is primarily promoted through European infrastructure programs.	In private projects, BIM is mainly used for industrial, logistics, and infrastructure projects with international participation.	Primarily 3D BIM training, with a gradual introduction of 4D and 5D concepts.
Croatia	There is no mandatory national BIM strategy, although there is active participation in European BIM initiatives.	BIM is mainly used for infrastructure, tourism, and international projects.	Focus primarily on 3D modeling and basic interdisciplinary coordination.
Greece	There is no clearly defined national BIM strategy. Digitalization is driven mainly by European infrastructure programs and the modernization of the construction sector.	BIM is primarily used in large-scale private investments, hospitality projects, and transport infrastructure with international involvement.	BIM integration in education remains limited, focusing primarily on 3D modeling and visualization.
Slovenia	The public sector has adopted BIM via the 'Action Plan for the Introduction of Digitalization for the Built Environment.' From 2025, BIM becomes mandatory for nationally significant projects, with policies further bolstered by the 'Digital Slovenia 2030' strategy.	BIM is widely adopted in both architectural and engineering practice, including public and infrastructure projects.	BIM is integrated at an advanced level, including 4D and 5D processes, supported by the activities of siBIM and buildingSMART Slovenia.

7. PERSPECTIVES FOR THE DEVELOPMENT OF BIM PRACTICE

The future development of BIM practice is characterized by a gradual transition from digital modeling to integrated environments for managing data, processes, and building operational performance. In this context, BIM is increasingly viewed not merely as a design tool, but as a foundation for building a comprehensive digital ecosystem. This environment integrates design, construction, operation, and the management of the building's life cycle.

A crucial factor for the advancement of BIM in the coming years will be the expansion of the regulatory and institutional framework related to the digitalization of the construction sector. A gradual introduction of BIM requirements in public procurement and a wider application of international standards, such as ISO 19650, is expected [6]. Within the context of Southeastern Europe, such policies could help overcome the fragmented design process and enhance the digital maturity of the sector.

The next stage in the evolution of BIM is linked to the integration of Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twin technologies. By connecting BIM models with operational data and automated systems, conditions are created for more efficient building management, resource optimization, and the development of more sustainable architectural solutions.

In a number of developed European countries, BIM is already being integrated with AI, IoT, and Digital Twin technologies as part of a broader digital transformation of the construction sector [13]. Compared to these trends, the countries of Southeastern Europe are still in an earlier stage of digital integration. BIM is primarily used for 3D coordination and documentation, while the implementation of AI and Digital Twin technologies remains limited mostly to large-scale international and infrastructure projects.

The future evolution of BIM practice can be envisioned as a transition from a digital modeling environment to an intelligent information infrastructure. This infrastructure unifies the design, analysis, operation, and management of the built environment. In this process, BIM, OpenBIM, AI, and Digital Twin technologies are gradually forming the foundation of the next generation of architectural and engineering practice.

8. CONCLUSION

This study examines BIM not merely as a digital modeling technology, but as an integrated information and organizational methodology that transforms the processes of design, coordination, and data management in architectural and construction practice. The analysis indicates that effective BIM implementation is linked not only to the use of specialized software but also to the establishment of standardized processes, interoperability, and a sustainable environment for information exchange.

The research on BIM maturity and the OpenBIM approach demonstrates that the countries of Southeastern Europe are in a transitional stage between traditional design practices and higher levels of digital integration. Despite the gradual development of

BIM in the region, there is still a limited regulatory framework, uneven digital maturity, and insufficient coordination among the various stakeholders in the construction and investment process.

In parallel, the development of AI, IoT, and Digital Twin technologies outlines the next stage in the evolution of BIM processes. BIM is gradually transforming from an environment for coordinating project information into an integrated digital infrastructure linked to data management, automation, and real-time analysis.

In the context of Southeastern Europe, successful digital transformation will depend not only on technological development but also on the ability of institutions, the educational system, and professional practice to build a shared digital culture, standardized processes, and effective mechanisms for information management. In this process, BIM, OpenBIM, and Digital Twin technologies are gradually forming the foundation of the next generation of architectural and engineering practice.

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Research paper

THE ROLE OF INTEGRATED EXTERNAL DRAWINGS IN SUSTAINABLE GREEN CIVIL ENGINEERING INFRASTRUCTURE

Sajad Akbar[1]

Abstract

Sustainable infrastructure depends not only on environmentally responsible materials and efficient buildings but also on the quality of coordination carried out before construction. This paper examines integrated external drawings as a practical coordination instrument for roads, grading, stormwater drainage, sewerage, potable water, fire protection, electrical systems, ICT and fibre-optic networks, renewable-energy interfaces, landscaping, and other site utilities. A qualitative, practice-based methodology was used to synthesize relevant literature on sustainable infrastructure, Building Information Modelling (BIM), digital coordination, clash detection, quantity take-off, and construction waste reduction, together with professional experience in quantity surveying, CAD drafting, infrastructure estimation, and construction management. The review indicates that the main value of integrated external drawings is not the drawing itself but the coordination process that it represents: common survey information, discipline interface management, early conflict identification, coordinated routing, quantity verification, construction sequencing, and sustainability review. An integrated coordination framework is proposed and illustrated through a simplified infrastructure case. The framework links topographic information and discipline-specific designs to an integrated external drawing, multidisciplinary review, clash resolution, quantity take-off, construction planning, and sustainability assessment. The study does not claim a statistically measured reduction in cost, waste, or carbon emissions for a single project; rather, it synthesizes evidence and practice-based observations showing how early coordination can reduce avoidable rework and resource inefficiency. The paper concludes that integrated external drawings should be treated as strategic coordination deliverables within digital and sustainable infrastructure workflows, particularly where multiple underground and above-ground systems compete for limited space.

Key words *Green Building; Sustainable Infrastructure; Integrated External Drawings; Utility Coordination; Multidisciplinary Coordination; BIM; Clash Detection*

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1. INTRODUCTION

Sustainable infrastructure is a central concern in civil engineering because infrastructure decisions affect resource consumption, environmental performance, resilience, construction cost, and long-term operation. Sustainability is often associated with energy-efficient buildings, renewable energy, low-carbon materials, water conservation, and green certification. However, surrounding infrastructure—including roads, grading, drainage, sewerage, water supply, fire water, electrical distribution, communications, gas, irrigation, and landscape systems—also determines project efficiency and sustainability. These systems are commonly developed by different disciplines and at different stages. A technically correct drawing may create conflicts when overlaid with another discipline's design. For example, a sewer line may conflict with a stormwater pipe, a duct bank may occupy a drainage corridor, a road profile may constrain gravity drainage, or irrigation may interfere with underground utilities. Such conflicts become more costly when discovered during construction, requiring excavation, redesign, material replacement, additional equipment, or disruption of completed work. Digital engineering has strengthened the management of these interfaces. BIM provides an information-rich environment for design and coordination, while GIS and survey information provide spatial context for infrastructure assets. ISO 19650 establishes principles for managing information across the asset life cycle, including planning, design, engineering, construction, operation, and maintenance [1]. Research on BIM-based clash detection, quantity take-off, and waste minimization indicates that coordination can move problem identification toward earlier project stages [2–5]. Despite this progress, many infrastructure projects still rely on two-dimensional discipline drawings and manual coordination. The role of an integrated external drawing as the practical interface between disciplines is less explicitly discussed than BIM as a general technology. This paper therefore focuses on the coordination process represented by the integrated external drawing and asks: (1) What coordination problems are most relevant to sustainable external infrastructure? (2) How can findings on BIM, digital coordination, and resource efficiency inform an integrated drawing workflow? and (3) What framework can connect design coordination with quantity take-off, construction planning, and sustainability objectives?

2. LITERATURE REVIEW

The literature was reviewed thematically rather than as a formal systematic review. Sources were selected because they address one or more of the following themes: sustainable infrastructure and development, BIM and information management, BIM/GIS integration, clash detection, quantity take-off, and construction-waste reduction. The purpose was to synthesize what existing studies indicate, identify limitations in current emphasis, and establish the research gap addressed by the proposed framework.

2.1. Sustainable Infrastructure and Resource Efficiency

Sustainable development requires infrastructure decisions to consider environmental, economic, and social performance over time. The UN 2030 Agenda links infrastructure and urban development with resource efficiency, resilience, and sustainable communities [6]. Sustainability therefore depends on constructability, maintenance, material use, water management, and future adaptability.

Resource efficiency is shaped by pre-construction decisions. Alignments, levels, pipe routes, utility corridors, access, and sequencing affect excavation, material handling, equipment movement, and maintenance. Sustainable planning should therefore consider system interactions rather than individual systems in isolation.

2.2. BIM, Information Management and Multidisciplinary Coordination

Sacks et al. [7] describe BIM as a digital approach supporting information exchange and interoperability across design, construction, and facility management [7]. ISO 19650 emphasizes organized information management, version control, information exchange, and collaboration across the asset life cycle [1]. These principles support integrated external drawings through reliable information, clear responsibilities, controlled revisions, and common references. Chen et al. noted that BIM provides detailed asset information while GIS adds geographic and environmental context [8]. For external infrastructure, utility geometry must therefore be considered alongside topography, existing services, right-of-way constraints, and site conditions. However, BIM-GIS integration faces interoperability challenges, so practical workflows should remain usable without fully federated models.

2.3. Clash Detection and Constructability

Clash detection is a key benefit of digital coordination. Seo et al. found that BIM-based clash detection can improve constructability by identifying conflicts before construction [3]. Chahrour et al. emphasized the cost benefits of resolving design problems before physical rework occurs [4]. Thus, earlier conflict identification can reduce downstream disruption. However, software does not replace engineering judgment; clearances, maintenance access, gravity, sequencing, and future expansion must also be considered. Integrated drawing review therefore requires both digital checking and multidisciplinary engineering review.

2.4. Quantity Take-off, Waste and Sustainability

Won and Cheng identified BIM opportunities for waste minimization through design review, 3D coordination, quantity take-off, phase planning, and site utilization [2]. Taghaddos et al. demonstrated BIM-supported automated quantity take-off for construction planning and estimation [9]. These findings show that coordinated geometry and controlled revisions improve quantity reliability and reduce conflicting estimates. Aftab et al. linked BIM with construction-waste quantification [10], while Handayani et al. connected BIM with circular-economy practices and material recycling [11]. Overall, better coordination can reduce rework, material replacement, excavation, and inefficient procurement while supporting resource planning and reuse.

2.5. Literature Synthesis and Research Gap

The literature shows broad agreement on four points. First, multidisciplinary coordination should occur early. Second, digital information environments can improve information exchange and conflict identification. Third, coordinated information can support quantity, planning, and waste-management decisions. Fourth, sustainability is increasingly evaluated across the project life cycle rather than only during building operation [1,2,7,10,11].

However, much of the literature focuses on BIM as a technology, adoption, or building-scale applications. Roads, grading, drainage, sewerage, water, fire water, electrical, ICT, renewable-energy interfaces, and landscape systems often require coordination within common external site space, where two-dimensional drawings remain widely used. The research gap is therefore practical rather than technological: how can the integrated external drawing function as a coordination layer connecting survey information, discipline designs, clash review, quantities, construction sequencing, and sustainability assessment?

3. RESEARCH METHODOLOGY

This study uses a qualitative, practice-based methodology combining thematic literature review with professional experience in quantity surveying, CAD drafting, infrastructure estimation, and construction management. The research develops a practical coordination framework rather than estimating a universal numerical effect. It comprises five stages:

- **Literature review:** BIM, information management, clash detection, infrastructure coordination, quantity take-off, waste minimization, and sustainability.
- **Project-information definition:** Survey data, existing utilities, design criteria, levels, alignments, and discipline requirements.
- **Multidisciplinary coordination:** Review of civil, structural, mechanical, electrical, ICT, environmental, and landscape information using common references.
- **Construction and quantity assessment:** Evaluation of quantities, procurement, sequencing, access, excavation, installation, and maintenance.
- **Sustainability assessment:** Identification of opportunities to reduce excavation, rework, material use, equipment movement, water losses, and maintenance constraints. Literature evidence and practice-based observations inform the workflow. The framework is a transferable engineering approach requiring project-specific validation, not a claim of fixed percentage savings.

4. INTEGRATED COORDINATION FRAMEWORK AND PRACTICAL APPLICATION

The proposed framework treats the integrated external drawing as a coordination layer rather than a final drawing sheet. It begins with reliable survey and project information and ends with a coordinated, construction-ready infrastructure layout. Each stage informs the next, with backward review when conflicts are identified.

Integrated External Drawing Coordination Workflow

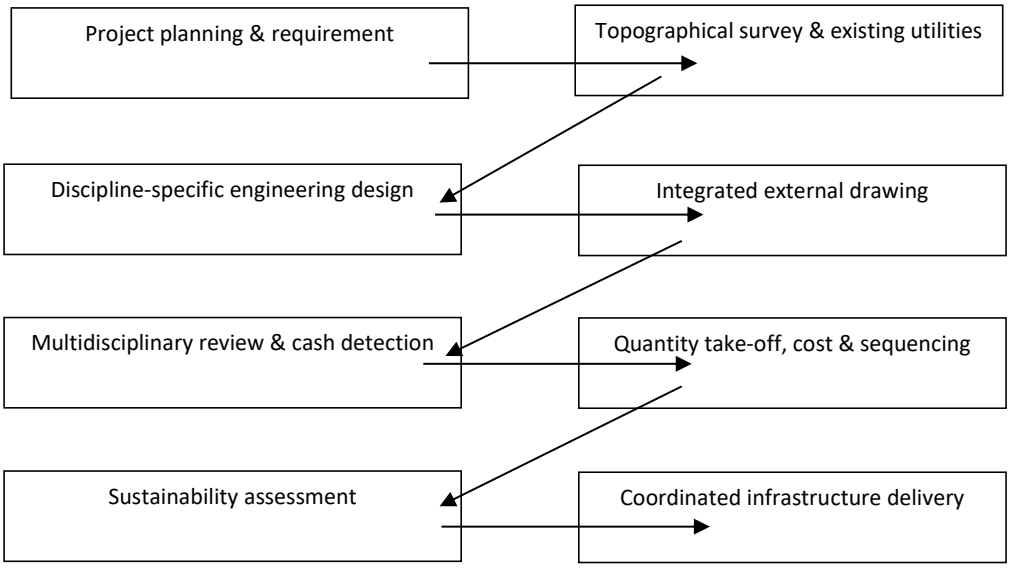


Figure 1. Integrated external drawing coordination workflow. Source: Developed by the author.

4.1. Stage 1: Survey, Existing Conditions and Common Reference

Topographic survey, site boundaries, existing services, benchmarks, road constraints, structures, and environmental conditions should be established first. All disciplines should use consistent coordinates, levels, naming, and revision data. Uncertain utility information should be clearly identified rather than hidden in the drawing.

4.2. Stage 2: Discipline-Specific Design

Individual disciplines develop designs according to applicable standards and project requirements. The integrated process retains discipline responsibility while adding interface review before designs create construction constraints. Typical systems include roads, grading, drainage, sewerage, water, fire protection, electrical, ICT, gas, irrigation, renewable energy, and landscape works.

4.3. Stage 3: Integrated External Drawing and Clash Review

Discipline information is combined on a common external plan and, where available, a coordinated digital model. Conflicts should be reviewed in plan and profile/section,

considering clearance, hydraulics, access, constructability, maintenance, expansion, levels, and sequencing. BIM checking can assist where models exist, while CAD overlays and sections remain useful for projects without complete BIM models.

4.4. Stage 4: Quantity, Procurement and Construction Sequencing

After coordination, quantities can be checked against the latest geometry and specifications. Changes in routes, levels, pipe sizes, trenches, manholes, duct banks, chambers, and roads can affect quantities and procurement. Coordinated information also supports sequencing, such as installing deep utilities before shallow services and completing underground works before roads and landscaping.

4.5. Stage 5: Sustainability Assessment

The final review should identify avoidable environmental and resource impacts, including excessive excavation, unnecessary pipe lengths, crossings, reinstatement, equipment movement, water losses, poor drainage, and restricted maintenance access. It should also consider rainwater harvesting, recycled water, permeable drainage, efficient lighting, renewable energy, and landscape water management.

4.6. Simplified Practical Case Illustration

Consider a hypothetical site with roads, sewerage, stormwater, potable and fire water, electrical and ICT ducts, irrigation, and landscaping. The case is illustrative and not based on measured project data. Initial survey information establishes road corridors and constraints, followed by discipline-specific designs. Integration may reveal conflicts such as sewer–stormwater crossings, electrical ducts occupying water-main corridors, and irrigation crossing major utilities. Routes can then be revised to preserve gradients and clearances, consolidate corridors, and sequence deep services before shallow ones. The key lesson is that integrated drawings shift conflict detection from construction to design, reducing the potential for redesign, delays, standby equipment, material replacement, and trade disruption.

5. RESULTS AND DISCUSSION

The literature synthesis and practice-based analysis indicate that integrated external drawing coordination provides five connected benefits: interface control, constructability improvement, quantity and procurement reliability, resource efficiency, and sustainability integration. These benefits should be interpreted as process-level outcomes rather than as universally quantified savings.

Table 1. Coordination Issues and Sustainability Implications of Major External Infrastructure Systems

Infrastructure system	Typical coordination issue	Coordination response	Resource / sustainability implication	Project-level effect
Roads & grading	Level and corridor conflicts	Common grading model/drawing review	Reduced unnecessary earthworks and equipment movement	Improved constructability
Stormwater drainage	Crossings and hydraulic constraints	Early profile and route coordination	Better drainage performance; less rework	Reduced installation disruption
Sewerage	Utility interference and gravity constraints	Clash review plus profile coordination	Reduced excavation changes and material waste	Improved reliability
Potable water	Clearance and alignment constraints	Shared utility corridor planning	Reduced route changes and future access problems	Improved serviceability
Fire protection	Conflicts with buried services	Coordinated network layout	More efficient installation sequencing	Improved safety and constructability
Electrical MV/LV	Duct-bank conflicts	Digital/2D coordination and sections	Reduced rework and avoidable excavation	Improved construction efficiency
ICT/fibre optics	Limited underground space	Shared corridor and separation planning	Optimized use of site space	Better future maintenance
Renewable-energy interfaces	Connection and equipment interfaces	Early electrical and civil coordination	Supports energy-efficiency integration	Reduced late design changes
Landscape & irrigation	Conflicts with buried utilities	Integrated landscape/utility planning	Better water management and reduced rework	Improved site quality

5.1. Interface Control as the Primary Result

The most important finding is that integrated external drawings provide a common interface for disciplines that otherwise operate through separate documents. This is consistent with the information-management principles of ISO 19650 and the collaborative function described for BIM [1,7]. The drawing therefore becomes a communication mechanism: it makes route, level, corridor, access, and sequencing decisions visible to all relevant disciplines.

5.2. Constructability and Clash Resolution

Research on clash detection supports early identification of geometric conflicts and improved constructability [3,4]. The proposed framework extends this principle by

requiring engineering review beyond geometric intersection. A route may be technically clear in a model but still be difficult to construct if access is inadequate, if the excavation sequence is impractical, or if a gravity system loses its required gradient. Accordingly, clash detection should be treated as one stage of a broader constructability review.

5.3. Quantity and Procurement Reliability

Coordinated drawings improve the basis for quantity take-off because the estimator is less likely to measure from inconsistent or superseded layouts. Literature on BIM-supported quantity take-off demonstrates the potential for linking model geometry with estimation and planning [9]. Even where a project uses conventional CAD, the same principle applies: the latest coordinated drawing should be the controlled source for measurement, while changes should be recorded through revision control.

5.4. Resource Efficiency and Carbon Implications

The relationship between coordination and carbon reduction is primarily indirect. Avoiding a redesign can avoid additional drawing production and site disruption; avoiding re-excavation can reduce plant operation, fuel use, disposal, imported fill, and replacement materials. Research on BIM and waste minimization similarly identifies design review, coordination, quantity take-off, and phase planning as opportunities to reduce waste [2,10]. However, the present study does not quantify a project-specific carbon saving. Such a result would require measured baseline data, quantities, equipment hours, material inventories, and an agreed life-cycle carbon methodology.

5.5. Sustainability Integration Beyond Conflict Avoidance

Integrated coordination can also create opportunities that are difficult to see when systems are designed independently. For example, rainwater harvesting can be coordinated with drainage and irrigation; recycled-water networks can be coordinated with landscape demand; energy-efficient lighting can be coordinated with electrical infrastructure; and renewable-energy connections can be reserved within the civil and electrical layout. Thus, the integrated drawing is not only a conflict-prevention tool but also a platform for embedding sustainability measures into the site infrastructure.

5.6. Limitations and Future Research

The study has three main limitations. First, the methodology is qualitative and practice-based rather than statistically validated. Second, the practical case is illustrative rather than a measured real-project dataset. Third, the benefits of coordination vary with project scale, design maturity, procurement method, survey quality, software capability, and team experience. Future research should test the framework on multiple infrastructure projects and measure indicators such as number of clashes before construction, rework hours, change orders, excavated quantities, material waste, equipment hours, design-review time, and life-cycle carbon. A controlled comparison between coordinated and non-coordinated workflows would provide stronger quantitative evidence.

6. CONCLUSION

This study examined the role of integrated external drawings in sustainable green civil engineering infrastructure. The literature indicates that BIM, information management, clash detection, quantity take-off, and waste-minimization practices can improve multidisciplinary coordination and enable earlier problem identification. However, practical coordination remains dependent on reliable survey information, discipline interfaces, engineering judgment, and controlled drawings. The proposed framework places the integrated external drawing at the centre of this process, connecting topographic information, discipline-specific design, multidisciplinary review, clash detection, quantity take-off, construction sequencing, and sustainability assessment. It is particularly relevant where roads, grading, drainage, sewerage, water, fire protection, electrical, ICT, renewable-energy, and landscape systems compete for limited space. The principal conclusion is that integrated external drawings should be treated as strategic coordination deliverables rather than drafting outputs. By improving interface visibility, supporting quantity verification, facilitating constructability review, and integrating sustainable systems, they can contribute to more resource-efficient, resilient, and lower-carbon infrastructure delivery. As this qualitative study lacks a controlled project dataset, the proposed benefits should not be interpreted as fixed numerical savings. Empirical validation using measured project data is recommended. Nevertheless, the framework provides a practical basis for multidisciplinary coordination and bridges conventional external engineering drawings with digital, BIM-enabled infrastructure delivery.

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

APPLICATION OF DIGITAL TECHNOLOGIES IN THE DEVELOPMENT OF GREEN BUILDINGS: EXPERIENCES FROM SOUTH KOREA

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Abstract

In the context of climate change and rapid urbanization, the construction sector plays a crucial role in achieving sustainable development. This paper analyzes the role of BIM, IoT, Digital Twins, and AI in green building development, with emphasis on South Korea. Using a qualitative case study approach (Songdo, Sejong, Busan Eco Delta City), the findings show that integrating these technologies optimizes energy performance and resource management. Successful implementation requires institutional support, data standardization, and long-term strategy. South Korea's experience offers valuable lessons for advancing sustainable construction in Serbia.

Key words: *Green buildings, Building Information Modeling (BIM), Internet of Things (IoT), Digital Twins, Energy efficiency*

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1. INTRODUCTION

Previous studies have demonstrated that smart technologies play a significant role in achieving sustainable development goals through improved energy efficiency, resource management, and enhanced resilience of urban systems [1, 2]. The Republic of Korea, through the development of smart cities such as Sejong, Songdo, and Busan Eco Delta City, has demonstrated the potential of integrating digital platforms, sensor networks, and data analytics systems into sustainable urban development [3, 4]. However, urban sustainability depends not only on infrastructure and city-wide systems but also on the performance of individual buildings that constitute the urban environment. In this context, green buildings represent the fundamental functional units of sustainable cities. Their importance is reflected in reducing energy consumption, promoting the efficient use of natural resources, and minimizing carbon dioxide emissions throughout the entire building life cycle [5, 6]. The development of green buildings is increasingly linked to the digital transformation of the construction sector. Technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), Digital Twins, and Artificial Intelligence (AI) enable the collection, processing, and analysis of data during the design, construction, and operation phases of buildings, generating significant environmental, economic, and operational benefits [7, 8]. The aim of this paper is to analyze the application of BIM, IoT, Digital Twins, and Artificial Intelligence in the development of green buildings, with particular emphasis on the experiences of the Republic of Korea and the potential for their implementation in the Republic of Serbia. Based on the research objective, the following research questions were formulated:

1. How are BIM, the Internet of Things (IoT), Digital Twins, and Artificial Intelligence (AI) applied in the development of green buildings in the Republic of Korea?
2. What are the key technological, regulatory, and institutional mechanisms that support the integration of these technologies within the Korean context?
3. Which elements of the Korean model can be adapted and implemented in the Republic of Serbia, considering its economic, institutional, and developmental specificities?

The answers to these questions are derived through case study analysis and a comprehensive literature review, as described in the following section.

2. MATERIALS AND METHODS

This study adopts a qualitative research strategy based on the integration of a case study approach and a systematic literature review. Such a combined methodology enables a deeper understanding of complex phenomena within their real-world context while ensuring the theoretical grounding of the findings [8].

2.1. Case Study Selection

The case studies were selected through purposive sampling according to the following criteria:

- Representativeness – the selected projects are widely recognized in academic literature and international reports as leading examples of smart city development in South Korea.
- Diversity – the projects represent different stages and approaches to smart city development, including Songdo as an early smart city concept, Sejong as a national pilot project, and Busan Eco Delta City with a strong focus on climate resilience.
- Data availability – all selected cases are supported by official reports, peer-reviewed publications, and documents published by international organizations.

Based on these criteria, the following case studies were analyzed: Songdo International Business District, Sejong Smart City, and Busan Eco Delta Smart City.

2.2. Data collection and analysis process

Data collection involved a review of scientific publications indexed in Scopus, Web of Science, and Google Scholar. In addition, official documents issued by the Government of the Republic of Korea, the Ministry of Land, Infrastructure and Transport, as well as reports published by the World Bank and the OECD, were analyzed. Only publications published between 2010 and 2025, written in English or Korean, and focused on the application of digital technologies in sustainable construction were included in the analysis. The collected data were analyzed using thematic analysis. The reviewed materials were coded according to predefined thematic categories, including BIM applications, IoT applications, Digital Twin applications, Artificial Intelligence applications, regulatory and institutional mechanisms, as well as barriers and implementation challenges. Based on these thematic codes, conclusions were drawn regarding the patterns of digital technology integration within South Korean green building projects. To facilitate understanding of the research process, Figure 1 presents a schematic overview of the methodological framework employed in this study. The framework illustrates the sequential flow from case study selection through data collection, thematic analysis, and synthesis of findings. This structured approach ensures transparency and replicability of the research process.

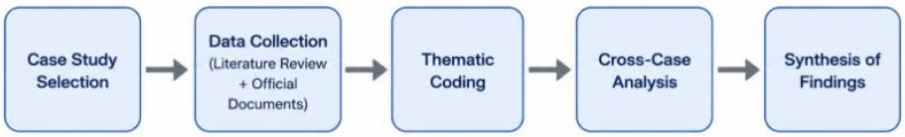


Figure 1. *Methodological framework: Case study selection → Data collection (literature review + official documents) → Thematic coding → Cross-case analysis → Synthesis of findings*

3. RESULTS AND DISCUSSION

3.1. Integration of Digital Technologies in Korean Green Building Projects

The analysis of the three case studies reveals distinct patterns in the application of digital technologies for green building development in South Korea. Table 1 provides a comparative overview of how BIM, IoT, Digital Twins, and AI are implemented across

the selected projects, highlighting both common approaches and project-specific characteristics.

The comparative analysis reveals that Songdo, as the earliest project, focused primarily on foundational infrastructure and integrated systems, establishing a baseline for subsequent developments [9]. Sejong represents a more advanced iteration, with stronger emphasis on data integration and predictive analytics, while Busan demonstrates the most sophisticated integration, particularly in the context of climate resilience and adaptive management. This evolutionary pattern suggests a learning trajectory in Korean smart city development, where each subsequent project builds upon the technological and institutional lessons of its predecessors.

Table 1. Comparative Analysis of Digital Technology Applications in South Korean Green Building Projects

Technology	Songdo IBD	Sejong Smart City	Busan Eco Delta City
BIM	Integrated BIM for design and construction coordination; LEED certification support	National BIM standards applied; energy performance simulation for all public buildings	BIM models integrated with GIS for flood risk assessment and climate resilience planning
IoT Sensors	Extensive sensor networks for energy monitoring; smart metering in all commercial buildings	Real-time monitoring of indoor environmental quality; smart water management systems	Comprehensive environmental monitoring (water quality, air quality, temperature); AI-integrated sensor networks
Digital Twins	City-scale digital twin for infrastructure management	Building-level Digital Twins for energy optimization; urban-scale simulation platform	Climate adaptation Digital Twin; building performance simulation for extreme weather scenarios
Artificial Intelligence	Predictive maintenance for building systems	AI-driven HVAC optimization; predictive energy demand forecasting	Machine learning for flood prediction; AI-optimized building energy management

Source: Authors' compilation based on analysis of Songdo IBD [9, 10], Sejong Smart City [3, 11], and Busan Eco Delta Smart City [4, 12]

3.2. Key Findings from Case Study Analysis

The analysis of the three case studies yields the following key findings:

Songdo International Business District: As one of the world's first large-scale smart city projects, Songdo demonstrates the importance of integrating digital infrastructure from the earliest planning stages. The project's building management systems

continuously monitor energy consumption and environmental conditions, achieving approximately 30% energy savings compared to conventional buildings [9]. However, the project also illustrates challenges, including high initial costs and the need for continuous system upgrades [13]. Sejong Smart City: Sejong represents a more comprehensive approach, integrating national BIM standards and establishing a Digital Twin platform for both urban and building-level management. The project has achieved significant improvements in energy efficiency, with public buildings demonstrating 25-35% reductions in energy consumption through AI-optimized HVAC systems [14]. The national pilot status of Sejong has enabled systematic testing and validation of innovative technologies. Busan Eco Delta Smart City: This project demonstrates the most advanced integration of digital technologies for climate resilience. The combination of AI-enhanced flood prediction models, real-time environmental monitoring, and Digital Twin simulation capabilities enables proactive adaptation to climate change impacts. The project's focus on water management and climate resilience distinguishes it from the other two case studies [4, 15].

3.3. Enabling Factors and Barriers

The cross-case analysis identifies several key enabling factors for successful digital technology integration in green building development. Strong government leadership and strategic planning emerge as critical success factors, with South Korea's national smart city strategy providing both funding and regulatory support [3]. Institutional capacity building, including training programs for BIM and digital literacy, has also been essential [16]. Furthermore, the establishment of data standards and interoperability frameworks has facilitated integration across different systems and platforms [17]. However, several barriers persist. High initial investment costs remain a significant challenge, particularly for smaller projects and retrofits. The complexity of integrating multiple technologies and ensuring interoperability between different systems also presents technical challenges [7]. Data privacy and security concerns, particularly regarding IoT sensors and building-level monitoring, require careful attention [16]. Finally, the shortage of skilled professionals with expertise in both digital technologies and sustainable construction continues to limit implementation capacity [18].

4. DIGITAL TECHNOLOGIES IN GREEN BUILDING MANAGEMENT

4.1. BIM as the Foundation of Digital Transformation

In South Korea, BIM has become one of the key digital technologies supporting the transition toward sustainable construction [13]. Since the implementation of the national BIM roadmap, its application has become mandatory for many public construction projects managed by the Public Procurement Service (PPS) and the Ministry of Land, Infrastructure and Transport (MOLIT) [14]. BIM has been widely adopted in large-scale projects, including administrative buildings, transport infrastructure, hospitals and public housing developments. The integration of BIM with energy simulation tools enables designers to evaluate alternative design solutions

during the early planning stages, resulting in improved energy performance and reduced embodied carbon [19]. In projects certified under the Korean Green Standard for Energy and Environmental Design (G-SEED), BIM supports compliance with energy efficiency requirements by facilitating daylight analysis, thermal simulations and life-cycle assessment [20]. These applications have significantly reduced design conflicts, shortened construction time and improved resource efficiency throughout the project life cycle.

4.2. IoT Sensors and Real-Time Data Collection

South Korea has extensively deployed IoT-based monitoring systems in green buildings and smart city districts such as Songdo International Business District, Sejong Smart City and Busan Eco Delta City [16]. Thousands of sensors continuously collect information on indoor environmental quality, occupancy, electricity consumption, water use and HVAC performance [17]. These data are integrated into centralized Building Management Systems (BMS), allowing real-time optimization of building operation. Several demonstration projects have reported energy savings ranging from approximately 15–30% through AI-supported HVAC optimization and occupancy-based lighting control [20]. Continuous monitoring also improves predictive maintenance and reduces operational costs while maintaining occupant comfort.

4.3. Artificial Intelligence and Digital Twins for Building Performance Optimization

South Korea is among the leading countries in implementing Digital Twin technology at both city and building scales [19, 21]. The national Digital Twin initiative, coordinated by MOLIT, has established digital replicas of urban infrastructure to support planning, maintenance and disaster management. At the building level, Digital Twins integrate BIM models with real-time IoT data to monitor energy performance, HVAC operation and indoor environmental quality [22]. In Songdo and Sejong smart cities, Digital Twin platforms are connected with urban Data Hubs, enabling simulation of different operational scenarios before implementation [22]. Artificial intelligence processes historical and real-time datasets to predict energy demand, detect equipment anomalies and optimize system performance. These technologies contribute to lower operational energy consumption, reduced maintenance requirements and improved carbon management.

4.4. Net-Zero Energy Buildings (NZEB) as a Future Development Direction

One of the most significant trends in contemporary sustainable construction is the development of Nearly Zero Energy Buildings (nZEBs) and Net-Zero Energy Buildings (NZEBs). These buildings are designed to minimize energy consumption while meeting their remaining energy demand through renewable energy sources. The implementation of BIM, IoT, Digital Twins, and Artificial Intelligence is a key prerequisite for the successful development of NZEBs. BIM enables energy performance simulations

during the design phase, IoT sensors provide continuous operational monitoring, while AI-based systems optimize energy consumption in real time [7, 11]. The development of NZEBs is particularly important in the context of European and global climate objectives, given that the building sector remains one of the largest consumers of energy and contributors to greenhouse gas emissions [21]. Consequently, net-zero buildings are expected to become one of the principal directions of sustainable construction development in the coming decades.

5. SOUTH KOREA AS AN EXAMPLE OF INTEGRATING DIGITAL TECHNOLOGIES AND GREEN BUILDINGS

The Republic of Korea is recognized as one of the global leaders in the implementation of smart city concepts and the integration of digital technologies into sustainable urban development. Through strategic government initiatives, substantial investments in digital infrastructure, and long-term planning, South Korea has developed several internationally recognized projects that combine smart city principles with environmental sustainability objectives. The most prominent examples include Songdo International Business District, Sejong Smart City, and Busan Eco Delta Smart City. These projects demonstrate how advanced digital technologies can contribute to the development of energy-efficient, resource-efficient, and environmentally responsible buildings and urban environments.

5.1. Songdo International Business District

Songdo International Business District represents one of the world's first large-scale smart city projects developed from the ground up. Beyond its smart city infrastructure, Songdo has achieved significant green building outcomes. The district includes multiple buildings certified under LEED and Korea's G-SEED certification system, with integrated building management systems enabling energy savings of approximately 30% compared to conventional buildings [23, 24]. The implementation of BIM throughout the design and construction phases facilitated coordination among stakeholders and enabled early-stage optimization of building energy performance. The district's centralized systems, including automated waste collection and district heating and cooling, demonstrate how building-level technologies can be integrated with urban-scale infrastructure to achieve sustainability goals [24].

5.2. Sejong Smart City

Sejong Smart City represents South Korea's flagship national smart city project, with particular emphasis on building-level innovation. The project mandates BIM for all public buildings, with integrated energy performance simulation and optimization throughout the design process [25, 26]. Public buildings in Sejong incorporate renewable energy systems, smart HVAC technologies, and AI-driven energy management, achieving 25-35% reductions in energy consumption. The Digital Twin platform extends to individual buildings, enabling real-time performance monitoring

and predictive maintenance. This building-level focus, combined with national BIM standards and data integration frameworks, makes Sejong a comprehensive testbed for green building technologies and practices [25].

5.3. Busan Eco Delta Smart City

Busan Eco Delta Smart City represents a new generation of smart city development characterized by a strong emphasis on climate resilience and environmental sustainability at the building level. The project integrates advanced water management systems, renewable energy technologies, and extensive IoT sensor networks that monitor building performance in real time [27, 28]. Buildings in Busan incorporate AI-assisted HVAC optimization, predictive maintenance systems, and climate-responsive design features. The Digital Twin platform enables building-level simulation of energy performance under various climate scenarios, supporting proactive adaptation to climate change. Through the integration of digital technologies and ecological principles at both urban and building scales, Busan Eco Delta City demonstrates how smart cities can contribute to both climate adaptation and sustainable development objectives [29].

6. IMPLICATIONS FOR SERBIA

The experiences of the Republic of Korea provide valuable insights for the future development of sustainable construction and digital transformation within the Serbian building sector. However, the direct transfer of Korean models is neither feasible nor desirable due to differences in economic conditions, institutional capacities, regulatory frameworks, and technological maturity. Instead, Serbia should focus on the gradual adoption of digital technologies through pilot projects, capacity-building initiatives, and the development of an appropriate regulatory environment. Particular attention should be given to strengthening BIM competencies, promoting interoperability standards, and establishing integrated digital platforms for building and infrastructure management. Public buildings represent a particularly suitable starting point for implementing innovative solutions. Schools, hospitals, administrative buildings, and other publicly owned facilities could serve as demonstration projects for the application of BIM, IoT technologies, Digital Twins, and Artificial Intelligence. Such projects would contribute not only to improved energy efficiency but also to the development of local expertise and institutional knowledge. Furthermore, stronger collaboration between government institutions, industry stakeholders, universities, and research organizations is essential for accelerating the adoption of digital technologies in the construction sector. The establishment of national standards and long-term strategic frameworks would provide additional support for sustainable digital transformation.

7. CONCLUSION

Contemporary challenges related to sustainable development, climate change, and increasing energy consumption require new approaches to the design, construction, and management of buildings and urban environments. The analysis of South Korean experiences confirms that the successful implementation of these technologies depends not only on technological innovation but also on institutional support, data standardization, long-term investment, and strategic planning. Projects such as Songdo International Business District, Sejong Smart City, and Busan Eco Delta Smart City illustrate how digital technologies can effectively connect the concepts of smart cities and green buildings, creating a foundation for sustainable and energy-efficient urban development. For Serbia, these experiences may serve as a valuable reference framework, provided that their application is adapted to local economic, institutional, and regulatory conditions. The gradual implementation of digital technologies, accompanied by the development of professional competencies, interoperable data platforms, and energy-efficient pilot projects, could significantly contribute to the modernization and sustainability of the national construction sector. Future research should focus on the quantitative assessment of energy savings and the economic feasibility of applying these technologies under different operational conditions.

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PHD | STUDENT PAPERS

GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Research paper

SOCIAL BENEFITS OF URBAN AGRICULTURE IN PUBLIC OPEN SPACES: EXPERIENCES FROM GERMANY

Maša Ranđelović[1], Natalija Ilić[2]

Abstract

Contemporary cities face numerous challenges related to the degradation of public open spaces, the decline in the quality of urban life, and the weakening of social ties among residents. In this context, urban agriculture is increasingly recognized as an instrument of urban regeneration, as it enables the spatial, ecological, and social renewal of neglected and underutilized public open spaces. In addition to its ecological and spatial-functional benefits, urban agriculture contributes to strengthening social cohesion, social inclusion, citizen participation, and the sense of belonging to the local community. The aim of this paper is to highlight the social potential of urban agriculture in the regeneration of these spaces, particularly through the development of shared activities, cooperation, and social interaction among users. Special attention is given to two examples of good practice from Germany — Internationale Gärten Göttingen and Prinzessinnengarten — which were selected as relevant examples of the transformation of degraded spaces into community urban gardens. In this way, the paper emphasizes the importance of urban agriculture as both a spatial-functional and a social instrument for the regeneration of public open spaces.

Key words: *urban agriculture, social regeneration, public urban spaces, Internationale Gärten Göttingen, Prinzessinnengarten*

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1. INTRODUCTION

Contemporary concepts of urban development increasingly emphasize the importance of preserving, improving and activating public open spaces, especially in conditions of intensive urbanization, spatial degradation, reduced availability of green areas and more pronounced social fragmentation of the population. Public open spaces play an important role in everyday life of the city because they enable outdoor living, meetings, communication, recreation and various forms of collective activities. However, in many urban environments these spaces remain underutilized, neglected, monofunctional or poorly connected to the needs of the local community.

Urban agriculture is increasingly seen in contemporary urban and planning discourses as an instrument of sustainable urban development and regeneration of public open spaces [1,2] because in addition to food production, it contributes to the ecological improvement of the urban environment, more rational use of land, the development of environmental awareness and the improvement of the quality of life of residents [3] Of particular importance within urban agriculture are communal urban gardens, based on the collective engagement of users in the process of arranging, using and maintaining space. Collective gardening is a form of joint action of residents, within which they voluntarily participate in the shaping of public open spaces, food production and the organization of joint activities [4,5]. In this way, communal urban gardens become more than a space for food production - they function as spaces for meeting, cooperation, learning, exchange and social integration.

The subject of this paper is the analysis of urban agriculture as an instrument of social regeneration of public open spaces. The paper specifically discusses the social benefits that arise through the application of urban agriculture, especially through shared urban gardens as spaces of collective gardening. The focus is not only on the physical transformation of space, but primarily on its social activation, i.e. on the possibilities for urban agriculture to contribute to strengthening social cohesion, citizen participation, inclusion of marginalized groups, intergenerational and intercultural exchange, education and development of a sense of community belonging. The aim of the paper is to highlight the potential of urban agriculture in the process of regeneration of public open spaces, with special emphasis on its social benefits and experiences from Germany.

2. METHODOLOGY

The research is based on a qualitative approach that includes an analysis of relevant scientific and professional literature, case study analysis and comparative analysis of selected examples of urban agriculture in Germany. The Internationale Gärten Göttingen and the Prinzessinnengarten in Berlin were selected as case studies because they represent internationally recognized examples of urban agriculture with significant social impacts while reflecting different organizational and spatial models. The analysis was conducted according to the following criteria: 1) the context of the project; 2) the

spatial framework and the way the space is used; 3) the users and the organizational model; 4) social effects; 5) the contribution to the regeneration of public open spaces. These criteria were selected to enable a systematic comparison of the case studies and to evaluate their contribution to the social regeneration of public open spaces.

The literature review included journal articles, conference papers, books and official project documentation related to urban agriculture, community gardens, public open spaces and social sustainability. The selected case studies were analyzed according to five predefined evaluation criteria in order to identify their similarities and differences. The findings obtained through the comparative analysis served as the basis for identifying the social benefits of urban agriculture and evaluating its role in the regeneration of public open spaces.

3. URBAN AGRICULTURE AND SOCIAL BENEFITS IN PUBLIC OPEN SPACES

Urban agriculture encompasses various activities of food and plant resource production in urban areas, with this paper focusing on communal urban gardens as participatory forms of public open space use [1]. Its application contributes to the activation of neglected and underutilized areas, their functional and ecological transformation, and the strengthening of social functions of space [2].

In addition to ecological and spatial-functional aspects, urban agriculture has the potential to transform public open spaces into places of meeting, cooperation, shared learning and local networking [1]. In this regard, it encourages social cohesion, citizen participation, social inclusion, intergenerational and intercultural exchange, education and the development of a sense of community. Through the shared use and maintenance of space, users become active participants in its shaping, thus urban agriculture contributes to the social regeneration of public open spaces and the improvement of the quality of urban life.

3.1. Social cohesion and participation

One of the most important social benefits of urban agriculture is the strengthening of social cohesion through joint activities such as planting, maintaining plants, landscaping, organizing workshops and exchanging products [6]. These activities develop trust, solidarity, mutual assistance and a sense of shared responsibility. Unlike public open spaces that are used mostly passively, shared urban gardens encourage everyday interaction between users and contribute to the development of neighborly relations [7]. At the same time, urban agriculture encourages the active involvement of citizens in the process of shaping, using and maintaining public open spaces. Through joint planning, organizing activities and daily care of the space, users take a more active role in the direct management of the urban environment. This transforms public open space from a space of passive use into a space of active civic engagement.

3.2. Inclusion, intercultural exchange and education

Urban agriculture can play a significant role in the inclusion of social groups that are often underrepresented in the public life of the city, such as the elderly, the unemployed, people with disabilities, migrants, children, young people and residents of lower socioeconomic status (Figure 1) [8]. Communal urban gardens provide an informal, open and accessible framework for their inclusion in local community activities, with social inclusion arising from joint work, direct cooperation and everyday interaction [9].



Figure 1: Social inclusion of marginalized groups through activities in community urban gardens
https://www.pexels.com/photo/group-of-smiling-people-sitting-together-5029775/
https://www.pexels.com/photo/woman-in-wheelchair-watering-garden-outdoors-33768885/
https://elmmagazine.eu/community-gardens-as-a-playground-for-social-inclusion/?utm

At the same time, communal urban gardens encourage integration and intercultural exchange. Older users pass on experiential knowledge about growing plants, while younger users contribute new ideas and modern ecological approaches [2] (Figure 2).



Figure 2: Intergenerational cooperation and knowledge exchange in community urban gardens
https://www.lewisginter.org/event/rhythm-blooms/twitter-ginter-urban-gardeners-2_edited-1/
https://www.pexels.com/photo/man-and-woman-standing-at-their-vegetable-garden-7658777/

Urban agriculture has a strong educational function because it enables direct learning through practical work and workshops. Users gain knowledge about food production, seasonal processes, healthy eating, composting, soil conservation, rational water use, biodiversity and the importance of green spaces in urban environments [9]. This is particularly evident in work with children and young people, through school gardens (Figure 3).



Figure 3: Educational role of urban agriculture through school gardens
https://inhabitat.com/more-than-50-of-new-york-citys-public-schools-now-have-gardens/
https://www.actionforhealthykids.org/school-gardens-here-we-grow/
https://agrilifetoday.tamu.edu/2021/06/10/youth-gardening-programs-grow-great-kids/

3.3. Sence of belonging and social regeneration

Urban agriculture contributes to improving the quality of life of users through outdoor activities, contact with nature and joint activities that positively affect physical and mental health [10]. At the same time, participation in the design, use and maintenance of shared urban gardens encourages the development of a sense of belonging to the space and the local community, as well as the creation of a local identity through joint events and activities. By linking spatial planning, ecological improvement and active citizen participation, urban agriculture represents a significant mechanism for the social regeneration of public open spaces. Its value is reflected not only in the physical transformation of space, but also in strengthening connections, social cohesion and shared responsibility for space while creating local identity.

The following paper analyzes selected examples of good practice from Germany, which serve as illustrations of the various ways in which urban agriculture can contribute to the regeneration of public open spaces, primarily through strengthening social cohesion, inclusion, participation, and a sense of belonging to the local community.

4. CASE STUDIES

The examples of *the Internationale Gärten Göttingen* and *the Prinzessinnengarten in Berlin* were selected for case studies as internationally recognized projects that demonstrate the potential of urban agriculture with a focus on the social aspect through different organizational and spatial models.

4.1. Internationale Gärten Göttingen

The International Gardens of Göttingen (Figure 4) represent one of the first and most significant examples of intercultural urban gardens in Germany.



Figure 4: Internationale Gärten Göttingen: Community gardens promoting social inclusion and intercultural exchange http://internationale-gaerten.de/

- **The context of the project**

The project was launched at the end of the 20th century, in 1996, on the initiative of migrant and refugee families who, faced with social isolation and difficult integration into the local community, recognized the urban garden as a space for meeting, cooperation and mutual support [11]. *The Internationale Gärten* e.V. association was officially founded in 1998 with the aim of encouraging social integration, connecting and including migrants and refugees with the local population.

- **The spatial framework and the way the space is used**

Today, activities are carried out within three urban gardens in the territory of Göttingen, covering a total area of about 1.1 ha, which bring together a large number of users from different social and cultural backgrounds [11]. The space is organized through shared garden plots, gathering spaces, educational activities and joint events. In addition to the production of fruit, vegetables and herbs, the shared urban gardens serve as places for everyday socializing, organizing cultural events and exchanging experiences among users.

- **The users and the organizational model**

The beneficiaries come from different countries and cultural backgrounds, including migrants, refugees and local residents. The management of the space is based on a participatory model, with the beneficiaries actively participating in decision-making, organizing activities and maintaining the space. Such an approach encourages the development of shared responsibility and long-term sustainability of the project.

- **Social effects**

The special value of this project is reflected in the fact that urban gardens are not viewed exclusively as production spaces, but as places of social interaction, knowledge exchange and community building (Figure 4). The contribution of this project is also reflected in the strengthening of social inclusion and intercultural exchange. Working together in the gardens enables the establishment of contacts between people of different backgrounds, reduces social isolation and contributes to the building of mutual trust. The project also has a pronounced educational role through workshops, activities for children and the promotion of sustainable practices.

- **The contribution to the regeneration of public open spaces**

The Internationale Gärten Göttingen are an example of how underused public open spaces can be transformed into active places for social interaction and collective action. Their significance goes beyond the physical design of the space, as they contribute to creating a more inclusive urban environment, strengthening local communities and improving social sustainability. In this way, the project is an example of urban regeneration through a participatory approach, in which the users themselves actively participate in shaping and maintaining the spaces they use. This model contributes to creating a more inclusive, resilient and sustainable urban environment.

4.2. Prinzessinnengarten

Prinzessinnengarten in Berlin (Figure 5) also represents one of the most significant examples of the application of urban agriculture in the function of sustainable urban development and social regeneration.

- **The context of the project**

The project was launched in 2009 in the Kreuzberg district of Berlin, on the neglected city plot of *Moritzplatz*, as a civic initiative aimed at revitalizing a neglected urban space [12]. The basic idea was to create an open space for food production, education, social activities and strengthening the local community through communal gardening.



Figure 5: Prinzessinnengarten> Mobile urban agriculture and participatory regeneration of public open space https://somethingcurious.wordpress.com/2011/06/08/prinzessinnengarten/ https://www.berlin.de/en/urban-gardening/community-gardens/9227217-9521509-prinzessinnengarten.en.html

- **The spatial framework and the way the space is used**

The specificity of the project is reflected in the application of a mobile model of urban agriculture based on growing plants in mobile containers, crates, planters and recycled pots. Such an approach allows for flexible land use and adaptation to changes in the urban context. The space is organized as a multifunctional entity that, in addition to areas for growing vegetables, fruits and herbs, includes spaces for workshops, educational programs, public events and various forms of social interaction. In this way, the Prinzessinnengarten functions as a multifunctional public space that combines ecological, social and educational content.

- **The users and the organizational model**

The project beneficiaries include residents of different age, social and cultural groups, as well as representatives of educational institutions, civil society and local initiatives [12]. The organization and management of the space are based on a participatory model, which involves the active involvement of users in planning activities, maintaining the space and making decisions. Such a model contributes to the development of cooperation, strengthening social responsibility, knowledge exchange and collective management of common resources.

- **Social effects**

The project analysis indicates a significant contribution to strengthening social cohesion and citizen participation in the use and shaping of public space. Through joint activities, workshops and public events, contacts are established between users of different backgrounds, generations and interests, which encourages social interaction, exchange of experiences and the development of local support networks. The project also achieves a significant educational function by promoting sustainable food production, environmental protection, biodiversity and responsible resource management. In this regard, urban agriculture becomes a means of informal education and encourages the development of environmental awareness.

- **The contribution to the regeneration of public open spaces**

Prinzessinnengarten in Berlin is a significant example of the regeneration of public open space through the temporary and flexible use of urban land. The transformation of a neglected urban plot has created an active public space that encourages social interaction, citizen participation and local community development [12]. Of particular importance is the demonstration of the possibility of the process of regeneration of

public open spaces through the active involvement of the community, i.e. users, in the creation, use and maintenance of the space. In this regard, the project can be seen as a relevant model for contemporary urban planning practice aimed at sustainability, inclusiveness and social resilience of urban environments.

4. DISCUSSION

The results of the case study analysis confirm the theoretical assumptions about the significant contribution of urban agriculture to the process of social regeneration of public open spaces. They are not only reflected in the physical improvement of the space but also in the strengthening of social ties and the activation of local communities. Although the Internationale Gärten Göttingen and the Prinzessinnengarten in Berlin were created in different urban and social contexts, both examples point to the importance of a participatory approach in the process of using and managing space. Their common feature is the active involvement of users in the design, maintenance and use of the space, which encourages social cohesion, the development of a sense of belonging and the creation of local cooperation networks. In both case studies, urban agriculture goes beyond its primary production function and becomes a means of social interaction, informal education and the development of sustainable patterns of behavior.

In the analyzed examples from Germany, certain differences were also observed (Table 1). *Internationale Gärten Göttingen* is primarily focused on the social inclusion of migrants and refugees, with the common urban garden functioning as a space for intercultural exchange and integration of different social groups. On the other hand, *Prinzessinnengarten* emphasizes the participatory regeneration of neglected urban space through a flexible land use model, with a strong educational and ecological component. While the first case study is dominated by the social-integrative aspect, the second emphasizes the potential of urban agriculture as an instrument for activating unused public open spaces and developing civic initiatives.

Table 1. Comparative analysis of case studies according to research methodology criteria

Criterion	*Internationale Gärten Göttingen*	*Prinzessinnengarten, Berlin*
Project context	Initiated by migrants/refugees (1996) for social inclusion	Civic initiative (2009) to regenerate abandoned urban land
Spatial framework and use of space	3 communal gardens, organized through shared plots and social/educational spaces	Flexible, mobile urban agriculture using containers and movable planting systems
Users and organizational model	Migrants, refugees and local residents; participatory NGO-based management (Internationale Gärten e.V.)	Local residents, civil society, institutions; participatory community-based management
Social effects	Strong intercultural exchange, social inclusion, reduces isolation, community building	Increased civic participation, intergenerational exchange, social interaction and network building
Contribution to the regeneracion of open spaces	Transformation of underused areas into inclusive social and intercultural spaces	Activation of abandoned urban land into multifunctional, adaptive public space

The analysis shows that the success of such projects does not depend solely on the spatial characteristics of the location, but primarily on the degree of user involvement, the organizational management model and the continuous development of joint activities. In this sense, the analyzed examples confirm that urban agriculture can contribute to the creation of more inclusive, sustainable and socially active public open spaces.

The comparative analysis also indicates that the successful implementation of urban agriculture projects depends on several contextual factors. Long-term institutional support, the availability of suitable public land, active community participation and effective organizational management appear to be essential for maintaining the social functions of shared urban gardens over time. In addition, differences in legal frameworks, governance structures and local social conditions may influence the transferability of these models to other urban environments. Therefore, although the German examples demonstrate significant social benefits, their application should be adapted to the specific characteristics and needs of each local context. These findings suggest that urban agriculture should be considered as an integral component of urban regeneration strategies, particularly in cities seeking to strengthen social cohesion, community participation and the multifunctional use of public open spaces. Overall, the analysis confirms that urban agriculture represents a valuable planning instrument that can contribute to more inclusive, participatory and socially resilient public open spaces.

5. CONCLUSION

The paper, after reviewing the research results, confirms that urban agriculture is an important instrument for the regeneration of public open spaces, the effects of which go beyond food production and include numerous social, educational and environmental benefits. The analysis of relevant literature and selected case studies from Germany has shown that urban agriculture can play a significant role in the regeneration of public open spaces by strengthening social cohesion, citizen participation and the development of local communities. Although they originated in different social and spatial circumstances, both projects confirm that the active involvement of users is a key factor in the successful transformation and long-term sustainability of the space.

The results of the comparative analysis indicate that urban agriculture has significant potential for application in contemporary urban and planning practice, especially in the context of sustainable urban development and regeneration of public open spaces. It can contribute to various aspects of social regeneration – from the integration of migrants and the promotion of intercultural dialogue, to the activation of neglected urban areas and the development of participatory models of spatial management. At the same time, the analyzed examples show that communal urban gardens go beyond their production function and become places of social interaction, education and joint action.

Although this study is based on a qualitative analysis of two selected case studies from Germany, the findings provide useful insights into the social potential of urban

agriculture in the regeneration of public open spaces. Future research could expand the comparative analysis by including additional case studies from different European countries and applying quantitative methods to further investigate the social impacts of urban agriculture in different urban context.

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Research paper

HUMANISTIC SCALE OF GREEN URBAN DESIGN

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Abstract

Against the backdrop of high-density urban expansion and increasingly scarce land resources, pocket parks, as miniature green public spaces, are becoming an important direction for urban renewal and green space construction in China. However, existing research largely focuses on the ecological functions and landscape aesthetics of pocket parks, with insufficient exploration of their socio-cultural significance in carrying urban green space culture which is how space carries memory, shapes behavior, and cohesive community spirit.

This paper constructs a three-dimensional analytical framework based on the theory of spatial narrative, cultural memory, and environmental behavior: the accessibility of perception, the inclusiveness of behavior, and the attachment of meaning. Through a comparative study of six cases, provides a typological reference for pocket parks and their social restoration significance.

The study suggests that urban green space culture is not only about grand landmarks, but also about whether or not individuals are willing to leave small, breathing spaces for each other at a very small scale. Green urban design should focus on people-centered spatial experiences under the diverse regional cultural contexts.

Key words: *pocket parks, urban green space culture, spatial narrative, cultural memory*

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1. INTRODUCTION

China's urbanization rate has exceeded 65%. While the high-density urban clusters have created economic miracles, they have also led to a severe squeeze on public space [1]. Pocket parks, also known as Vest-pocket parks, typically refer to small park green spaces with an area of 400 to 10,000 square meters, open to the public, and possessing certain recreational functions [2]. In the Chinese context, pocket parks have gained particular prominence as a strategy for urban renewal in high-density old districts, where conventional large-scale park development is physically and economically infeasible. Chinese pocket parks are frequently embedded within densely populated residential neighborhoods and serve as functional substitutes for the traditional alleyway (hutong\nongtang) social spaces that have been largely lost to rapid urban redevelopment [3]. Their fragmented layout and high accessibility make them as key hubs in repairing the urban public space network.

This study adopts a multi-case comparative research method to demonstrate the diversity and flexibility of pocket parks in specific practical contexts. The aims of comparison are threefold: to understand specific pocket park practices based on conceptual framework; to evaluate how each case performs across perceptual accessibility, behavioral affordance, and meaning attachment; to derive typological classifications based on dominant dimensional profiles. The study emphasizes that, unlike quantitative evaluations of physical area and ecological indicators, the human scale emphasizes sensory accessibility, behavioral affordance, and psychological belonging.

2. CONCEPTUAL FRAMEWORK: URBAN GREEN SPACE FROM A HUMANISTIC PERSPECTIVE

Space is not merely a physical container, but a dynamic process of social production. Henri Lefebvre argued that space is a product of social relations, not a neutral geometric existence [4]. Nigel Thrift's Non-Representational Theory reminded us that the narrative meaning of space exists not only in formal texts such as monuments, plaques, official explanatory texts, but also accumulates more extensively in preconscious, everyday, and practical bodily experiences [5]. An elderly person dozing in the sun on a bench, two children chasing and playing in the shade of a tree, several dog walkers meeting on the same lawn—these seemingly trivial daily practices constitute the most vivid and authentic narrative of urban green spaces.

Aleida Assmann pointed out that memory is always activated and reinterpreted in the present [6]. Pierre Nora argued that "memory fields" (les lieux de mémoire) are material, symbolic, and functional, commemorative [7]. While grand historical spaces play an irreplaceable role in shaping collective identity, they are quite distant from the daily experiences of ordinary citizens. Daily life memories are small in scale, scattered in form, and lack in historical documentation, yet they play the most gentle and resilient cohesive role in the intergenerational transmission of the community [8].

What exactly makes people willing to enter a space and stay? Jan Gehl argued "gathering first, space later," meaning that the effectiveness of public space does not primarily depend on its aesthetic quality, but rather on its ability to induce and accommodate human activity [9]. High-quality spatial design can effectively transform necessary activities into spontaneous activities, thereby fostering social activities. He pointed out that in public spaces, people often don't plan how long they will sit initially, but rather decide to stop after walking through and observing. Gibson also believed that the environment provides or endows organisms with the possibility of certain actions [10]. Design is not only about shaping physical forms, but also about shaping the space of possible behaviors.

In summary, spatial narrative theory emphasizes that users constantly rewrite the meaning of space in their daily practices, cultural memory theory suggests the profound role of micro-memory places in social cohesion, and environmental behavior focuses on how spatial conditions induce or inhibit real physical activity. Based on this, this paper constructs a three-dimensional framework for humanistic scale of urban green space:

Dimension One: Perceptual Accessibility. Even the largest and most well-equipped urban green spaces fail culturally if they are isolated from the street by walls, elevation differences, or visual barriers, making them seem inaccessible or unwelcoming to outsiders. Perceptual accessibility requires visual transparency and psychological safety in design: activities inside should be clearly visible from a distance, entrances should not feel cramped or dark, and boundaries should be friendly rather than defensive.

Dimension Two: Behavioral Affordance. Specific indicators include: Are there sufficient and reasonably arranged seating facilities? Do the seats cater to the psychological needs of all activity groups? Do activity areas avoid direct conflicts between different behavioral groups, such as children running and the elderly sitting quietly? Are necessary auxiliary facilities such as shade, lighting, and drinking water provided? More importantly, does the spatial design allow multiple people to engage in spontaneous activities simultaneously without interfering with each other or feeling cramped?

Dimension Three: Meaning Attachment. Refers to whether a space possesses a symbolic density that transcends mere function; that is, whether it carries stories, memories, identities, or local emotions. This meaning can come from the site's own historical relics, such as ancient trees, old wells, and industrial components, or from conscious coding in design. However, the more fundamental source is the emotional experience spontaneously bestowed by residents through long-term use. "Topophilia" precisely captured this emotional dimension of the relationship [11].

The three dimensions mentioned above are not linearly progressive, but rather mutually supportive and reinforcing. Perceived accessibility is a prerequisite for behavioral inclusiveness, behavioral inclusiveness is the foundation for the attachment of meaning, and the attachment of meaning, in turn, enhances residents' willingness to maintain and the frequency of use, further improving perceived accessibility and behavioral inclusiveness, thus forming a virtuous cycle.

3. CASE STUDY

3.1 Case Selection Criteria

Geographic and urban context diversity. Cases were chosen from provincial capital or municipality, which prominently reflect the issues between population and urban green space. And the different urban morphologies (delta city, basin city, mountainous city, industrial heritage city, urban village)

Size range control. All cases fall within the typical pocket park area range of 3,000–10,000 m², ensuring comparability of scale [2].

Typological variation. Cases were selected to cover different primary function, enabling the identification of distinct humanistic design strategies.

Data availability. Each case has sufficient published documentation (design statements, photographs, post-occupancy usage reports) to support multi-dimensional analysis.

3.2 Individual Case Descriptions

Leshan Green Space, Shanghai



Figure 1. Leshan Green Space, Shanghai, VIASCAPE design on gooood

Leshan Green Space was built in the 1970s. Before the renovation, it was enclosed by walls, had outdated facilities, and was plagued by uncivilized behavior. The designer adopted the concept of "one design, multiple functions," incorporated residents' conceptual demands for Chinese landscape gardens through natural curved surface design, creating a rest space for all ages. After the renovation, Leshan Green Space became one of the most popular and frequently used pocket parks in Xuhui District, with daily visitor traffic comparable to some parks several times larger.

Perceptual accessibility was fundamentally enhanced by the removal of walls, creating visual permeability from surrounding streets. Behavioral affordance is

reflected in the precise configuration of multifunctional spaces, such like morning exercise areas, bird-walking zones, chess tables, and childcare corners each receive matching spatial support. Meaning attachment stems from the sense of psychological ownership brought about by the full participation of residents in the design process.

Fuzhou Songshan Cultural Park

Fuzhou Songshan Cultural Park was an undeveloped corner of land, with two ancient banyan trees surrounded by walls and temporary prefabricated houses. The transformed park, centered on the ancient banyan trees, has become an important activity space for surrounding residents. Meaning attachment is particularly prominent, that the ancient banyan trees not only provide physical shade but also become visual anchors for collective memory and emotional landmarks of community identity. Perceptual accessibility is moderate due to partial street visibility. Behavioral affordance includes shaded seating areas that accommodate elderly gathering and children's play.

The design team implemented a series of protective measures for the ancient banyan trees, including laying breathable materials to protect their root systems, clearing excess trees to create space, and planting Fuzhou's city flower, jasmine, and city fruit, the Fuzhou tangerine, to comprehensively showcase Fuzhou's characteristics.The dual qualities of landscape immersion and historical narrative place it at the intersection of urban green space design.

Xi'an Taohuatan Pocket Park

The Xi'an Taohuatan Pocket Park is situated within an area of urban industrial heritage. This area was once part of the old industrial base, such as the Xi'an Textile City. The pocket park's transformation strategy involves converting existing industrial components, such as abandoned railway tracks, machine parts, and factory structures, into landscape elements, preserving industrial memory while incorporating new public living functions.Its distinguishing feature from traditional memorial parks lies in creating memory spaces through the presence of material remains, achieving green redesign of existing buildings.

Meaning attachment is achieved through material preservation of industrial relics, transforming abandoned ruins into commemorative spaces bearing witness to a specific historical period. Perceptual accessibility is enhanced by open boundaries. Behavioral affordance includes multi-generational activity zones integrated with industrial artifacts.

Chongqing Fuling Tashuiqiao Pocket Park

Originally a corner plot of land in the city, With "age-friendly" as its core concept, the park is divided into children's play areas, a non-standard basketball court, leisure trails, and a woodland interaction area to demonstrates a refined response to people of all ages in terms of behavioral inclusiveness.The park also incorporates smart facilities such as smart rest stations, sensor lighting, smart trash cans, and dynamic monitoring, allowing more than 5,000 households in the surrounding area to see greenery from their windows and enter the park right outside their doors.

Chongqing, as a mountainous city, faces a scarcity of flat land, making hill climbing a common part of daily life. Behavioral affordance is the dominant dimension, the

Tashuiqiao case shows that even in terrain where complete accessibility is not possible, sophisticated designs such as tiered seating, multi-level platforms, and corner benches can still create diversity urban green spaces.

Guangzhou Wangnan Park



Figure 2. Wangnan Park,Guangzhou, http://www.archina.com

The original site of Wangnan Park suffered from outdated public facilities,,safety hazards in some areas where pedestrians and vehicles shared the same paths. After renovation, the park provides a safe space for community residents. Behavioral affordance includes diverse activity zones integrated with cultural heritage elements. Perceptual accessibility is high due to open boundaries and the "shared space" concept. The design cleverly integrates local history and culture, which is connecting ancient alleys while respecting the old village layout to create a flowing landscape.

Urban village renewal often involves the displacement of original residents and the rupture of collective memory. Meaning attachment is achieved through preservation of ancestral hall square, feng shui pond, and traditional meeting spaces under large trees, grafting modern design language onto the traditional village structure, rather than using standardized modern spaces to eliminate the chaotic historical fabric. Therefore, Wangnan Park is not only a relax space in a high-density modern city but also a cultural buffer zone connecting the past and present, easing the gap between old and new communities.

Caojiadu Garden, Shanghai

Caojiadu Garden was originally designed and built by Japanese architect Yoshiro Hoshino in 2003. The 2021 renovation adopted a micro-renovation strategy, abandoning the complex, zigzag lines of the traditional garden and incorporating nautilus curves to create rest spaces, providing appropriate areas and facilities for morning exercisers and bird walkers. Behavioral affordance is the core strength that the concept lies in integrating paths, nodes, and rest areas into an organic whole through the continuity and envelopment of the nautilus curve, allowing residents to naturally choose to stop or pass through while walking.



Figure 3. Caojiadu Garden, VIASCAPE design on gooood



Figure 4. floor plan, author's drawing

This case reveals that the design within a small area is not about cramming in as many functions as possible, but about creating possibilities for behavioral transformation. Perceptual accessibility is medium (street-visible but compact). Meaning attachment stems from long-term neighborhood familiarity and the distinctive curved spatial experience.

3.3 Comparative Analysis Matrix

Table 1 reveals several cross-cutting patterns. First, all six cases achieve at least medium scores across all three dimensions, suggesting that pocket parks inherently possess multi-dimensional humanistic potential. Second, meaning attachment is the dimension with the widest variation, ranging from low (Tashuiqiao) to high (Songshan, Taohuatan, Wangnan) indicating that the presence of tangible heritage elements (ancient trees, industrial relics, ancestral halls) significantly enhances this dimension.Third, behavioral affordance is consistently high or medium-high, reflecting that basic activity support is achievable even on constrained sites.Fourth, perceptual accessibility correlates strongly with boundary treatment.

Table 1. Comparative evaluation of six pocket parks across the three humanistic dimensions

Case	Location	Size (m^2)	Primary User Groups	Perceptual Accessibility	Behavioral Affordance	Meaning Attachment	Dominant Typology
Leshan Green Space	Shanghai	5600	Mixed ages, elderly, parents with children	High (wall removal, visual permeability)	High (multi-functional zones, chess tables, exercise areas)	Medium (resident participation in design)	Socially Driven
Songshan Cultural Park	Fuzhou	~4000	Elderly, families	Medium (partial street visibility)	Medium (shaded seating, open lawn)	High (ancient banyan trees as cultural symbols)	Landscape Immersive
Taohuatan Pocket Park	Xi'an	~5000	Mixed ages, history enthusiasts	High (open boundaries)	Medium (industrial artifacts integrated with activity zones)	High (industrial heritage preservation)	Historical Narrative
Tashuiqiao Pocket Park	Chongqing	~4500	Elderly, children, families	Medium (terrain constraints)	High (age-friendly design, smart facilities, tiered seating)	Low (limited heritage elements)	Terrain-adaptive
Wangnan Park	Guangzhou	6000	Village residents, mixed generations	High (open boundaries, shared space concept)	High (cultural square, leisure corridors, fitness zones)	High (ancestral hall, feng shui pond, tree meeting spaces)	Historical Narrative
Caojiadu Garden	Shanghai	3000	Morning exercisers, bird walkers, elderly	Medium (street-visible but compact)	High (nautilus curve enabling natural stopping behaviors)	Medium (long-term neighborhood familiarity)	Socially Driven

Note: High (green), Medium (orange), Low (red) indicate relative performance within the case set. Detailed rationale for each rating is provided in the case descriptions.

4.DISCUSSION

Based on the comparative analysis of the cases, this paper proposes four typological classifications of pocket parks:

Category 1: Socially Driven. Represented by Leshan Green Space, This type of pocket park primarily serves the daily social needs of surrounding residents.

Category 2: Landscape Immersive. Typical examples include Fuzhou Songshan Cultural Park and Chongqing Tashuiqiao, emphasizes the therapeutic function of natural space. This type of pocket park provides natural spiritual comfort, offering a moment of closeness to nature plants.

Category 3: Historical Narrative. Represented by Xi'an Taohuatan and Guangzhou Wangnan Park, the core is transforming historical spaces into memory spaces. These pocket parks serve as spaces for collective memory, responding to the need for identity recognition.

Category 4: Terrain-adaptive. Taking Chongqing's Fuling Tashui Bridge as a key reference, this type employs special strategies for mountainous or high-altitude sites. Even with unavoidable terrain limitations, it still faced the needs of vulnerable groups such as the elderly and caregivers of infants.

It is worth noting that the above four types are not mutually exclusive; a pocket park often possesses characteristics of multiple types simultaneously. However, typological identification helps in understanding the prioritization of design decisions. Research shows that contemporary Chinese green urban design is shifting from the early single goal of landscape decoration to a multi-faceted integration of functional complexity and cultural embedding. The unique value of pocket parks also lies in the diversity of their typological characteristics.

The Value of Pocket Parks in Urban Green Space Culture:

On the level of physical and mental health restoration, pocket parks, by enhancing perceptual accessibility, transform the cold, impersonal spaces of high-density cities into warmer places, effectively alleviating the mental and physical stress of urban life.[12][13][14] In contemporary society, where involution and atomization are increasingly prevalent, pocket parks offer a low-cost psychological refuge. Unlike the commercial consumption attributes of cafes or the closed nature of private residences, they provide open, free, and safe spaces for observation. For groups such as elderly people living alone, stay-at-home parents, and migrant workers, public interaction without the pressure of consumption is especially valuable.

On the level of connecting social collective relationships, pocket parks, through their behavioral inclusiveness, catalyze individualized necessary activities into social activities such as conversation, games, and group entertainment. Pocket parks, through everyday scenarios such as dog-walking socializing, parent-child alliances, and game matches, provide physical carriers and behavioral references for the reconstruction of "neighborhood." They are high-frequency places where weak connections are formed between strangers, and these weak connections are the micro-foundation of community resilience.

On the level of cultural intergenerational transmission, pocket parks rely on the attachment of meaning to transform material relics such as ancient trees, industrial

components, and traditional village textures into carriers of daily micro-memories. For example, Fuzhou Songshan Cultural Park uses ancient banyan trees to anchor local cultural symbols, and Xi'an Taohuatan Park revitalizes industrial relics to form historical narratives, so that daily activities can transcend grand memorial sites and be softly passed down between generations, ultimately achieving the cultural transformation from physical space to emotional support.

5.CONCLUSION

This paper selected pocket parks as a micro-case study, integrating spatial narrative, cultural memory, and environmental behavior theories to construct a three-dimensional humanistic scale analysis framework.Through a comparative study of six pocket parks and analyzed using a structured comparative matrix (Table 1), reveals the social functions of pocket parks in achieving physical and mental restoration, social connection, and intergenerational cultural transmission based on flexibility and diversity.

The contribution of this study lies in operationalizing the humanistic scale into analyzable three-dimensional indicators, providing a new analytical tool for urban green space culture research.Practical case studies suggest that the core of green city construction lies not in the continuous expansion of green space area, but in the precise response of each space to the needs of real life. Pocket park design should adhere to the principles of visual transparency and psychological safety, multi-level behavioral inclusion, and revitalization of local memory, while also acknowledging the usage rights of marginalized groups and avoiding standardized replication that diminishes local cultural diversity.

This study argues that urban green space culture is not a technical indicator of vegetation coverage or landscape aesthetics, but rather a value choice. The social significance of pocket parks lies in their ability to demonstrate a city's humanistic level at a minimal material cost by respecting the smallest, most vulnerable, and most everyday spatial needs. Only when the consensus on contemporary green city construction shifts from quantitative expansion.

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Research paper

DESIGN FOR RESTORATION: COMPARATIVE ANALYSIS OF TWO OPEN PUBLIC SPACES IN BELGRADE

Tamara Mladenović[1]

Abstract

This paper examines the role of open public urban spaces in supporting users' psychological restoration within dense built environments. The research is based on the concept of restoration in environmental psychology, which refers to the process of "renewing physical, psychological, and social resources that have been depleted through everyday activities". The paper addresses a gap in the existing literature by questioning the methodological bias that arises from assessing restoration in urban spaces through the recurring opposition between "positive natural" and "negative urban" environments.

The paper aims to develop an evaluation matrix for analysing the design characteristics of open public urban spaces, and to test its applicability through a pilot study of two such spaces in Belgrade. The matrix is developed based on theoretical analysis, by combining Bornioli and Subiza-Pérez's theoretical model, structured around three levels of evaluation (containment, passive restoration, and active restoration), with Grave, Neven, and Mohammadi's classification of spatial elements.

The matrix was applied to two public spaces in Belgrade, Cvetni trg (Flower Square) and Park Starine Novaka. Pilot evaluation was conducted through field observation, photo-documentation, and multi-criteria expert evaluation using a 1–5 rating scale. The results indicate that, although the selected spaces are similar in size and position within the urban structure, they contribute to restorativeness at different levels and through different spatial characteristics. Park Starine Novaka shows stronger potential through natural elements of passive restoration, while Cvetni trg contributes more through architectural diversity, historical complexity, and symbolic identity. The paper proposes an evaluation matrix as an analytical tool for researchers and defines practical guidelines for design improvements for the two selected public spaces in Belgrade.

Key words: *Psychological restoration, Public open spaces, Urban design, Evaluation matrix, Belgrade*

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1. INTRODUCTION

Contemporary cities face growing challenges regarding reduced physical activity, higher stress levels, and social isolation. These challenges arise from urbanization, with projections that in 2050, about 68% of all people will live in cities [1]. In this context, the open public spaces of cities are becoming increasingly important as spatial typologies that have the potential to support the everyday public life of all citizens equally.

Concerning these challenges, contemporary literature highlights different concepts, one of which is the new paradigm of "restorative cities". Restorative cities draw on the basic concept of restoration that originated in environmental psychology in the 1980s and 1990s. Restoration refers to the process of restoring physical, psychological, and social resources that are depleted in the performance of everyday activities [2]. In a similar regard, restorative city promotes "the implementation of urban design for mental health and well-being"[3].

Existing restoration theories are based on the assumption that contact with environments that possess certain qualities can help in the recovery of attention fatigue and emotional exhaustion of users [4,5]. Key restoration theories (ART - Attention Restoration Theory, SRT - Stress Reduction Theory) emphasize natural environments and their inherent predisposition for achieving restorative effects.

In recent years, research has increasingly shifted towards restoration in urban environments. Previous studies have highlighted a significant methodological bias arising from comparisons between "positive natural" and "negative urban" environments [6,7,8,9], while others have emphasized the growing need to address these questions in both built and mixed environments [10,11].

Starting from the premise that urban open public spaces should be improved in ways that support restorative effects more effectively, this paper examines how restorative potential can be recognized, analyzed, and enhanced through the spatial and design characteristics of such spaces.

The paper aims to structure an evaluation matrix for analyzing the design characteristics of open public spaces in urban environments, based on the relevant theoretical framework, and to further test it through a pilot application in two open public spaces in Belgrade, Serbia. Research on restoration in the context of Belgrade, Serbia, is particularly relevant, given the high level of development in central city zones, traffic pressure, and the uneven quality of public space. Many of Belgrade's open public spaces are characterized by intensive use, noise, a limited share of greenery, and inconsistent maintenance, and for this reason, the city provides a relevant context for testing criteria related to restorative urban environments.

The research is based on the development of a theoretical framework based on analysis of the existing literature in restorative environments and open public spaces, which is further implemented in the comparative analysis and evaluation of two open public spaces in Belgrade, which will be discussed in the following chapters.

2. THEORETICAL FRAMEWORK

The theoretical framework of the paper is based on the concept of restoration within environmental psychology, as well as on state-of-the-art approaches that extend this concept to built urban environments in the context of design and planning.

2.1. Basic theories

The research in restorative environments has been led by two main theories: Attention Restoration Theory - ART, and the Psycho-Evolutionary Theory of Stress Reduction - SRT [6].

ART positions on the idea that daily activities, decision-making, orientation, and exposure to information require attention, and that long-term use of attention leads to mental fatigue and reduced focus. ART highlights the qualities and values of environments that prompt higher restoration capacities, namely: “being-away” environments that enable "escape" from everyday demands, that possess a degree of fascination, coherence, and compatibility [4]. Recent literature addresses these abstract ideas, translating them into more manageable characteristics of spaces that contribute to their restoration potentials [12,8].

On the other hand, SRT measures users’ emotional and physiological responses to the environmental characteristics. The premise of this theory is that certain environments can contribute to stress reduction through rapid affective reactions and changes in the users’ physiological state [5,13].

Both theories focus on natural environments, but newer research insists on the value of examining the relationship between the built urban environments and nature.

2.2. The spatial shift in focus of research in restoration

With the recent shift in research focus towards urban environments, studies have shown that exposure to positive urban built environments without the presence of nature can lead to affective and/or cognitive benefits [11], but also to neutral or negative effects [14,15,16]. Of particular interest are spaces that enable activities supporting recovery from attention fatigue and stress, with increasing focus on rest and recreation environments, whose improvement can contribute to public health in cities [8].

For this purpose, studies have analyzed spaces such as urban parks, cafes, restaurants, shopping centers [8], squares [17], museums [18], and other historical spaces [19], which have been shown to have restorative potential. The quality of these spaces is examined by measuring their “restorative potential”, which includes factors that reduce stress and support restoration [17].

Studies analyze both positive and negative factors that affect spaces in supportive or hindering ways. The analysis of these factors is highly complex and includes various categories. Grave et al. (2024) [20] propose categorizing the characteristics of spaces with restorative effects in built environments as follows: natural characteristics, such as vegetation and water; landscape characteristics, such as topography, slopes, and

infrastructure; and architectural characteristics, such as openness, refuge, design, and shaping.

In the following chapter, one of the most recent models of restorative research in urban areas is presented.

2.3. Models for studying restorativeness in the built environment

Bornioli and Subiza-Pérez (2023) [6] offer a model for studying restoration in built urban settings. The model they propose consists of three levels, each contributing to the assessment of the restorative value of built space.

The first level is Containment, referring to the basic conditions of space that enable a restorative experience. The purpose of this level is to control or mitigate the negative impacts of the environment and prepare it for further improvements. It implies the absence of stressors (noise, pollution, crowds); perception of safety; compatibility of social landscape and acceptable climatic and thermal conditions.

The second level, called Passive restoration, includes bottom-up features of space, such as green and blue infrastructure, biophilic design, historic elements of the environment, moderate complexity, architectural variation, moderate prospect, and multisensory stimulation. It helps reduce stress, increase positive affect, and restore attention.

The third level, Active restoration, introduces top-down characteristics, such as personal engagement in a cultural-social context, memories of a particular place, attachment to a place, social interaction, sense of community, and belonging. Benefits of these characteristics include stress reduction, attention restoration and stimulation, cognitive engagement, positive affect, and eudaimonic wellbeing.

The paper expands these levels by combining them with systematized environment characteristics and elements that affect restoration potential from Grave et al. (2024)[20]. The combined theoretical insights are formed into a new matrix for assessing and evaluating restorative values of open public spaces in cities, which will be elaborated in the next chapter.

3. METHODOLOGY

The research methodology combines literature analysis, formation of an evaluation matrix, and its pilot application through a comparative analysis of two open public spaces in Belgrade. The research is organized in two phases.

The first phase includes the analysis of existing literature in the field of restorative environments and open public spaces of cities. After establishing the primary theoretical framework (ART and SRT), the study conducts a search and selection of other relevant research papers. The literature search was conducted through keywords and by using the Research Rabbit tool for snowballing and citation. Two significant papers were singled out as the most relevant for establishing the evaluation matrix. The matrix structure draws on Bornioli and Subiza-Pérez's (2023)[6] three levels of restorability (containment, passive restoration, and active restoration), while the subdivision of the passive layer follows Grave, Neven, and Mohammadi's (2024)[20]

classification of natural, landscape, and architectural elements. The reviewed literature served as the basis for developing the evaluation matrix presented in Figure 1.

The second phase of the research involves the pilot application of the evaluation matrix through a comparative analysis of two open public spaces in Belgrade. The case study selection was based on several criteria: (1) both spaces needed to be located in the dense urban fabric of Belgrade; (2) be publicly accessible; (3) have similar surface areas; (4) while also having differences in character and design, with one featuring hard surfaces, and the other more green areas. Cvetni trg and Park Starine Novaka were selected as they meet these conditions while also representing two recurring, contrasting typologies of open public space within the city's traditional urban fabric.

Cvetni trg (Flower Square) represents a predominantly paved, urban, and functionally active public space in Belgrade's Vračar municipality, while Park Starine Novaka (The Park of Starina Novak) offers a more pronounced green character within the dense urban fabric of Palilula.

The analysis was carried out through a single documented site visit per location, combining field observation, photographic documentation, spatial mapping, and multi-criteria expert evaluation. This allowed the scores to be checked against recorded material after the visit. Scores were assigned on a 1-5 scale (1 - criterion absent or severely deficient, 3 - moderate/acceptable, 5 - optimally satisfied) according to pre-defined criteria composed from theoretical analysis, and the same criteria set was applied identically to both cases to ensure comparability. As a single-rater pilot assessment, however, the results remain indicative rather than final, with inter-rater validation planned for future phases. Given that active restoration criteria are contingent on individual users' experiences, their evaluation is deferred to a future phase that employs survey instruments and behavioural observation. This phase assesses the matrix's local applicability, its strengths and limitations, and informs the resulting comparative overview and design guidelines.

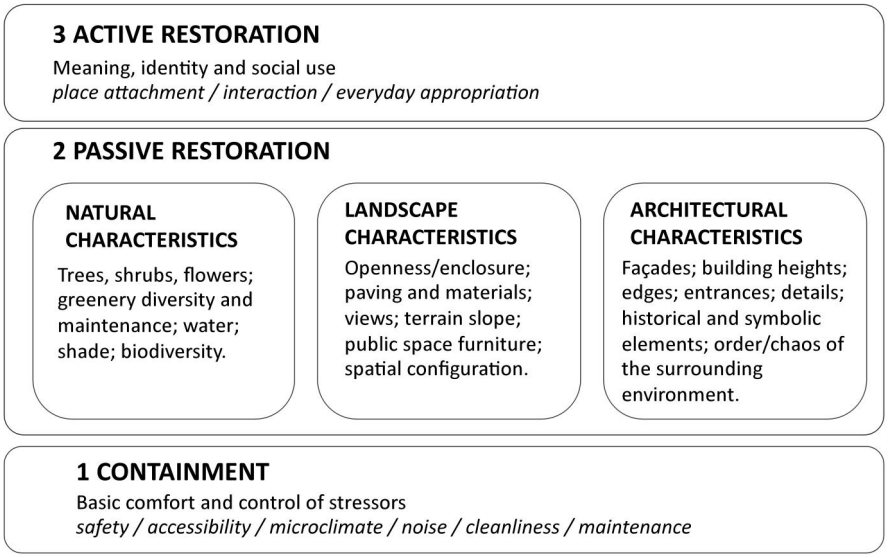


Figure 1. Methodological matrix for assessing restoration in built urban environments, author's illustration, based on Bornioli and Subiza-Pérez (2023) and Grave et al. (2024).

4. PILOT EVALUATION: CASE STUDY OF CVETNI TRG AND PARK STARINE NOVAKA

As outlined in the Methodology, Cvetni trg and Park Starine Novaka were selected as a contrasting pair of comparable size. A paved, symbolic square is set against a greener park, enabling the matrix to be tested across differing spatial characters within Belgrade's dense urban fabric (Figure 2).



Figure 2. Pilot-study locations in Belgrade: A) Cvetni Trg; B) Park Starine Novaka (author's illustrations on photos from https://earth.google.com/web/).

The basic urban parameters emphasize the contrast between the two spaces. Cvetni trg covers approximately 2,830 m², with green areas accounting for only about 0.4% of its total area, while Park Starine Novaka has a comparable area of 2,824 m², but with green spaces comprising 65%. Another difference between the two spaces lies in their urban significance. Cvetni trg is a public space of city-wide importance, located near Slavija, the most prominent roundabout in Serbia, and next to the Yugoslav Drama Theatre. By contrast, Park Starine Novaka has a more local significance, primarily within its immediate urban surroundings. The locations differ in spatial character, functional intensity, and the balance between green and paved surfaces, as shown in Figure 3.



Figure 3. Two pilot-study locations, a) Cvetni trg and b) Park Starine Novaka (author's photographs)

4.1. Containment

At the containment level, the assessment included safety, visibility and accessibility, microclimatic quality, noise acceptability, and the acceptability of maintenance and cleanliness levels (Table 1).

Based on the expert evaluation, Park Starine Novaka achieved a significantly higher average score (3.50) than Cvetni trg (2.75). At Cvetni trg, the main issues identified

were high noise levels, inadequate maintenance of urban equipment, proximity to traffic, and a high share of paved surfaces. Park Starine Novaka shows an adequate level of formal maintenance, while cleanliness remains problematic due to user neglect and littering. Its microclimatic quality is considerably better than that of Cvetni trg.

Table 1. Containment comparative evaluation

	Cvetni trg		Park Starine Novaka	
	score	note	score	note
Safety, visibility, accessibility	4	Good lighting and visibility; medium accessibility	4	Good lighting and visibility; medium accessibility
Microclimate quality	3	High percentage of paved surfaces; proximity to traffic	4	Adequate microclimate quality
Noise level	2	Proximity to traffic and noise	3	Proximity to traffic
Maintenance and cleanliness	2	Medium paving quality; inadequate maintenance	3	Adequate maintenance; poor cleanliness
	2.75		3.50	

4.2. Passive restoration

Passive restoration was assessed through three sets of characteristics. The first set refers to natural characteristics, including vegetation, water features, shade, and biodiversity. Landscape characteristics included the balance between openness and enclosure, the quality of ground surfaces and materials, moderate changes in elevation, and the presence of views. The final set refers to architectural and design characteristics, including moderate building height, moderate diversity of details, the presence of aesthetically pleasing surrounding structures, biophilic materials, historical, symbolic, and other elements, as well as order, coherence, and viewpoints (Table 2).

Table 2. Passive restoration comparative evaluation

	score	Cvetni trg	score	Park Starine Novaka
Natural characteristics	3.33	Limited vegetation; fountain as a water element; low shade, and biodiversity.	4.00	Diverse vegetation and strong shade; water present indirectly; varied planting.
Landscape characteristics	3.75	Mostly open with some enclosure; medium paving quality; elevation differences reduce accessibility; views present.	4.00	Good balance of open and enclosed zones; good material variety; mild elevation differences; some views.
Architectural / design characteristics	4.00	Rich architectural variation, façade details, and symbolic elements; lack of natural materials.	3.25	Weaker architectural and symbolic elements; some biophilic materials; stronger sense of order.
Overall passive restoration potential	3.69	Stronger through architectural and symbolic qualities than through natural elements.	3.75	Stronger through natural and landscape qualities than through architectural articulation.

In the natural elements segment, Cvetni trg was evaluated as being less restorative than its counterpart, due to the lack of quality green elements, shade and biodiversity. The square does feature a water fountain, which supports this segment. Park Starine Novaka scored higher with larger amounts of vegetation, trees, green areas, shade, and biodiversity. In terms of landscape characteristics, Cvetni trg was rated slightly lower than Park Starine Novaka, mostly due to slight inaccessibility from stairs and changes in elevation. Park Starine Novaka has a better balance between more public and more intimate zones, gentler height differences, and greater material diversity. Architectural characteristics show different results. Cvetni trg has stronger potential in this category, led by architectural diversity, façade details, historical elements, and symbolic landmarks. Park Starine Novaka has a less pronounced architectural and symbolic framework.

4.3. Active restoration

Since active restoration is closely related to individual experience in space, this study only identifies relevant assessment criteria within this framework. These could be further examined in future research through survey-based methods. Active restoration would evaluate:

1. opportunities for personal socio-cultural engagement,
2. place attachment,
3. social interaction,
4. and a sense of community and belonging.

Assessing these categories would provide a more complete understanding of the identity, meaning, and individual experiential potential of the examined spaces. This assumption is further supported by initial studies conducted through the course Urban Design: Principles and Methods, within the second year of the Integrated Academic Studies in Architecture at the University of Belgrade, where four generations of students examined the same spaces through on-site observation and evaluation. Within future research, based on these student observations, it may be assumed that Cvetni trg would achieve a higher score at this level, given its more pronounced urban identity, historical and symbolic elements, central location, and stronger role in the social life of the city.

4.4. Synthesis of Comparative Findings and Improvement Guidelines

The comparative evaluation shows that Cvetni trg and Park Starine Novaka achieve restorative potential through different spatial characteristics. Cvetni trg received a lower score at the containment level, primarily due to the strong impact of traffic and noise, the high proportion of paved surfaces, limited shade, and issues related to the maintenance of urban equipment. Its stronger potential is identified in its architectural and symbolic characteristics, including the presence of façades, historical elements, views, and a distinct urban identity.

Park Starine Novaka shows a more balanced restorative profile, with higher scores in containment, natural, and landscape characteristics, supported by greenery, shade,

diverse plant elements, quality ground surfaces, and a better balance between open and enclosed zones. Its limitations relate to a less pronounced architectural and symbolic framework, as well as issues of cleanliness and maintenance.

Based on these results, design guidelines for Cvetni trg should focus on mitigating the impact of traffic, increasing shade, introducing additional green and water elements, and improving accessibility, while preserving the space's urban identity. For Park Starine Novaka, priorities include improving maintenance, more clearly defining entrances, paths, and areas for staying, as well as introducing additional sensory, water-related, and socially activating elements.

CONCLUSION

This paper examined the restorative potential of open public urban spaces through the development and pilot application of an evaluation matrix based on contemporary theories of restorative environments. By combining the levels of containment, passive restoration, and active restoration with natural, landscape, and architectural characteristics, the research proposed a framework for analysing how specific design features may support psychological restoration in dense urban settings.

The pilot evaluation of Cvetni trg and Park Starine Novaka showed that spaces of similar size and position within the city can contribute to restorativeness in different ways. Park Starine Novaka demonstrated stronger potential through greenery, shade, microclimatic comfort, and landscape qualities, while Cvetni trg showed greater value through architectural diversity, historical references, and symbolic identity. This indicates that restorative potential in urban environments cannot be reduced only to the presence of natural elements, but should be understood through the relationship between basic comfort, spatial qualities, and socio-symbolic meaning.

The main contribution of the paper is the proposed evaluation matrix, while its limitation lies in the pilot character of the research. The active restoration level, intentionally left for user-based methods, constitutes the next phase of this research, to be addressed through surveys and behavioural observation. The matrix can also be replicated as an exploratory diagnostic tool in similar dense urban contexts. The pattern observed here, stronger architectural and symbolic qualities compensating for weaker natural elements, and vice versa, is likely to recur in cities with comparable historical urban fabric. However, its extent will depend on local spatial and cultural conditions.

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Research paper

HYBRIDIZATION OF PUBLIC SPACES AS A TOOL FOR ADAPTING CITIES TO CLIMATE CHANGE

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Abstract

The paper examines the application of the concept of hybridization in the design of public spaces in the function of adaptation of cities to climate change. The concept of hybridization is a relevant topic that discussed in this paper from the point of view of contemporary demands of climate change. As a process, hybridization implies combining and mixing different urban structures, programs and activities, which creates complex, heterogeneous urban spaces. Contemporary problems of overheating, flooding and droughts, which occur more and more often, establish new requirements for the design of public open spaces and their adaptation to the areas of influence. In this regard, the new climate function encourages the development of new hybrid types of public spaces due to the addition of new functions and programs, as well as the establishment of new relationships between natural and built elements in public spaces. In this sense, the goal of this paper is to define why and how hybridization of public spaces is used in the present-day city as a means of adapting to climate change. Analysing examples of good practice of adaptation of public open spaces to climate change in a systematized way shows which types of public open spaces hybridization can be recognized as a function of adaptation, in which domains hybridization is realized and which climatic and other additional functions are implemented by these new types of public open spaces. The results of the work indicate that the application of the concept of hybridization of open public spaces, in addition to adaptation to climate change, has the potential to contribute to the realization of multiple benefits, including increasing social inclusiveness, integration of nature, flexibility of space, reduction of resource consumption, as well as the overall quality of urban life.

Key words *hybridization, public spaces, climate change, adaptation*

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1. INTRODUCTION

Cities are undergoing rapid urban transformation due to densification of the population, intensive and diverse uses and users, increasing mobility, new and complex living conditions. In response cities need to create urban spaces that can respond to the emerging hybrid conditions and expectations. Hybrid spaces are defined as "contemporary spaces shaped by a dynamic process which aims to synergize the various aspects of urban design from spatial configuration and programming to utilization and management" [1].

Emerging hybrid urban space typologies can be dynamic and contested, reflecting the synergies and tensions between spatial configurations, programmes, patterns of use, and governance. Within this context, the concept of public space today is more open to new urban types such as "shared spaces or relational spaces, as well as diversified typological hybrids" [2].

Climate change represents one of the greatest challenges facing contemporary society. It manifests through rising temperatures, changing precipitation patterns, sea-level rise, and the increasing frequency and intensity of extreme weather events, affecting human health, natural resources, biodiversity, ecosystems, and numerous sectors of development. In this context, public open spaces are recognized as particularly vulnerable to climate impacts while also offering significant potential for implementing measures that mitigate these effects and enhance urban resilience [1]. This study is founded on the premise that the climate adaptation function should be integrated into the design of public spaces, enabling the emergence of new hybrid public space types that simultaneously perform multiple functions and generate benefits for both people and nature. Such hybrid public spaces are increasingly being conceptualized, planned, and implemented in practice, and a growing body of research has demonstrated their benefits [3], [4]. However, the existing literature lacks a systematic conceptualization that explicitly links the diverse domains of climate change adaptation with the specific modalities of hybridization through which these adaptive capacities are realized.

The aim of this study is to explain why and to explore how the hybridization of public open spaces can serve as a tool for climate change adaptation by establishing a clear and systematic framework for understanding the relationship between hybridization, climate change, and public open spaces.

2. METHODOLOGY

This paper uses a qualitative research approach combining conceptual analysis and case study analysis. The research was structured in two complementary stages.

In the first stage, a review of the relevant literature was conducted to examine the concepts of hybridization and public open spaces and to provide an overview of public space typologies that adopt an ecological approach to design. Particular attention was given to explaining how climate adaptation functions contribute to the emergence of new hybrid public space types.

In the second stage, five selected international examples of hybrid public spaces were analysed using a structured analytical framework. The case studies were selected because they represent implemented examples of different public space typologies addressing climate-related hazards through ecological design. Each case was analysed according to the type of public open space, the climate change hazard addressed, the climate adaptation function performed, the domain of hybridization, the spatial methods of hybridization, and the resulting environmental and social benefits. The findings were compared and discussed to identify patterns in the relationship between hybridization and climate change adaptation, as well as the benefits of applying hybridization as a strategy for adapting public open spaces to climate change.

3. HYBRIDIZATION AND PUBLIC SPACE

3.1. What is hybridization?

Hybridization is defined as a process in which separate and distinct entities or processes create a new entity or process (hybrid), which may share certain characteristics with each of its sources. Hybridization as a process is as old as history itself, but the pace of mixing accelerates and its scope expands due to major structural changes, such as new technologies or new environmental demands.

Hybridity (hybridization) has been investigated within various disciplines such as biology, genetics, racial perspective, chemistry, language and culture. In French, "bricolage" has long been a common term. Mixing, blending, fusing, and blending are other terms and nuances with longer origins than the term "hybridity." Mixing plays a role in agriculture (mixing crops), cooking (ingredients), weaving (tissues, motifs), healing (herbs, methods), art (genres, materials), fashion (styles), etc.

Hybridity in the context of architecture and urban planning is most often associated and sometimes identified with the concepts of mixed-use, flexibility and multifunctionality [2]. Contemporary hybrid development can redefine the urban form, scale and location of public spaces, as well as the ways in which public spaces relate to their surroundings, as well as the ways in which they are used, experienced and managed [1]. Urban space can become fully hybridized with other development functions. At the city level, places can be reinvented through new uses of space and interactions that people empower. The concept of hybridization, in space, is manifested in the form of high-density residential buildings, industrial urban zones, infrastructural-transit spaces, recreational green hybrids and urban voids [1]. Neighborhoods can be hybrid for several reasons: built-up density; density of population and users; concentration and diversity of functions and activities. "The hybridization of space is based on a multifunctional connection with the inner city structure and suburban areas" [6].

The concept of public spaces today is more open to new urban types, such as "common spaces or relational spaces, as well as diversified typological hybrids". Infrastructural and technological nodes are transformed into "common places" or defined as "interspaces" [2].

3.2. Forms and domains of hybridization in public space

The ambiguity of the concept of hybridization and the complexity of the concept of public space allow the concept of hybridization in the context of public spaces to be broken down into five individual domains (cultural, functional, nature/built, private/public and digital/physical), as shown in Table 1.

Table 1. Domains of hybridization in public space

Domain of hybridization	Definition
Cultural	Mixing of different cultural identities, social practices and symbolic meanings in space. Hybrid urban spaces in this domain are created through the meeting of different traditions, styles, cultural narratives and ways of using space [7].
Functional	Combination of different functions and activities within the same space or structure through layered organization and interweaving of programs, increasing flexibility and intensity of use [8].
Nature / built	Integration of architectural and infrastructural elements with natural and landscape systems. Hybrid spaces are created through the merging of urban fabric with green infrastructure, landscape elements, ecological principles and natural processes [6].
Private / public	Interweaving of public and private spaces and functions, creating semi-public and transitional spaces where public and private activities coexist [2].
Digital / physical	Integration of digital technologies with physical urban space. Digital systems, communication technologies, smart infrastructure and virtual platforms influence the way space is used and perceived, creating hybrid urban environments [2].

Shaping hybrid spaces requires a departure from formal models and established typologies, as well as an assessment of the potential of spatial situations. Certain design methods that create hybrid spaces can be identified, including program layering, spatial and/or program connectivity, intersection of programs and functions through existing natural and/or infrastructural elements, combining landscape and architectural design, multidisciplinary approach and mixing of typologies. Complex forms, dispositions, hybrid internal and external connections, underground, multi-level or elevated public spaces are some examples of manifestations of hybrid public space [1].

4. CLIMATE CHANGE AND PUBLIC SPACE

4.1. The problem of public spaces in response to climate demands

The future will bring warmer and wetter winters, hotter and drier summers, rising sea levels, more flooding and other extreme weather. Because of the delayed effects from greenhouse gas emissions, we are locked into significant climate change, regardless of any emission reductions that we may secure now. Adaptation to climate change means making towns and cities more resilient. Well-designed, flexible public spaces are their best chance to adapt to these threats. Spaces that are softer, greener, more organic and natural will store water and are critical to modifying urban temperatures [9].

Encouraging higher urban densities makes urban areas more efficient, for instance in their use of resources and the provision of public services. But it does increase pressure on green space. In particular, small-scale local spaces, which will make life in a warming city tolerable, are being permanently lost to development [10].

Green spaces with a generous planting of trees link to form a network offering cooler, cleaner air. Adaptation demands understanding how towns and cities work naturally. Urban green spaces form a natural infrastructure that is as critical to support urban life as streets, railways, drainage and sewers — and just like these, it is an infrastructure that needs investment. At the same time, this will create much more beautiful, healthier places. Good urban design should provide solutions for the management of water, temperatures and biodiversity [9]. The main climate change hazards and the corresponding adaptation measures are summarized in Table 2.

Table 2. Climate change hazards and adaptation measures relevant to open spaces [5, 9]

Climate change hazard	**Adaptation options**
High temperatures	• Development of high-quality green infrastructure • Increasing the availability and use of water surfaces • Shading and orientation that reduces the influence of solar radiation • Ensuring ventilation by matching the location, orientation and morphology of buildings, green and water surfaces • Using "cold" materials for covering the ground and roofs in order to increase reflexivity
Floods	• Securing the land needed to manage flooding (*Fluvial floods* occur when rivers, lakes or streams overflow onto neighboring land, responsibilities are regional or national; *Pluvial floods* occur when extreme rainfall causes flooding independent of overflowing rivers or lakes, responsibilities are typically local) • Creation of solid barriers against flooding, when necessary • Mitigation of flooding through the adequate selection of location, organization, and space design in the new development of the settlement • Use of sustainable urban drainage and stormwater management approaches to slow runoff water and integrating it into the natural cycle • Understanding the logic and path of flooding - creating a place for water: a) using green infrastructure and recreating functional floodplains valley, b) by providing temporary spaces for retaining water in the flow extreme events, c) planning reservoirs and greening the coast in order to retain and reduce the outflow of water, d) by directing the flow flooding away from sensitive areas and by constructing secondary channels flooding
Droughts	• Creation of reservoirs in the upper and lower reaches of the river • Provision of space for rainwater treatment and water recycling • Use of urban water management approaches • Use of separate drainage systems • Use of plants with a low need for water, underground capacities water conservation and search for new sources of water for use in crisis periods

4.2. New hybrid public spaces in response to climate change

The following section presents overview of different types of public spaces that use an ecological approach in design, with a special focus on their role in responding to the challenges of climate change and improving the resilience of modern cities. The new climate function encourages the development of new hybrid types of public spaces, presented in Table 3. It requires the integration of new functions and programs, such as water management. Also, it establishes new relationships between natural and built elements within public spaces, helping to mitigate overheating and prevent the formation of urban heat islands, etc.

1. Sponge Parks / Floodable Parks
What they do: absorb rainwater, cool the city and reduce the possibility of flooding.
• Lawns, wetlands and sunken fields absorb storm water
• Can be temporarily flooded without damage
• When dry, they can have other functions [11]

2. Urban Forest Plazas
What they do: reduce heat, improve air quality and boost biodiversity.
• Dense tree canopies above public squares
• Permeable substrates instead of classic paving
• Lower temperatures (often 5–10°C cooler in summer) [12]

3. Climate Cooling Spaces
What they do: mitigate the urban heat island effect.
• Earthen embankments, trees, porous rock
• Orientation of the space to catch the wind
• Bright or vegetated areas [13]

4.Biodiversity Squares
What they do: restore biodiversity within the city.
• Meadows of wild flowers instead of classic lawns
• Nesting habitats, dead wood, "hotels" for insects
• Seasonal changes are accepted as a quality, not a disadvantage [14]

Table 3. Potential climate change hazards and suitable hybrid types of open public spaces

Climate change hazard	**Hybrid type of open public space**
High temperatures	• Urban Forest Plazas • Climate Cooling Spaces • Biodiversity Squares
Floods	• Sponge Parks / Floodable Parks

5. HYBRIDIZATION AND CLIMATE-RESPONSIVE URBAN DESIGN

The analysis of examples of good practice in adapting public open spaces to climate change allows us to verify whether the hybridization of public open spaces in the function of adaptation can be linked to different types of public open spaces and whether hybridization in these cases is realized in different domains. In addition, through the examples, potential new types of hybrid spaces that realize climate functions, as well as multiple benefits, in addition to climate, provided by selected public open spaces, have been identified, as summarized in Table 4.

Table 4. Examples of hybrid public spaces and their adaptation to climate change hazards

01 Example	**Climate adaptation**		
 *Figure 1. Water Square Benthemplein, Netherlands, https://www.urbanisten.nl/work/benthemplein*	Type of open public space	Climate change hazard	Function
	Sponge / Floodable square	Floods High temperatures	Storm water storage Controlled infiltration and delayed drainage systems
Hybridization			
Domain of hybridization	Spatial methods	Benefits	
Nature / Built Functional	Regeneration Integration and combination of function Program layering	**Climate benefits:** Preventing flooding; Increasing thermal comfort during heatwaves **Other:** Flexibility and multifunctionality Social cohesion and local development.	

02 Example	**Climate adaptation**		
 *Figure 2. Stork Meadow Nature Park, Denmark, https://www.archdaily.com/1021185/stork-meadow-nature-park-cf-moller-architects*	Type of open public space	Climate change hazard	Function
	Climate Cooling Space / Public nature park	Floods Drought	Wastewater management - rainwater is collected in purification basins Storm surge protection
Hybridization			
Domain of hybridization	Spatial methods	Benefits	
Nature/built Functional	Intersection of programs and functions through existing natural elements Spatial connectivity	**Climate benefits:** Preventing flooding; Preserving the nature; Improving urban biodiversity **Other:** Creation of activity node Flexibility and multifunctionality	

03 Example	**Climate adaptation**		
 *Figure 3. Piazza Matteotti Public Gardens, Italy, https://www.archdaily.com/1024703/innovations-in-public-spaces-gardens-plazas-and-landscape-parks-of-2024*	Type of open public space	Climate change hazard	Function
	Climate cooling space / Public garden	High temperatures	Addition of shade-providing trees Draining pavements Adding water surface

Hybridization		
Domain of hybridization	Spatial methods	Benefits
Nature / built Cultural	Integration of function Redefinition of meaning	**Climate benefits:** Urban cooling and reduction of heat island effect; Microclimate regulation; Improving urban biodiversity; **Other:** Flexibility and multifunctionality

04 Example	**Climate adaptation**		
 *Figure 4. Climate islands, Spain, https://www.simonprize.org/work2022/climate-islands-public-spaces-in-barcelonas-port-vell/sheet/*	Type of open public space	Climate change hazard	Function
	Climate cooling space / Promenade	High temperatures	Water clouds (system of vapor masts with sequential activation) Pavement with a low thermal index

Hybridization		
Domain of hybridization	Spatial methods	Benefits
Nature / built Functional	Integration and combination of function Reshaping/Transformation	**Climate benefits:** Improving urban biodiversity; Reducing the 'heat island' effect; Lowering pollution; **Other:** Social cohesion and local development.

05 Example	**Climate adaptation**		
 *Figure 6. The Cloud Forest Plaza, China,https://worldlandscapearchitect.com/the-cloud-forest-plaza-wuhan-china-terrain-studio/?v=3a2d7564baee*	Type of open public space	Climate change hazard	Function
	Urban Forest Plaza	Floods High temperatures Drought	Stormwater collection Passive water filtration and retention systems Mist cooling systems Rain gardens and bioswales

Hybridization		
Domain of hybridization	Spatial methods	Benefits
Nature / built Functional	Integration of function Combination of landscape and urban design	**Climate resilience:** Preventing flooding; Delayed drainage; Heat reduction; Improving urban biodiversity **Other:** Social cohesion and local development..

The selected case studies demonstrate that, in practice, emerging hybrid public spaces are primarily designed to address climate-related challenges associated with rising temperatures and flooding, whereas strategies for managing drought are considerably less represented. Flood mitigation emerges as the most prominent climate adaptation function of these new public spaces, followed by urban heat reduction and biodiversity enhancement. In addition to these climate-related benefits, multifunctionality and social inclusion represent important other benefits that arise from climate-adaptive design.

6. CONCLUSION

Given the complexity of spatial hybridization as a concept that can be interpreted and applied in various ways, this study examines it as a tool for adapting public open spaces to climate change. The analysis is based on selected case studies of public open spaces, through which the domains and spatial methods of hybridization are identified and explored in relation to their contribution to climate adaptation, particularly in mitigating high temperatures and floods while drought related adaptation measures are less evident in the selected case studies and require further research.

By deconstructing hybridization into its key domains (cultural, functional, nature–built, private–public, and digital–physical) and climate change into specific hazards (high temperatures, floods, and droughts), the research establishes a clear and systematic framework for understanding the relationship between hybridization, climate change, and public open spaces.

Through this analytical approach and the examination of diverse public spaces selected for their climate-adaptive characteristics, the study demonstrates that the hybridization of public open spaces can be associated with a variety of spatial typologies, including floodable squares, public nature parks, public gardens, promenades, experimental ecological gardens, and urban forest plazas. Furthermore, hybridization can be realized across multiple domains, particularly the nature–built, functional, and cultural domains.

The findings also suggest that the growing need for climate adaptation is itself driving the emergence of new types of public open spaces. Beyond their environmental role, these spaces generate additional benefits, including greater flexibility and multifunctionality, stronger social cohesion and local development, and the creation of new activity nodes. Overall, the research confirms the significance of hybridization as an effective tool for climate change adaptation, highlighting its contribution to urban design and the development of more sustainable, resilient, and vibrant public open spaces.

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Research paper

APPLICATION OF ATRIUMS AS BIOPHILIC AND BIOCLIMATIC ELEMENTS IN THE DESIGN OF CONTEMPORARY PUBLIC BUILDINGS

Marko Jeremić [1], Jana Lambić [2]

Abstract

The paper explores the role of the atrium as a spatial element in the context of biophilic and bioclimatic design of contemporary public buildings. In conditions of intensive urbanization and climate change, atriums are recognized as a significant tool for improving the quality of the indoor environment, energy efficiency and user experience. The aim of the paper is to analyze how atriums integrate biophilic and bioclimatic principles, as well as to examine their performance through selected case studies. The research includes a theoretical analysis and a comparative study of three contemporary buildings: Oodi Central Library, Finland, Manitoba Hydro Place, Canada and Jewel Changi Airport, Singapore. The methodology is based on a literature review and a comparative case study, while the results relate to the identification of key biophilic and bioclimatic principles in atrium design. Research shows that atriums simultaneously contribute to improving the quality of the indoor environment, social interaction, and energy efficiency of buildings, with significant potential for application in contemporary public architecture.

Key words: *Atrium, Biophilic design, Bioclimatic architecture, Sustainable architecture, Public facilities*

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1. INTRODUCTION

Modern cities face the challenges of intensive urbanization, climate change and the need to create a better and more sustainable living environment. In such conditions, sustainable architecture takes on an increasingly significant role through the application of solutions that contribute to energy efficiency, improving the quality of the indoor environment and reducing negative environmental impacts [1].

One of the approaches that has gained special importance in recent decades is biophilic design, based on the integration of natural elements and processes into the built environment. The use of natural lighting, vegetation, water, natural ventilation and visual connection with nature contributes to the creation of a healthier and more pleasant space for users [2].

Atriums stand out as spatial elements that combine biophilic and bioclimatic principles through the provision of natural lighting, ventilation, microclimate regulation and the possibility of integrating vegetation. Their application in modern public buildings can contribute to improving the quality of the indoor environment, energy efficiency and user experience [3].

The subject of the work is the analysis of the atrium as a biophilic and bioclimatic element in the design of modern public buildings. The aim of the research is to assess the role of the atrium in improving the quality of the indoor environment and the energy efficiency of buildings, as well as to identify the possibilities of their application in public buildings in Serbia.

2. RESEARCH METHODOLOGY

The research is based on an approach that includes analysis of relevant literature and comparative analysis of case studies. The research question refers to the way in which atriums integrate biophilic and bioclimatic principles in modern public buildings and the possibilities of their application in Serbia.

The case studies were selected based on the presence of a central atrium, the application of biophilic and bioclimatic principles, the different uses of the buildings and the availability of relevant documentation. The objects analyzed were Oodi Central Library (Finland), Manitoba Hydro Place (Canada) and Jewel Changi Airport (Singapore).

A comparative analysis was carried out by comparing the biophilic and bioclimatic characteristics of buildings, including natural lighting, vegetation, natural ventilation, microclimate regulation and energy efficiency, based on which guidelines were defined for the use of atriums in the design of public buildings in Serbia.

3. BIOPHILIC AND BIOCLIMATIC PRINCIPLES OF THE ATRIUM

Atriums represent spatial elements that enable the integration of natural elements and processes into the interior of the building, which is why they play a significant role in modern sustainable design. Their specific spatial organization enables the simultaneous application of biophilic and bioclimatic principles, thus contributing to the

improvement of the quality of the internal environment, the well-being of users and the energy performance of the building. For this reason, in modern architecture, atriums are increasingly viewed as active elements of sustainable design, and not only as spaces for communication and distribution of users [2], [4].

Biophilic design is based on the assumption that humans have an innate need to connect with nature. The theory of biophilia was defined by Wilson, emphasizing that contact with the natural environment has an important role in preserving the physical and psychological well-being of man [5]. In conditions of intense urbanization and increasing time spent indoors, biophilic design seeks to integrate natural elements into the built environment. Atriums represent one of the most effective spatial elements for achieving this goal because they enable the integration of natural light, vegetation, natural ventilation and visual connection with nature within a unique space [2], [6].

Natural lighting is one of the most important biophilic principles that is realized by the use of the atrium. Through skylights or transparent roof structures, the penetration of daylight deep into the interior of the building is enabled, which improves the visual comfort of users and reduces the need for artificial lighting [7]. The results of modern research show that the increased availability of daylight in atrium spaces contributes to better visual comfort, regulation of circadian rhythms and greater user satisfaction, while simultaneously reducing the need for artificial lighting, which can contribute to a reduction in energy consumption for lighting [8].

The integration of vegetation represents another important biophilic principle. Atriums enable the formation of internal gardens, green walls and spaces with a high proportion of plant species, which allows users to have direct contact with nature. In addition to aesthetic value, vegetation contributes to improving air quality, microclimate regulation and creating a more pleasant environment for living [2], [3]. Research shows that the presence of vegetation in indoor spaces has a positive effect on the psychological well-being of users, reduces the level of stress and contributes to the quality of the indoor environment, while in combination with natural ventilation it can have a positive effect on local microclimate conditions [9].

Atriums also enable the realization of a visual connection with nature, which represents one of the most significant patterns of biophilic design. Views towards vegetation, sky and natural light contribute to reducing mental fatigue and creating a better user experience. The special importance of this principle is reflected in public facilities such as libraries, cultural centers, educational and health institutions, where users spend long periods of time in closed spaces [5], [7].

In addition to biophilic aspects, atriums play a significant role in achieving the bioclimatic performance of the building. Thanks to their geometry and the vertical connection of the space, they enable natural ventilation by applying the air buoyancy effect (stack effect). Heated air is naturally raised and discharged through higher-positioned openings, while fresh air is introduced through the lower parts of the building. In this way, the quality of indoor air is improved and the need for mechanical ventilation is reduced [10], [11]. Recent research based on CFD simulations and experimental analyzes confirms that properly designed atriums can improve natural

ventilation, improve thermal comfort and reduce energy consumption for ventilation and heating [12].

Atriums also contribute to the formation of a specific microclimate and improvement of thermal comfort. As transition zones between outdoor and indoor space, they can mitigate temperature oscillations, achieve passive solar gains during the winter period and reduce the risk of overheating during the summer [13], [14]. The effectiveness of these strategies has been confirmed by recent research that indicates that the geometry of the atrium, glazing and the method of ventilation have a decisive influence on the thermal comfort and energy efficiency of the building [12].

By combining natural lighting, vegetation, visual connection with nature, natural ventilation and microclimate regulation, atriums unite biophilic and bioclimatic principles within a unique spatial element. Therefore, they represent an important tool of modern sustainable architecture, enabling the creation of healthier, more pleasant and energy-efficient public buildings [4], [7].

In order to make it easier to understand the interconnection of biophilic and bioclimatic principles, Figure 1 shows a conceptual diagram of the atrium with the most significant natural processes and their impact on the quality of the internal environment and the performance of the facility (Fig. 1).



Figure 1. Conceptual presentation of biophilic and bioclimatic principles applied in the atrium space, Source: [author]

In order to systematize the most important biophilic and bioclimatic aspects of the atrium, below is an overview of their basic principles, methods of application and potential effects on the quality of the indoor environment and the performance of the facility (Table 1).

Table 1. Biophilic and bioclimatic principles of the atrium and their effects

Principle	Application in Architecture	Effects
Natural daylighting	Skylights and transparent roof structures	Visual comfort, regulation of circadian rhythms, reduced electricity consumption
Integration of vegetation	Indoor gardens, trees, and green walls	Improved indoor air quality, stress reduction, and enhanced indoor microclimate
Visual connection with nature	Views of greenery and the sky	Psychological well-being, improved concentration, and greater user satisfaction

Natural ventilation	Stack effect and natural airflow	Improved indoor air quality and reduced reliance on mechanical ventilation
Dynamic microclimate	Variations in daylight, temperature, and airflow	Enhanced thermal comfort and a more natural spatial experience
Passive solar gains	Heat gain through glazed surfaces	Reduced heating demand during colder periods
Thermal mass	Heat storage and gradual heat release	Stabilization of indoor temperature fluctuations
Social interaction	Central space for gathering and communication	Strengthened social interaction and enhanced sense of place
Energy performance	Integration of passive design strategies	Reduced overall energy consumption and improved building sustainability

The analysis of the presented principles shows that atriums realize biophilic and bioclimatic functions at the same time, connecting the needs of users with the requirements of sustainable design. By integrating natural lighting, vegetation, ventilation and passive energy strategies, atriums contribute to improving the quality of the indoor environment, energy efficiency and overall sustainability of modern public buildings.

Although atriums provide numerous biophilic and bioclimatic benefits, their implementation requires careful design. Large glazed surfaces can lead to summer overheating, glare and increased heat losses during the winter period if appropriate shading systems and high-performance glazing are not applied. Additional challenges relate to the organization of the smoke evacuation system in case of fire and the maintenance of glazed surfaces and vegetation. That is why atriums today are designed through an integrated approach that combines architectural, energy and technical requirements [8].

4. CASE STUDIES

In order to see the application of biophilic and bioclimatic principles, three representative examples of public buildings were analyzed. The analysis includes biophilic characteristics, bioclimatic performance and spatial organization of the atrium in order to identify principles applicable in the design of public buildings in Serbia.

4.1. Case study analysis - Oodi Central Library, Finland

The Oodi Central Library in Helsinki is a modern example of public architecture with pronounced biophilic and bioclimatic design principles. The facility is located in the central urban area of Helsinki, opposite the parliament building, which fulfills a significant symbolic role of public space for citizens (Fig. 2) [15].

Within the biophilic design, the application of natural lighting through large glazed surfaces and open interior spaces is especially highlighted. Daylight penetrates deep into the interior, improving visual comfort and reducing the need for artificial lighting. On the upper level of "Book Heaven", a strong visual connection with the external environment and the city landscape is realized, which further improves the quality of the user's stay (Fig. 3 and 4) [16].





Figure 2. Oodi Central Library – exterior, Source [15], Figure 3. Oodi Central Library – interior, Source [16], Figure 4. Oodi Central Library – interior, Source [16]

The visual connection with the external environment - the square, the park and the urban landscape - represents an important biophilic principle that contributes to the quality of the user's stay. The use of natural materials, especially wood, additionally strengthens the tactile connection with the space, while the open and atrium-organized parts encourage social interaction and gathering of users. From the bioclimatic aspect, the building uses large glazed areas for maximum use of daylight and reducing the need for artificial lighting. The design of the facade and canopies contributes to protection from unfavorable climatic conditions and improvement of the microclimate of the immediate environment [17]. Although Oodi does not have a classic atrium, its central open volumes and vertical connections achieve similar functions through natural lighting, visual connectivity and better user orientation, thus exemplifying the integration of biophilic and bioclimatic principles in public architecture.

4.2. Case study analysis - Manitoba Hydro Place, Canada

Manitoba Hydro Place represents one of the most significant examples of contemporary bioclimatic architecture in North America (Fig. 5). The facility was designed with the aim of reducing energy needs in the extreme climate conditions of Winnipeg through the application of passive strategies and the use of natural energy potentials [18].

The central atrium is a key element of the bioclimatic concept and functions as a "climate module" of the building. Shaped as a triple glass conservatory, it enables natural ventilation, accumulation of solar energy during winter and removal of excess heat during summer, thereby reducing the need for mechanical heating and cooling systems [19]. The "solar chimney" system - vertical ventilation towers that enable the natural extraction of warm air and stabilization of the internal microclimate, is of additional importance, while the high-performance facade cladding contributes to the reduction of heat losses (Fig. 6) [19]. From the aspect of biophilic design, the atrium integrates vegetation, natural light and visual connections between work spaces, thus contributing to the psychological comfort of users and creating a more pleasant work environment (Fig. 7). Atrium simultaneously enables vertical connection, orientation in space and improvement of quality of stay, showing how it can function as a spatial, energetic and ecological element of contemporary architecture.



Figure 5. Manitoba Hydro Place – exterior, Source [15], Figure 6. Vertical ventilation tower, Source [16], Figure 7. Manitoba Hydro Place – atrium, Source [16].

The combination of passive strategies, optimized envelope and intelligent climate management made it possible to achieve high energy performance of the facility, making Manitoba Hydro Place an example of successful integration of architecture and natural climate processes.

4.3. Case study analysis - Jewel Changi Airport, Singapore

Jewel Changi Airport represents one of the most significant contemporary examples of the integration of biophilic and bioclimatic principles in public architecture. The building was designed by Moshe Safdie (Safdie Architects) and opened in 2019 as a central public space connected to the terminals of Singapore Changi Airport (Fig. 8). The complex combines the functions of a transport hub, a shopping center and an inner urban park, with a monumental atrium under a large glass dome as the central spatial element [20].

Biophilic principles represent the basis of the concept of the facility. In the atrium is the Shiseido Forest Valley – a multi-story interior landscape with more than 2,000 trees and numerous plant species, which forms a natural environment in the interior (Fig. 9). Vegetation contributes to improving air quality, microclimate regulation and creating a more pleasant environment for users. A special element is the Rain Vortex, the largest indoor waterfall in the world, which through the visual and sensory experience of water additionally connects users with natural processes (Fig. 10). The transparent dome allows abundant natural lighting and visual connections with vegetation, water and the outside environment [20].



Figure 8. Jewel Changi Airport – exterior, Source [20], Figure 9. Shiseido Forest Valley, Source [20], Figure 10. Rain Vortex, Source [20].

From the bioclimatic aspect, the building uses a combination of natural lighting, a high-performance glass dome and natural elements to regulate the microclimate. Vegetation and water surfaces contribute to cooling the air through evapotranspiration, while the geometry of the dome allows control of solar gains, distribution of daylight

and natural air circulation in the central space. The atrium represents the main organizational element of the complex, integrating functional, biophilic and bioclimatic roles. By connecting nature, users and architectural space, Jewel Changi Airport represents one of the most complete modern models of sustainable design of public facilities [21].

4.4. Comparative analysis of case studies

The analysis of selected case studies shows that atriums in modern public buildings play an important role in integrating biophilic and bioclimatic design principles. Although all three analyzed examples use the atrium as a central spatial element, their functions differ according to the design concept and building purpose. Oodi Central Library emphasizes natural lighting, visual connection with the environment and social interaction, while Manitoba Hydro Place uses the atrium as an active component of natural ventilation and energy strategies. Jewel Changi Airport represents the most integrated approach, combining vegetation, water, natural lighting and microclimate regulation. Table 2 presents a comparative analysis of the main biophilic and bioclimatic principles identified in the selected case studies.

Table 2. Comparative analysis of biophilic and bioclimatic principles in selected case studies

Principle	Oodi Library	Manitoba Hydro Place	Jewel Changi Airport
Natural daylighting	++	++	++
Visual connection with nature	++	++	++
Integration of vegetation	+	++	+++
Presence of water	-	-	+++
Use of natural materials	+++	+	+
Visual connections between floors	++	++	++
Dynamic spatial experience	++	+	+++
Connection with natural processes	+	++	+++
Social interaction and gathering	+++	++	+++
Sense of place	+++	++	++
Natural ventilation	+	+++	++
Stack effect	-	+++	++
Passive solar gains	+	+++	++
Microclimate regulation	+	++	+++
Reduced need for artificial lighting	++	++	+++
Energy efficiency	++	+++	++
Integration of vegetation in climate regulation	-	++	+++
Building envelope optimization	++	+++	++
Thermal comfort	++	+++	++
Reduced reliance on mechanical systems	+	+++	++
Legend: +++ very pronounced; ++ present; + partially present; – not significantly represented;			

The comparative analysis confirms that atriums can have different functional and ecological roles depending on the design concept. While the Oodi Central Library prioritizes the quality of the user experience and the biophilic characteristics of the space, the Manitoba Hydro Place is an example of bioclimatically guided design. Jewel

Changi Airport achieves the highest level of integration of both approaches, demonstrating that an atrium can simultaneously contribute to the quality of the indoor environment, energy efficiency and the creation of a distinctive public space. At the same time, the analyzed examples show that achieving such performance requires careful consideration of the issues of solar radiation control, thermal losses, smoke extraction and maintenance of atrium spaces.

5. POSSIBILITIES OF APPLICATION IN DESIGNING PUBLIC BUILDINGS IN SERBIA

The analysis of theoretical foundations and selected case studies indicates that atriums have significant potential for improving the quality of public buildings in Serbia. In addition to their spatial and functional role, they can contribute to a better quality of the indoor environment, greater energy efficiency and strengthening the user's connection with the natural environment. In the conditions of climate change and increasing demands for sustainable construction, atriums represent an important element of contemporary architectural design.

The climatic characteristics of Serbia favor the application of bioclimatic strategies in atrium spaces. By using natural lighting, passive solar gains, natural ventilation and the stack effect, it is possible to reduce energy consumption and improve the thermal comfort of users. At the same time, the integration of vegetation, natural materials and open visual connections contributes to the realization of biophilic principles and the creation of a more pleasant and healthy indoor environment.

The greatest potential for the application of these principles is recognized in cultural, educational, health and administrative facilities, where atriums can function as spaces for social interaction, natural lighting and microclimate regulation. Although their application requires larger initial investments and an integrated approach to design, special attention should be paid to preventing summer overheating, controlling glare, reducing heat losses, solving smoke exhaust systems and planning the maintenance of vegetation and glazed surfaces. However, the long-term benefits in terms of space quality, energy efficiency and user comfort justify their wider application. The experiences of analyzed international examples indicate that the integration of biophilic and bioclimatic principles can represent a guideline for the future design of more sustainable public facilities in Serbia.

6. CONCLUSION

The conducted research showed that atriums represent an important element of modern sustainable design, because they enable the integration of biophilic and bioclimatic principles in public buildings. Their application contributes to the improvement of the quality of the indoor environment, energy efficiency and the quality of the user experience.

Case study analysis of Oodi Central Library, Manitoba Hydro Place and Jewel Changi Airport showed that atriums can have a variety of functions – from spaces for social interaction and natural lighting to active elements of natural ventilation and microclimate regulation. The greatest potential is realized by their integrated application within a unique architectural concept.

The results obtained indicate that there are real opportunities for the wider application of such solutions in the design of public buildings in Serbia, especially in cultural, educational, healthcare and administrative buildings. Atriums, designed as biophilic and bioclimatic elements, can represent an important contribution to the development of sustainable architecture and a higher quality built environment.

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Research paper

ANALYSIS OF INSULATION AND ORIENTATION IMPACT ON ENERGY CONSUMPTION IN DETACHED HOUSES

Marislav Stanojković[1]

Abstract

Modern architectural practice faces the complex challenge of balancing aesthetic, functional, and environmental requirements in the context of the global climate crisis. The focus of this research is to analyze the impact of thermal insulation, spatial orientation, and macroclimatic conditions on the annual energy consumption for heating and cooling of single-family residential buildings, which, due to an unfavorable shape factor, exhibit exceptional sensitivity to external microclimatic factors. Using advanced software tools for dynamic thermophysical simulations, EnergyPlus and OpenStudio within the SketchUp environment, a reference model of a two-story residential building (GF+1) with 11 independent thermal zones was developed. The parametric analysis encompassed a matrix of 18 simulation cycles generated by crossing three independent levels of thermal insulation, two spatial orientations, and three different European climate zones represented by the cities of Niš, Copenhagen, and Athens. Dynamic simulations confirmed that applying uniform thermal protection solutions, regardless of the geographical context, leads to energy and economic inefficiency. Shifting from an uninsulated to a standard insulated model generates massive energy savings for heating in colder climates. Conversely, further investment in an advanced level of insulation yields minimal and negligible benefits. Research proves that thermal insulation alone cannot ensure optimal summer energy performance in warm climates and should be complemented by effective ventilation and solar control strategies, confirming that energy-efficient architectural design requires a balanced and location-specific approach.

Key words: *energy efficiency, thermal envelope, dynamic simulations, single-family houses, climate zones, spatial orientation*

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1. INTRODUCTION

Modern architecture faces the complex challenge of balancing aesthetic, functional, and environmental requirements. In the context of the climate crisis and energy market instability, optimizing building energy performance has become a primary focus of research in civil engineering and architecture [1]. The building sector accounts for over one-third of global final energy consumption, with detached single-family houses contributing the largest share of greenhouse gas emissions [2]. Due to an unfavorable shape factor—specifically, a higher surface-to-volume ratio—these houses are exceptionally sensitive to external climatic conditions and heat losses [3].

The building envelope directly dictates the thermal behavior of the structure, acting as a filter between indoor comfort and dynamic outdoor microclimate [3, 4]. The uniform application of thermal protection solutions ignores the fact that the same architectural model generates fundamentally different energy needs depending on the climate zone [5]. Northern Europe is dominated by the need to reduce transmission heat losses during long heating seasons, the Mediterranean region faces building overheating and high cooling demands due to intense solar radiation [6, 12], while the moderate continental climate of the Balkans requires balanced solutions addressing both winter and summer conditions [1, 14].

For reliable performance assessment during the design phase, dynamic thermophysical simulations have become an indispensable standard [7, 15]. High-resolution tools such as EnergyPlus (integrated via OpenStudio within the SketchUp environment) enable the calculation of hourly heat flows, accounting for meteorological data, solar radiation, internal gains, and air infiltration [8, 9].

However, techno-economic optimization of the building envelope remains an open issue. Increasing insulation thickness and implementing advanced glazing (with low-emissivity coatings and inert gases) linearly reduce the heat transfer coefficient, yet annual energy benefits exhibit a non-linear trend [10]. According to the law of diminishing returns, beyond a critical insulation thickness, further investment yields negligible energy savings alongside a sharp increase in material costs [11]. Furthermore, over-insulated houses in warmer climates can trap internal heat gains, paradoxically increasing cooling energy demand during summer months [6, 12].

The aim of this study is to evaluate the combined impact of envelope insulation, spatial orientation, and climate context on residential energy demand using dynamic OpenStudio/EnergyPlus simulations across three European climate zones (Copenhagen, Niš, and Athens).

2. METHODOLOGY

The first phase of the research encompassed geometric modeling and spatial definition of the building within the SketchUp software package, using the official OpenStudio extension [9]. Architectural and functional zoning of the interior was performed by assigning a dedicated thermal zone to each room on the ground and upper floors, resulting in a total of 11 independent thermal zones (Figure 1). To simulate realistic conditions, shared partition surfaces were precisely matched (Figure 2)

to define boundary conditions for heat transfer, while all ground floor surfaces were set directly on the ground. Following geometric preparation in OpenStudio, the model was imported into EnergyPlus [8], where detailed thermophysical configuration of all building envelope elements was conducted. Prior to running the simulations, occupancy profiles (*Schedule:Compact*) and the physical characteristics of the building materials were defined.

The simulation plan was based on a multidimensional matrix of 18 cycles, generated by crossing three independent variables: envelope insulation thickness, spatial orientation, and geographic-climatic location. The physical characteristics of the unventilated thermal envelope and transparent elements were defined across three energy efficiency levels: The first variant (V1) represents an uninsulated model (0 cm of thermal insulation on external walls and flat roof) with standard single glazing featuring a high overall heat transfer coefficient of $U = 5.8\ \mathrm{W/m^2K}$. The second variant (V2) represents a standard level of protection, with 10 cm of insulation on external walls, 15 cm on the roof, and standard double glazing with $U = 1.5\ \mathrm{W/m^2K}$. The third variant (V3) was defined as an advanced high-efficiency model, with 15 cm of insulation on external walls, 30 cm on the flat roof, and triple glazing featuring a low heat transfer coefficient of $U = 0.5\ \mathrm{W/m^2K}$. Furthermore, no dynamic external shading devices, overhangs, or internal blinds were included in the simulation models, allowing an unhindered evaluation of direct solar gains on the building's thermal zones.

Each of the three variants was simulated under two orientation scenarios (by rotating the main axis by 180°), shifting the heavily glazed living room between north and south to analyze the impact of solar radiation. These parametric boundary conditions were selected because the primary glazed areas and main living spaces are concentrated along these two key facades. By isolating the north orientation (minimal direct solar gains) and south orientation (maximum controllable solar radiation), the model captures the maximum physical contrast in solar irradiance. The matrix of 6 variants (three insulation levels × two orientations) was fully replicated for three cities representing distinct European macroclimatic conditions: Niš (moderate continental climate), Copenhagen (cold climate), and Athens (Mediterranean climate), using standardized meteorological files (.epw format) [15].

This methodological approach established the geometric and thermophysical baseline for tracking heat flows, mapping heat transition, and conducting a detailed comparative analysis of the final annual energy consumption for the building's heating and cooling demands.

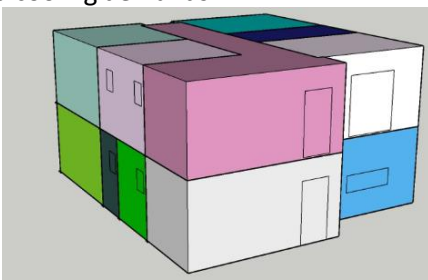


Figure 1: Thermal Zones in OpenStudio program, Source: Author

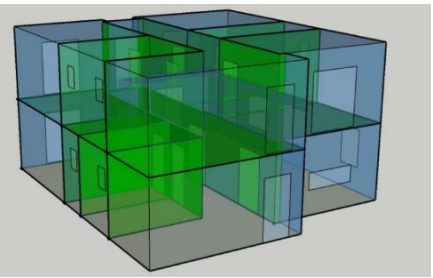


Figure 2: Matched surfaces OpenStudio program, Source: Author

2.1 CONCEPTUAL DESIGN OF THE REFERENCE MODEL FOR SIMULATION PURPOSES

For the purpose of conducting dynamic energy simulations, a reference model of a detached single-family residential building was developed, featuring a ground floor and one upper floor (GF+1), a flat roof, and a compact, orthogonal geometry. In order to precisely map internal thermal loads and occupancy profiles within the EnergyPlus software package, the functional spaces were integrated into separate thermal zones.

The spatial layout of the ground floor (Figure 3) is structured so that the total volume is divided into a primary, dynamic living area with a dining room and a kitchen, and a more passive zone comprising one bedroom, a restroom, and a bathroom. All rooms are directly connected via a central hallway that extends along the longitudinal axis of the ground floor, generating the main circulation artery of the building, within which the vertical circulation core with a double-flight staircase is positioned. The upper floor (Figure 4) is fully conceptualized as a night zone; its spatial structure consists of three edrooms and two bathrooms. The internal communication system on the upper floor consistently follows the layout matrix of the ground floor, where all rooms are again organized around a central longitudinal hallway connected to the vertical staircase core, thereby achieving continuity of the circulation tract throughout the entire volume of the building. The entire indoor volume is modeled as a fully conditioned space.

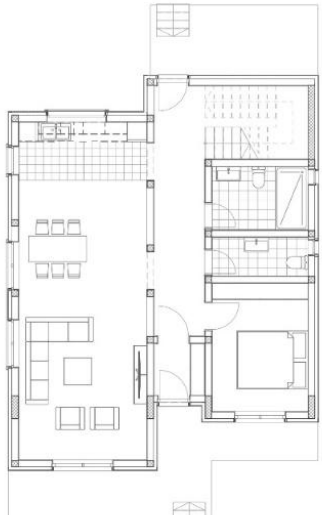


Figure 3: Ground floor, Source: Author

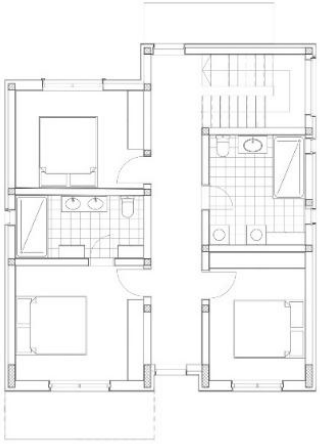


Figure 4: First floor, Source: Author

3. RESULTS AND DISCUSSION

A total of 18 simulations were conducted across 3 different cities in distinct climate zones: Niš, Athens, and Copenhagen. For each city, 6 simulations were carried out, consisting of 3 simulations with varying insulation levels—where V1 represents an uninsulated building, V2 a well-insulated building, and V3 an excellently insulated building (Table 1). The remaining 3 simulations per city were generated by rotating the

building by 180°, thereby shifting the orientation from north to south. Within the simulations, a north or south orientation signifies that the living room is facing that respective direction. To assess the economic feasibility and simple payback periods for the thermal envelope upgrades across the three locations, representative average electricity and heating tariffs were applied: €0.13/kWh for Niš (Serbia), €0.17/kWh for Athens (Greece), and €0.40/kWh for Copenhagen (Denmark). These financial evaluations account for local energy market pricing to reflect realistic operational cost reductions.

Table 1: Parameters applied in the simulation, Source: Author

Alternative solutions – Insulation of external elements			
	V1	V2	V3
External walls – Insulation thickness (cm)	0	10	15
Roof – Insulation thickness (cm)	0	15	30
Windows - U value (W/m2 K)	5.8	1.5	0.5
Conditioned floor area:	Ground floor: 85 m^2	First floor: 80 m^2	Total: 165 m^2
HVAC Setpoints	Cooling: 26 °C (constant) / Heating 22 °C (constant)		
Infiltration & Ventilation	0.5 ACH (Air changes per hour)		
Internal heat gains	Lighting: Equipment: Occupancy		
Building orientation			
0° i 180° (north and south)			
Location			
Niš Athens Copenhagen			

3.1 SIMULATION RESULTS IN NIŠ

Niš is located in a climate where the energy consumption for heating is twice as high as the energy consumption for cooling in an uninsulated detached house. With the introduction of thermal insulation, the energy required for heating drops significantly because the building retains heat better and cools down more slowly; however, in return, the cooling energy demand increases.

By improving the thermal envelope through the transition from V1 to V2 layers, the required heating energy is reduced by approximately 90 %, while the cooling energy demand increases by only about 20 %, resulting in an annual energy saving of around 20,000 kWh, which would result in annual financial savings of around €2,700 under Serbian conditions. Subsequently, when moving from V2 to V3 layers, the heating energy demand decreases slightly compared to the previous comparison, while the cooling energy demand remains approximately the same, around 3200 kWh less. This results in an annual saving of around €435, while the additional investment in improving the thermal envelope would cost approximately €3,300. To pay off the investment, a simple payback period of 8 years is required. It can be concluded that energy-efficient architectural design can make a major difference in a building's energy

performance, provided that the building is high-quality insulated. This does not necessarily imply optimizing heating through orientation alone; it is also possible to reduce the required cooling energy by implementing natural ventilation principles—such as cross ventilation, the stack effect, wind catchers, etc.—which were not applied in these simulations.

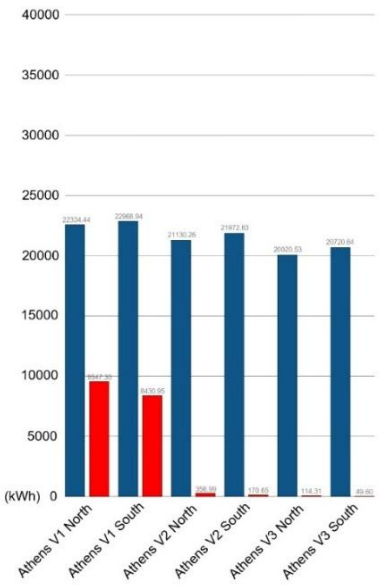


Figure 5: Annual energy consumption for heating and cooling (kWh), Niš, Source: Author

Table 2: Annual energy consumption for heating and cooling (kWh), Niš, Source: Author

Niš / kWh		North	South
V1	Cooling	12,847.12	12,706.19
	Heating	27,005.99	26,099.27
V2	Cooling	16,108.92	16,331.18
	Heating	3,054.83	2,480.42
V3	Cooling	16,032.98	16,247.75
	Heating	1,427.73	1,036.04

3.2 SIMULATION RESULTS IN ATHENS

The Mediterranean climate of Athens implies hot, dry summer days with an average temperature of 35 °C, while winters are rainy with an average temperature ranging from 10 to 15 °C; consequently, the majority of the building's energy consumption is attributed to cooling. Improving the thermal envelope through the transition from V1 to V2 layers resulted in energy savings of approximately 5 % for cooling and around 96 % for heating, resulting in an annual energy saving of around 10,000 kWh, which would result in annual financial savings of around €1,700 under Greek conditions.

Furthermore, it is noticeable that the differences in energy consumption between the V2 and V3 simulations are almost non-existent (Figure 6), making the V3 simulation inefficient due to its far more expensive materials compared to V2, while yielding identical energy performance. The transition from V2 to V3 would cost an additional €4,000, yielding annual savings of only about €250, requiring a payback period of approximately 16 years for this investment to break even [10, 11].

It can be concluded that in dry and warm climates, such as the one in Greece, building thermal insulation does not represent as energy-efficient of a solution as natural and contemporary, artificial ventilation systems would [4, 6].

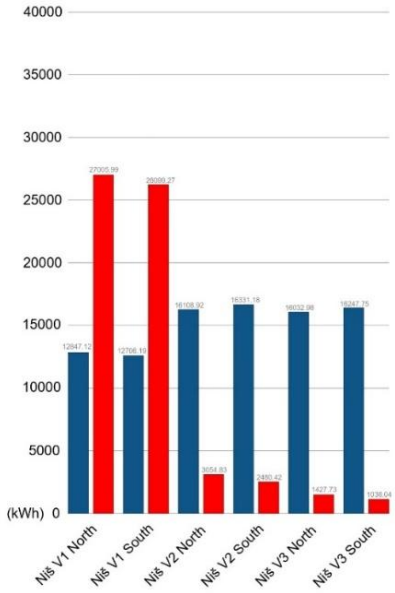


Figure 6: Annual energy consumption for heating and cooling (kWh), Athens, Source: Author

Table 3: Annual energy consumption for heating and cooling (kWh), Athens, Source: Author

Athens / kWh		North	South
V1	Cooling	22,334.44	22,968.94
	Heating	9,547.30	8,430.95
V2	Cooling	21,130.26	21,927.63
	Heating	356.99	170.65
V3	Cooling	20,020.53	20,720.64
	Heating	114.31	49.50

3.3 SIMULATION RESULTS IN COPENHAGEN

Although Copenhagen is located at a similar latitude to Moscow and Southern Alaska, its climate is milder and more temperate; therefore, the winters are not as harsh. As this is the northernmost city in the simulation, the heating demand accounts for the highest energy consumption in its simulation cycles. Improving the thermal envelope through the transition from V1 to V2 layers resulted in a heating energy saving of 85 %, which amounts to approximately 32,000 kWh—by far the largest reduction among all heating simulations. Conversely, cooling energy consumption increased with the improvement of the thermal envelope, recording a rise of 80%, or about 6,500 kWh. The pronounced surge in cooling demand following the application of thermal insulation in Copenhagen can be attributed to the physical phenomenon of trapping internal heat gains (generated by occupants, lighting, and electrical equipment) [12, 13]. In an uninsulated building (V1), this internally generated thermal energy naturally dissipates into the outdoor environment through highly conductive walls and single-pane glazing. However, once high-efficiency thermal insulation and multi-pane glazing are implemented (V2 and V3), the building envelope acts as a barrier that hinders this natural heat dissipation during

warmer summer periods.

Consequently, internal heat remains trapped within the thermal zones, forcing the automated HVAC systems to consume additional energy for active space cooling.

Taking all this information into account, the total energy savings for HVAC transitioning from V1 to V2 layers amount to around 27,000 kWh, meaning that the implementation of a thermal envelope is a significant investment, despite the sharp spike in cooling energy consumption. This level of energy efficiency would result in an annual cost reduction of approximately €10,800.

With the subsequent transition from V2 to V3 layers, a slight increase in cooling energy and a minor decrease in heating energy consumption are observed, resulting in the transition from V2 to V3 requiring an additional investment of around €4,500 and yielding annual savings of approximately €750, with a payback period of about 6 years.

The simulation in Copenhagen demonstrates that this type of climate achieves the greatest benefit from improving the building's thermal envelope (Figure 7).

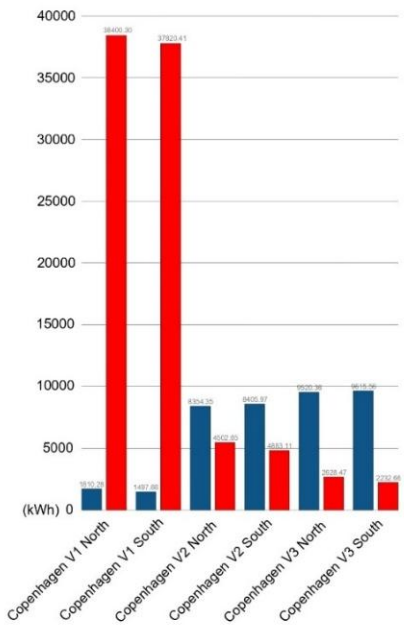


Figure 7: Annual energy consumption for heating and cooling (kWh), Copenhagen, Source: Author

Table 4: Annual energy consumption for heating and cooling (kWh), Copenhagen, Source: Author

Copenhagen / kWh		North	South
V1	Cooling	1,810.29	1,497.68
	Heating	38,400.30	37,820.41
V2	Cooling	8,354.35	8,405.97
	Heating	4,502.65	4,883.11
V3	Cooling	9,520.38	9,615.56
	Heating	2,628.47	2,232.66

4. CONCLUSION

The comprehensive analysis reveals how different physical mechanisms dominate the building's energy balance depending on the insulation level and climate. In uninsulated baseline models (V1), heat transfer is overwhelmingly dominated by transmission losses through the envelope due to high thermal transmittance ($\boldsymbol{U}$-values). Under these conditions, building orientation plays a negligible role, as high transmission losses mask any energy contributions from solar heat gains [10, 15].

While transitioning from an uninsulated model to a standard insulation level (V2) yields massive energy savings—reducing wall and roof transmission losses by up to

90%—upgrading further to an advanced level (V3) offers diminishing returns. Once a high-quality thermal envelope is established, the primary winter energy balance shifts toward ventilation losses (air infiltration), while summer dynamics are dominated by solar radiation and internal heat gains. Thus, proper orientation and passive solar management become effective tools only after basic thermal insulation is secured, maximizing passive winter gains in cold and temperate climates like Copenhagen and Niš.

Table 5: Total annual energy consumption per simulation for north and south orientation (kWh), Source: Author

kWh		V1	V2	V3
Niš	North	39,853.11	19,163.75	17,460.71
	South	38,805.46	18,791.60	17,283.79
Athens	North	31,881.74	21,487.25	21,134.84
	South	31,399.89	22,143.28	20,770.24
Copenhagen	North	40,210.56	12,857.00	12,148.83
	South	39,315.07	13,289.08	11,848.22

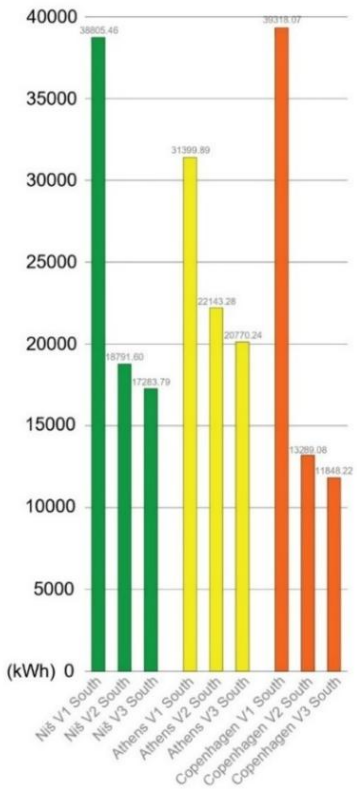


Figure 8: Total annual energy consumption per simulation for north orientation (kWh), Source: Author

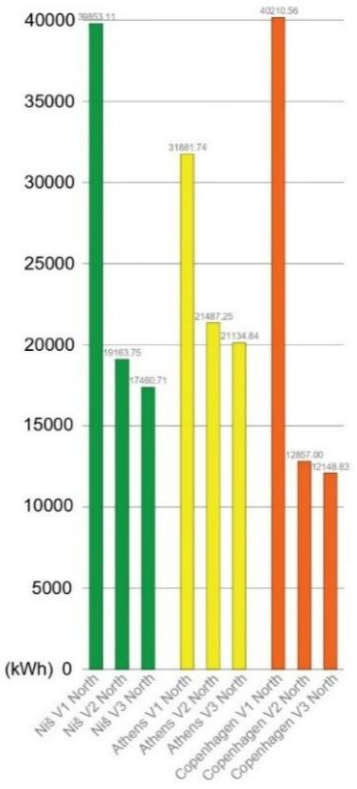


Figure 9: Total annual energy consumption per simulation for south orientation (kWh), Source: Author

Conversely, in warm Mediterranean climates like Athens, the energy consumption difference between V2 and V3 is negligible, making V3 economically unjustified due to high material costs. Furthermore, extensive insulation traps internal heat gains generated by occupants, lighting, and equipment during warmer periods. While uninsulated envelopes allow natural heat dissipation, highly insulated envelopes hinder it, forcing HVAC systems to consume additional energy for space cooling. Therefore, in warm climate zones, thermal insulation cannot replace essential strategies such as solar shading and natural ventilation (e.g., cross-ventilation and the stack effect) [4, 6].

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GREEN BUILDING CONFERENCE
INNOVATIVE SOLUTIONS FOR A GREENER BUILT ENVIRONMENT

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Review paper

GREEN ROOFS AND GREEN FACADES AS COMPLEMENTARY NATURE-BASED SOLUTIONS FOR URBAN HEAT ISLAND MITIGATION

Jana Lambić[1], Marko Jeremić [2], Gordana Kozić[3]

Abstract

Rapid urbanization, climate change, and the growing frequency of extreme heat have intensified thermal conditions in cities worldwide. Among the most significant urban climate phenomena is the Urban heat island (UHI) effect, whereby urban areas experience higher temperatures than surrounding rural environments due to high-density built environment, low vegetation cover, anthropogenic heat emissions, and the presence of heat-retaining materials. This paper examines green roofs and green facades as complementary, climate-responsive nature-based strategies for reducing the UHI effect and improving urban environmental quality. The review focuses on their thermal performance, environmental co-benefits, and contribution to sustainable urban development. Evidence demonstrates that green roofs can reduce building cooling loads by up to 70% and lower indoor temperatures under specific climatic conditions, while green facades effectively cool vertical surfaces and street-level urban canyons. Together, these systems deliver synergistic environmental benefits, including improved air quality, carbon sequestration, stormwater retention, biodiversity support, and noise reduction. It is concluded that the integrated deployment of green roofs and green facades represents an effective and urgently needed measure for climate-resilient urban development, with significant potential for application in Serbian cities.

Key words: *Urban heat island, green roofs, green facades, urban climate resilience*

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1. INTRODUCTION

Urban areas are increasingly exposed to the combined effects of rapid urbanization and climate change. According to the United Nations, more than 55% of the world's population currently lives in urban areas and this proportion is expected to reach 68% by 2050 [1]. The progressive replacement of natural landscapes with buildings, roads, and other impervious surfaces affects the urban energy balance and constitutes a primary driver of the Urban heat island (UHI) effect, whereby urban temperatures are typically 2-5°C higher than those of surrounding rural areas [2]. This thermal imbalance is further intensified by climate change, as 2024 has been confirmed as the warmest year on record, with global mean temperatures approximately 1.55°C above pre-industrial levels [3]. Elevated urban temperatures negatively affect energy consumption, outdoor thermal comfort, public health, and overall environmental quality.

Recent climate projections indicate that heat waves will become more frequent and intense in many regions, including southeast Europe [3]. Cities therefore need adaptation strategies that reduce thermal stress while supporting sustainable urban development. In dense urban areas, expanding conventional green infrastructure is often limited by space constraints and competing land uses, which increases interest in building-integrated vegetation systems that use roofs and facades without requiring additional land [4].

Nature-based solutions are widely recognized for providing multiple environmental and social benefits beyond temperature reduction [4]. Green roofs and green facades are among the most applied building-integrated systems [4]. By using existing building surfaces, they increase urban greenery while contributing to cooling through shading, evapotranspiration, and improved thermal insulation, thereby reducing surface temperatures, cooling demand, and urban heat stress [5].

The aim of this paper is to synthesize current evidence on the thermal performance of green roofs and green facades, with a focus on their complementary mechanisms, potential synergistic effects when combined, and their role as scalable nature-based solutions for climate-resilient urban development.

2. RESEARCH METHODOLOGY

This study applies a structured narrative literature review to synthesize current knowledge on the contribution of green roofs and green facades to Urban Heat Island (UHI) mitigation. The review includes peer-reviewed journal articles, international reports, and selected case-study sources published primarily between 2008 and 2025, supplemented by the foundational study of Oke [2]. Sources were selected according to their relevance to four analytical criteria: (1) thermal performance, (2) environmental co-benefits, (3) energy-saving potential, and (4) applicability in dense urban environments. The evidence was first analysed separately for green roof and green facade typologies and then comparatively, with particular attention to their complementary effects and implementation potential in Serbian cities. Because locally

measured performance data remain limited, the applicability assessment relates evidence from Mediterranean and Central European climates to available climatic and morphological data for Niš [4] [8] [10].

3. THE URBAN HEAT ISLAND EFFECT

The UHI effect is driven by four primary physical mechanisms: the high thermal mass of urban materials that absorb solar radiation by day and release it at night; reduced evapotranspiration from limited vegetation cover; anthropogenic heat from transportation, industry, and air conditioning; and urban canyon geometry that traps radiation and restricts airflow [2]. The consequence is a self-reinforcing cycle: elevated temperatures increase cooling energy demand, which generates additional waste heat and greenhouse gas emissions, further accelerating warming. Studies across European cities indicate cooling energy demand rises 10-20% per degree Celsius of urban warming above the rural baseline [5].

Nature-based solutions directly interrupt this cycle by restoring evapotranspiration and shading processes to the built environment. Among these, building-integrated vegetation occupies a strategically important position – it can be deployed on existing structures without land-use transformation, making it particularly relevant for dense urban fabric where spatial constraints preclude other approaches [4].

4. GREEN ROOFS

4.1. Typology and components

Green roofs consist of vegetated layers installed above conventional roof structures. Their cooling effect is primarily achieved through evapotranspiration, shading of roof surfaces, and thermal insulation provided by the substrate layer. Green roofs are engineered systems comprising, from base to surface: a waterproofing membrane, root barrier, drainage layer, filter layer, growing substrate, and vegetation. Green roofs are generally classified as extensive, semi-intensive, or intensive systems according to substrate depth, vegetation type, maintenance requirements, and accessibility. Extensive roofs are typically inaccessible and require minimal maintenance, whereas intensive roofs are generally designed for regular human use and support a wider variety of vegetation. In addition, green roofs enhance urban environmental quality by mitigating the urban heat island effect and providing habitats that support biodiversity in densely built environments [5]. The components and typological differences between these green roof systems are presented in Figure 1.

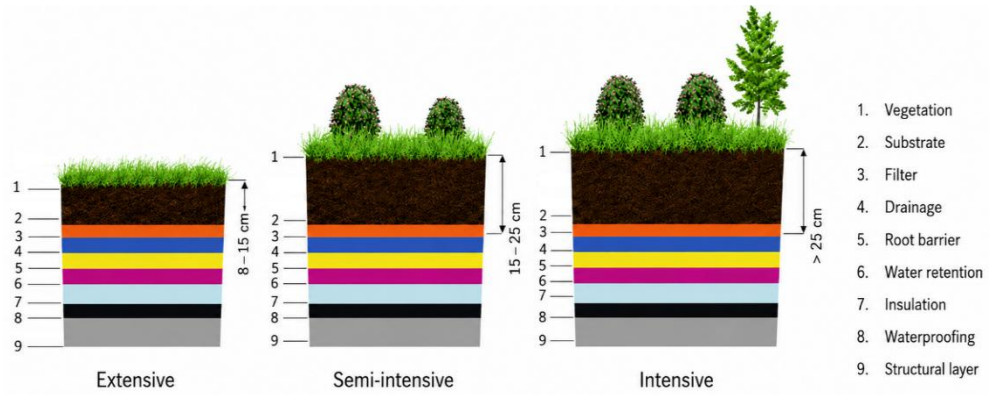


Figure 1 - Comparison of extensive, semi-intensive, and intensive green roof system layers [5]

4.2. Thermal mechanisms and quantified performance

The primary thermal mechanism of green roofs is evapotranspiration: plants and substrate release moisture that converts solar radiation into latent heat rather than sensible heat, directly cooling the roof surface and the air above it [5]. Shading by the vegetation layer intercepts radiation before it reaches the substrate, while the substrate itself provides thermal mass that delays heat transfer to the building interior. Research demonstrates that increasing the Leaf area index (LAI) from 0.5 to 3.5 reduces canopy air temperature oscillations from 11.6°C to 3.6°C, underscoring the importance of vegetation density [5].

The effectiveness of evapotranspiration depends on several factors, including plant species, leaf area index, substrate moisture content, climatic conditions, solar radiation, wind speed, and irrigation regime. Under prolonged drought conditions, evapotranspiration rates decrease considerably, reducing the cooling performance of green roofs. Therefore, appropriate plant selection and substrate design are essential for maximizing thermal efficiency [5].

In Mediterranean climatic conditions, such as those recorded in Athens, which share certain similarities with the warmer regions of Serbia, studies have reported annual energy savings of up to 37%, while extensive green roofs consumed 20% less energy than conventional black roofs under non-insulated conditions, and semi-intensive green roofs achieved reductions of 60–70% [6]. Across climates, green roofs can reduce building cooling loads by up to 70% and lower indoor temperatures by up to 15°C [5]. Beyond improvements in building energy performance, green roofs may also enhance the efficiency of photovoltaic systems when integrated with them, while simultaneously contributing to reductions in greenhouse gas emissions, highlighting their broader synergistic potential within urban energy systems [7].

5. GREEN FACADES

5.1. Typology and components

Green facades introduce vegetation to vertical building surfaces through climbing plants or modular living wall systems. Similar to green roofs, their cooling performance is based on shading and evapotranspiration. However, unlike green roofs, green facades directly influence the thermal environment at pedestrian level by reducing wall surface temperatures and improving microclimatic conditions within urban canyons [4]. The principal typologies and working principles of green facade systems are illustrated in Figure 2.

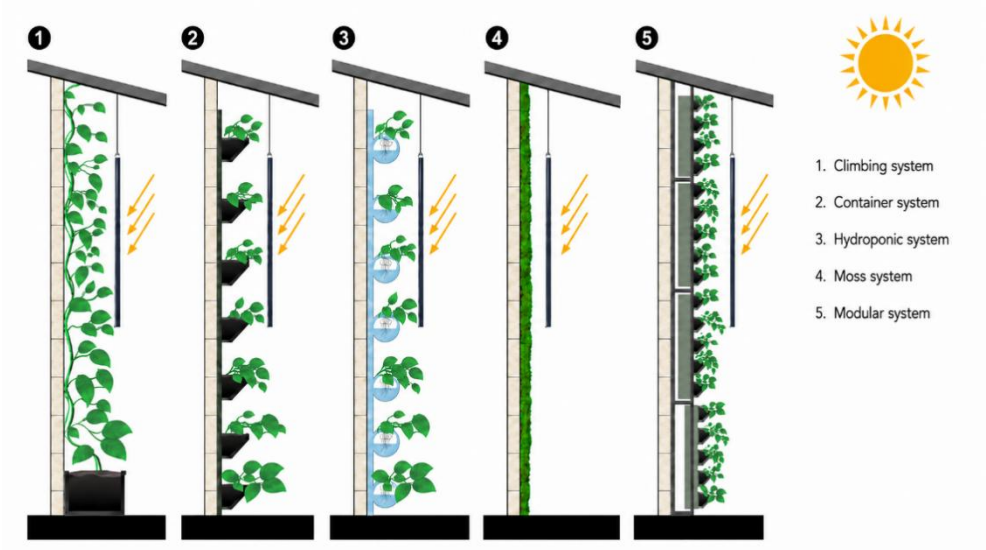


Figure 2 - Typology and working principles of green facade systems [7]

5.2. Thermal mechanisms and street-level cooling

Green facades reduce thermal gain on building walls through two complementary mechanisms [4] [8]. Shading by the vegetation layer intercepts radiation that would otherwise heat the wall surface; dark wall materials can reach 50-70°C on summer days, while green facades reduce these temperatures by 10-30°C. Evapotranspiration from plant surfaces cools the adjacent air layer, and the air gap in indirect systems provides additional convective cooling. These combined effects result in annual energy savings of 5-25% depending on facade orientation, wall construction, and climate [4] [8].

The critical distinction of green facades lies in their direct impact at pedestrian level. Reduced-scale experimental studies have been conducted to compare the microclimatic performance of street canyons with and without vegetated envelopes under summer conditions, showing relevant differences in thermal behavior. Their results showed that green facades reduced air temperature in the street canyon by up to 1.5°C, reduced the mean radiant temperature by up to 4°C on clear summer days, and increased relative humidity by 6-8% through evapotranspiration – directly improving outdoor thermal comfort [9]. Simulation studies across nine cities found

maximum canyon air temperature reductions of up to 26°C in hot and dry climates when facades were fully greened, with average reductions of approximately 12.8°C across all studied climates [8]. This pedestrian-level effect is the most important functional difference between green facades and green roofs.

Deciduous species offer an intrinsic seasonal adaptation: maximum shading and evaporative cooling in summer, followed by leaf fall that allows solar radiation to reach and warm the wall in winter – a passive response to seasonal energy needs that evergreen species cannot provide [4].

6. COMPARATIVE ANALYSIS AND INTEGRATED IMPLEMENTATION

The thermal and environmental performance of green roofs and green facades is complementary rather than competitive. Green roofs primarily benefit the building interior and the urban energy balance at roof level, whereas green facades act directly on the street environment, where thermal comfort is most immediately experienced by pedestrians. Together, they provide comprehensive thermal protection of the building envelope and contribute to cooling at both the building and urban scales simultaneously [4] [9].

Table 1. Comparative thermal performance of green roofs and green facades [4] [5] [8]

Performance indicator	Green roofs	Green facades
Primary surface	Horizontal roof	Vertical walls
Cooling load reduction	Up to 70%	Up to 50%
Indoor temp. reduction	Up to 15°C	3-8°C (top floors)
Street-level cooling	Indirect / limited	Direct and significant
Mean radiant temp. reduction	Limited	Up to 4°C [9]
Annual energy savings	10-60%	5-25%

Beyond comparing green roofs and green facades, performance differences within each system category should also be considered. Among green roof typologies, extensive, semi-intensive, and intensive systems differ primarily in substrate depth, structural load, maintenance requirements, vegetation diversity, and thermal performance. Extensive systems, characterized by shallower substrates and relatively low structural loads, are generally the most suitable option for retrofitting existing buildings. Semi-intensive systems represent an intermediate solution, providing greater vegetation density, moisture retention, and cooling potential while maintaining moderate structural and maintenance requirements. Intensive systems, with deeper substrates and more diverse vegetation, generally provide the greatest thermal mass, stormwater retention capacity, and ecological potential. However, they also require greater structural capacity, regular irrigation, and more intensive maintenance [5] [6]. These differences demonstrate a trade-off between environmental performance and technical requirements, meaning that the selection of an appropriate typology should depend on the structural capacity of the building, the intended use of the roof, and available maintenance resources.

A comparable internal differentiation applies to green facade systems. Direct greening systems, in which climbing plants are rooted at ground level, generally require limited structural modification and lower initial investment, but vegetation coverage develops gradually and depends on the growth characteristics and maximum height of the selected species. Indirect systems use supporting structures that separate vegetation from the building wall, thereby improving air circulation and reducing direct contact between plants and the facade surface. Modular living wall systems provide faster and more uniform vegetation coverage and enable greater control over plant distribution and irrigation, but they generally require higher initial investment, permanent irrigation infrastructure, and more intensive maintenance [4] [7]. Green facade typology should therefore be selected according to building height, orientation, irrigation availability, and maintenance capacity.

7. CASE STUDY: ACROS FUKUOKA, JAPAN

The ACROS Fukuoka Prefectural International Hall, designed by architect Emilio Ambasz and completed in 1995, is one of the most cited examples of building-integrated vegetation in a high-density urban context. Constructed on the last remaining open space in central Fukuoka – the Tenjin Central Park – the building was designed so that 15 stepped vegetated terraces on its south elevation would return to the city nearly the entire park area displaced by the structure [11] [12]. The design simultaneously applies the thermal mechanisms of green roofs (evapotranspiration, substrate insulation) and green facades (shading, surface cooling) across a single continuous envelope, demonstrating in built form the complementary action described earlier. The project demonstrates that, in densely built city centres, it is possible to reconcile economic interests, the need for civic infrastructure, and the preservation of public green space [11]. The stepped vegetated envelope of the ACROS Fukuoka building is shown in Figure 3.



Figure 3 - ACROS Fukuoka Prefectural International Hall with stepped vegetated terraces integrated into the building envelope [14]

In terms of measured performance, a thermal survey conducted in 2000 by Takenaka Corporation, Kyushu University, and the Nippon Institute of Technology recorded a surface temperature difference of up to 15°C between vegetated terraces

and exposed concrete surfaces on the same building, confirming significant UHI mitigation [13]. The planting expanded from 76 to 120 species and from 37,000 to over 50,000 plants through natural seed dispersal over approximately 25 years [12] [13], illustrating the long-term ecological development of intensive building-integrated vegetation systems. The case is particularly relevant to Serbian city centres where ground-level green space is scarce and flat-roofed building surfaces represent the primary available resource for nature-based interventions.

8. APPLICABILITY IN SERBIAN CITIES

The conditions in Serbian cities create both an intensified UHI problem and a strong technical case for building-integrated vegetation solutions. The city of Niš records an absolute maximum temperature of 44.2°C and an average of 49 tropical days per year, with building coverage ratios in the central zone reaching 68% and street canyon aspect ratios of 0-1.3 [10]. These morphological characteristics, which are the same parameters that intensify UHI formation, also create favorable conditions for green facade performance, as taller and narrower canyons amplify the cooling effect of vegetated surfaces.

The large stock of flat-roofed collective housing constructed between the 1950s and 1980s presents a technically accessible opportunity for extensive green roof deployment. The lightweight nature of extensive systems reduces structural reinforcement requirements compared to intensive alternatives. The structural load-bearing capacity of existing buildings should be assessed before retrofitting [10].

Policy instruments that have proven effective in western European cities include mandatory green roof installation on new public buildings, grant programs for retrofit projects, inclusion within municipal energy efficiency frameworks, and simplified permitting for facade greening. Pilot projects on schools, collective housing blocks, and municipal buildings in Belgrade, Niš and Novi Sad would generate locally relevant performance data while building professional capacity and public awareness, which are essential preconditions for scaling up implementation [10].

Similar pilot projects implemented in Mediterranean and Central European cities have demonstrated that locally adapted vegetation species and irrigation strategies significantly improve long-term thermal performance. These findings indicate that pilot projects in Serbia should prioritize native and drought-tolerant plant species adapted to regional climatic conditions [4] [8].

Despite their numerous environmental benefits, the implementation of green roofs and green facades remains constrained by several technical and economic challenges. Initial installation costs are generally higher than those of conventional roofing and facade systems, while existing buildings may require structural assessment to determine their load-bearing capacity before retrofit interventions. Long-term performance also depends on appropriate plant selection, regular maintenance, and irrigation, particularly in regions experiencing prolonged summer droughts. Although these systems require higher initial investment, their costs may be partly offset over the building life cycle through reduced energy consumption, extended roof service life,

improved stormwater management, and broader environmental benefits [5] [7]. Their long-term economic feasibility nevertheless depends on climatic conditions, system design, maintenance requirements, irrigation demand, and the scale of implementation.

Successful implementation in Serbia will require supportive legislation, technical guidelines, financial incentives, and integration into new construction and renovation projects.

9. CONCLUSION

Green roofs and green facades represent a technically developed and complementary pair of building-integrated strategies for urban heat island mitigation. Green roofs reduce building cooling loads by up to 70% and indoor temperatures by up to 15°C through evapotranspiration, shading, and thermal mass effects. Green facades cool vertical surfaces and street-level air in urban canyons – reducing air temperature by up to 1.5°C and mean radiant temperature by up to 4°C – providing pedestrian-level thermal comfort benefits that green roofs alone cannot achieve.

The primary conclusion of this review is that the integrated deployment of both systems produces effects that are synergistic rather than additive: green roofs reduce the heat load entering the urban system from above, while green facades reduce the heat exchanged between building walls and the street canyon below. Together they constitute a comprehensive building-scale response to UHI conditions.

In the Serbian context, hot summers, compact urban morphology, high building coverage ratios, and large stocks of flat-roofed buildings create conditions in which these systems are both most needed and most applicable. Integrating green roofs and green facades into building renovation programs and urban development policy, along with targeted financial instruments and locally calibrated pilot projects, represents a concrete and urgently relevant step toward climate-resilient, healthy, and sustainable urban environments. Future research should prioritise long-term monitoring in Southeast European climates and investigate integrated applications with photovoltaic systems, smart irrigation, and environmental monitoring under Serbian climatic conditions.

ACKNOWLEDGMENT

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Research paper

ENERGY PERFORMANCE ANALYSIS OF A BUILDING USING OPENSTUDIO AND ENERGYPLUS

Tijana Živković[1]

Abstract

This paper analyses the energy performance of an architectural building, the Visitor Centre within the Ćele Kula (Skull Tower) memorial complex in Niš, using the OpenStudio and EnergyPlus software tools. The aim was to assess the influence of architectural decisions, materials, the building envelope, orientation and climatic conditions on the overall energy efficiency of the building. The paper describes the architectural and functional organisation of the building, the modelling of its geometry, the formation of thermal zones and the definition of space-use schedules required for an accurate simulation. Simulations were carried out for three levels of envelope thermal insulation, two building orientations and three climatic locations (Niš, Copenhagen and Athens). Particular attention was paid to the selection of materials and glazing systems, including solar-radiation control by means of brise-soleil and the definition of transparent elements with appropriate U-factor and SHGC values, which directly affect heat gains and losses. The results show that improved insulation and better glazing do not by themselves guarantee lower energy use; their effect depends on the climatic context and on the control of solar gains, so that a measure beneficial in a cold climate may increase the cooling demand in a warm one.

Key words: *energy efficiency, building energy simulation, building envelope, climate, EnergyPlus*

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1. INTRODUCTION

Buildings account for a substantial share of global energy use, between 20% and 40% in developed countries, which makes their energy efficiency a key priority for both policy and design [1, 2]. The subject of this paper is the analysis of the energy performance of an architectural building using the OpenStudio and EnergyPlus software tools. The building selected for the analysis is the Visitor Centre within the Ćele Kula memorial complex in Niš (basement and ground floor, B+GF). It is free-standing and compact in form, with façade openings on all four sides for daylighting and natural ventilation, an insulated envelope, a flat roof with linear roof lanterns, and movable timber panels (brise-soleil) for solar-radiation control. The moderation of heating and cooling loads through climate-responsive envelope, orientation and solar-control decisions is a long-established principle of bioclimatic design [3, 4]. Such design decisions make it a suitable example for examining the influence of architectural design on energy efficiency.

The analysis was carried out through variant solutions covering three levels of envelope thermal insulation (V1, V2 and V3), two orientations (0° and 180°) and three climatic locations, Niš, Copenhagen and Athens. The building was modelled in OpenStudio (geometry, seventeen thermal zones, systematic naming of elements, surface matching and IDF export) and simulated in EnergyPlus on the basis of climate (EPW) files, operating schedules, internal loads, HVAC control and the thermal properties of the materials and glazing. Standard heat-balance algorithms were applied (TARP and DOE-2 for convection, the CTF method for conduction). Building performance simulation of this kind is a well-established approach for assessing energy demand and comparing design alternatives before construction [5]. The aim is to assess the influence of design decisions, orientation, envelope and climate on the building's overall energy demand.

2. ARCHITECTURAL AND FUNCTIONAL CONCEPT OF THE BUILDING

The Visitor Centre is located near the Ćele Kula monument, separated to the east by the Gabrovačka River, with a bridge providing a direct pedestrian link (Figure 1).

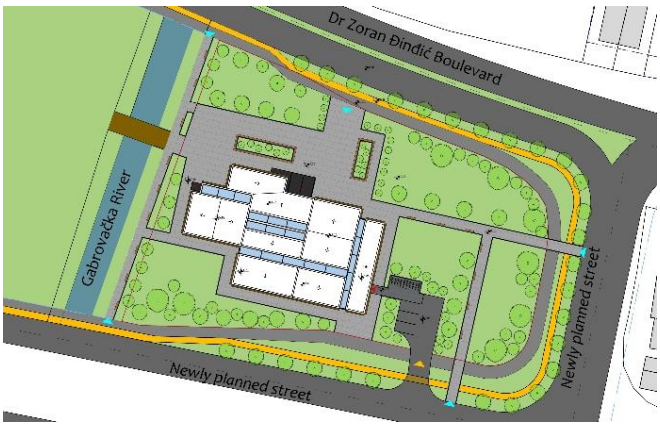


Figure 1. Site plan of the designed building, Author (AutoCAD)

Technical rooms occupy the basement; the ground floor contains the entrance (porter's lodge, ticket office, reception and cloakroom), a central hall, a bookshop with a souvenir area, the exhibition spaces (the permanent display and the memorial room dedicated to Stevan Sinđelić), a multipurpose hall to the south and the administration in the western wing, providing a clear visitor route from the entrance to the exit towards the monument (Figure 2).

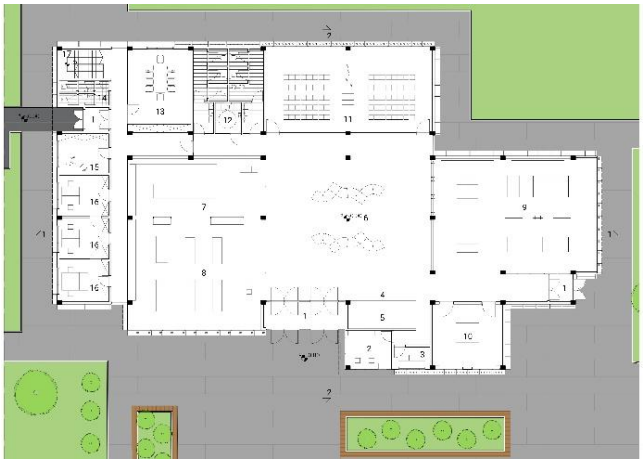


Figure 2. Floor plans of the designed building, Author (AutoCAD)

Façade openings on all four sides enable uniform daylighting and natural ventilation, the eastern façade establishing a visual link with the monument, while their dimensions are balanced against heat losses and gains (Figure 3). The envelope is compact, with insulated external walls, a flat roof with linear roof lanterns and a ground-bearing floor, and movable timber brise-soleil that reduce summer overheating and allow passive solar gains in winter. On this basis the energy model was created and simulated through the variant solutions described below.



Figure 3. Section and Elevations of the Designed Building, Author (AutoCAD)

3. OPENSTUDIO MODELLING METHODOLOGY

The analysis was carried out in OpenStudio, an open-source platform built on the EnergyPlus engine, used as a SketchUp plug-in that links the architectural 3D model

directly to EnergyPlus [6]. The geometry followed the design documentation (dimensions, storey heights, openings and the boundaries of the heated space); the building comprises seventeen spaces and, besides windows and a curtain wall, fixed roof windows (light strips). The model was checked through the render by surface type and render by boundary condition views (Figure 4 and Figure 5).

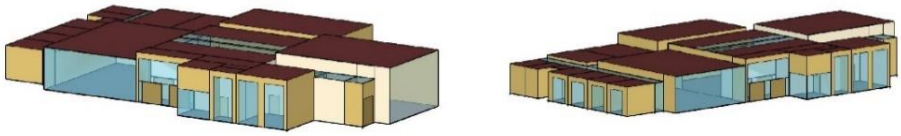


Figure 4. Model in the render by surface type view, Author (OpenStudio)

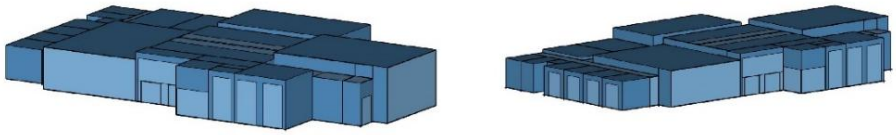


Figure 5. Model in the render by boundary condition view, Author (OpenStudio)

All elements were named systematically (surfaces by function and orientation, spaces and zones by purpose), and the Surface Matching procedure with the Intersect option ensured the correct connection of adjacent surfaces and accurate inter-zone heat exchange. The building was divided into seventeen thermal zones, with public, administrative and technical rooms treated as separate units, after which the model was exported to the IDF format for simulation in EnergyPlus.

4. ENERGYPLUS SIMULATION METHODOLOGY

In EnergyPlus, a widely used and validated whole-building energy simulation program [7], the building's energy behaviour was simulated from climate data, envelope characteristics, internal gains and modes of use. General settings were mostly left at their defaults (EnergyPlus 25.1; zone sizing; an annual run; City environment; Full Exterior solar distribution; Timestep 6), with the Building class North Axis set to 0° or 180° for the orientation variants. Standard algorithms were applied – TARP and DOE-2 for convection, the CTF method for conduction and the Third Order Backward Difference scheme for the zone air heat balance, following established heat-balance methods [8]. The manually defined classes that shaped the simulation variants are summarised below.

4.1. Location, climate and simulation period

The Site:Location class was set for three cities depending on the variant – Niš (43.32° N, 21.90° E, +1, 198 m), Copenhagen (55.68°, 12.57°, +1, 14 m) and Athens (37.98°, 23.73°, +2, 42 m) – each with its own EPW climate file and design days (SizingPeriod:DesignDay). The annual simulation (RunPeriod) ran from 1 January to 31 December, with daylight saving from the last Sunday in March to the last Sunday in October (Figure 6).

Field	Units	Obj1	Obj2	Obj3
Name		Nis	Kopenhagen	Atina
Latitude	deg	43.3192	55.6759	37.9839
Longitude	deg	21.8959	12.5655	23.7278
Time Zone	hr	1	1	2
Elevation	m	198	14	42
Keep Site Location Information		No	No	No

Figure 6. Site:Location class, Author (EnergyPlus)

4.2. Schedules and their limits

Using ScheduleTypeLimits, the permitted ranges of schedule values were defined (Fraction, On/Off, Control Type, Temperature, Activity Level, Any Number), and with Schedule:Compact time-varying modes of use were created per room type (offices, vestibules, staircases, sanitary facilities, meeting and conference rooms, the memorial room, corridors and other public spaces), together with schedules for infiltration, equipment, the heating and cooling setpoints and HVAC control. These were linked to the People, Lights and ElectricEquipment classes, to infiltration and to thermostatic control.

4.3. Materials, glazing systems and constructions

Within the Material class, the non-transparent materials of the walls, floors and roof were defined to match the actual design layers, reproducing their thermal storage, conductivity and capacity [9] (Figure 7).

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		Krecni malter Zid	Opekarski blok 25	Kamena vuna SZ	Vazdusni sloj	WPC Drvena imitac
Roughness		MediumRough	Rough	VeryRough	Smooth	MediumSmooth
Thickness	m	0,015	0,25	0,12	0,04	0,018
Conductivity	W/m-K	0,72	0,6	0,035	1	0,15
Density	kg/m3	1800	800	80	1,2	600
Specific Heat	J/kg-K	1000	1000	1030	1000	1800
Thermal Absorptance		0,9	0,9	0,9	0,9	0,9
Solar Absorptance		0,7	0,7	0,7	0,7	0,7
Visible Absorptance		0,7	0,7	0,7	0,7	0,7

Figure 7. A part of the Material class, Author (EnergyPlus)

Three window types were defined with WindowMaterial:SimpleGlazingSystem in accordance with the national Rulebook on the Energy Efficiency of Buildings [10] and the broader European energy-performance framework [2], each with a U-factor and an SHGC; these three glazing levels, together with the level of envelope insulation, form the basis of variants V1, V2 and V3 (Figure 8).

Field	Units	Obj1	Obj2	Obj3
Name		Jednostruko staklo I	2struko niskoemisivn	3struko niskoemisivn
U-Factor	W/m2-K	5,8	1,5	0,5
Solar Heat Gain Coefficient		0,83	0,61	0,48
Visible Transmittance				

Figure 8. WindowMaterial:SimpleGlazingSystem class, Author (EnergyPlus)

The WindowMaterial:Blind class defined the fixed external timber brise-soleil on the façade openings (slat width and spacing, tilt angle, reflectance and transmittance), while the roof openings remained unshaded (Figure 9); external shading of this kind is a widely studied and effective strategy for controlling solar gains [11]. Layered assemblies were formed in the Construction class and assigned to the surfaces and sub-surfaces.

Field	Units	Obj1
Name		Brisoleji vertikalni
Slat Orientation		Vertical
Slat Width	m	0,2
Slat Separation	m	0,2
Slat Thickness	m	0,00025
Slat Angle	deg	45
Slat Conductivity	W/m-K	221
Slat Beam Solar Transmittance		
Front Side Slat Beam Solar Reflectance		0,3
Back Side Slat Beam Solar Reflectance		0,3
Slat Diffuse Solar Transmittance		
Front Side Slat Diffuse Solar Reflectance		0,3
Back Side Slat Diffuse Solar Reflectance		0,3
Slat Beam Visible Transmittance		0

Figure 9. A part of the WindowMaterial:Blind class, Author (EnergyPlus)

4.4. Geometry, zones and surfaces

The geometry rules (GlobalGeometryRules) and the zone list (Zone) were imported directly from the OpenStudio model. Three zone lists (ZoneList) were formed, vestibules; corridors, staircases and toilets; and other rooms, for the common schedules and infiltration. Non-transparent surfaces used BuildingSurface:Detailed (each with its construction and zone) and transparent ones FenestrationSurface:Detailed (with solar gains and shading interaction), while the internal, mostly glazed partitions were modelled with InternalMass to capture their thermal inertia without additional zoning.

4.5. Internal loads: people, lighting and electric equipment

Occupancy was defined with the People class (the actual number of people per zone, a radiant fraction of 0.7 and an activity schedule); artificial lighting with the Lights class (15 W/m² in offices and 5 W/m² in vestibules, corridors, staircases and toilets); and electric equipment with the ElectricEquipment class for all rooms except the vestibules (the watts/area method).

4.6. Infiltration and HVAC operation

Infiltration was defined with ZoneInfiltration:DesignFlowRate by zone lists (0.5 air changes per hour, constant in time). Through ZoneControl:Thermostat each zone was linked to a thermostat, with control schedules selecting heating or cooling; the control objects were ThermostatSetpoint:SingleHeating and ThermostatSetpoint:SingleCooling, with setpoints of 22 °C for heating and 26 °C for cooling, uniform for all zones (Figure 10). A simplified HVACTemplate:Zone:IdealLoadsAirSystem determined the energy needed to maintain these setpoints, keeping the focus on the building's architectural and thermal characteristics; the sizing factors were set to 1 and the equipment lists and connections were generated automatically.

Field	Units	Obj1
Name		SNGH
Setpoint Temperature Schedule Name		HVACTemplate-Always 22

Field	Units	Obj1
Name		SNGC
Setpoint Temperature Schedule Name		HVACTemplate-Always 26

Figure 10. Thermostat setpoints for heating and cooling, Author (EnergyPlus)

4.7. Simulation outputs

Outputs were defined with Output: VariableDictionary, OutputTable: SummaryReports (all summary) and OutputControl: Table: Style (HTML, joules converted to kWh). The Zone Ideal Loads Total Heating and Total Cooling variables (Output:Variable) and the total heating and cooling energy (Output: Meter) over the simulation period form the basis for comparing the variants.

5. SYNTHESIS OF THE OBTAINED RESULTS

The energy performance was analysed across three climatic contexts (Niš, Copenhagen and Athens), two orientations (0° and 180°), different levels of envelope thermal protection and three window types, with most façade openings protected by vertical brise-soleil and the roof openings unshaded. This makes it possible to examine the interplay of climate, orientation and envelope quality in the demand for heating and cooling.

Each variation label combines the key parameters: the first letter denotes the city (N – Niš, K – Copenhagen, A – Athens), the first number the orientation (0 for 0°, 1 for 180°) and the third element the variant (1 – basic envelope, 2 – improved insulation and windows, 3 – the most energy-efficient variant) (Figure 11).

Variant solutions – insulation of external elements			
Construction type:	V1 **1**	V2 **2**	V3 **3**
External walls – thermal insulation thickness (cm)	0	10	15
Roof – thermal insulation thickness (cm)	0	15	30
Windows – U-value (W/m²K)	5.8	1.5	0.5
Building orientation			
0 0° and 180° (north and south) **1**			
Location			
Copenhagen **K**	Niš **N**	Athens **A**	

Figure 11. Method of labelling the variations, Author

In Niš at the 0° orientation (Figure 12, left), the basic variant shows a very high heating demand, approximately equal to the cooling demand, indicating significant winter transmission losses. With medium insulation and better windows the heating demand drops sharply while cooling rises and becomes dominant, and with the highest insulation and triple glazing heating is minimal while cooling remains high – the building shifts from a heating-dominated to a cooling-dominated regime, additionally intensified by the unshaded skylights. At the 180° orientation (Figure 12, right) the pattern is the same; orientation only slightly shifts the absolute values, while the level of insulation remains the decisive factor. This shift towards cooling as the envelope improves reflects the climate-dependence of energy performance highlighted by Valladares-Rendón et al. [13], indicating that in a temperate climate such as that of Niš the control of solar gains becomes as important as the reduction of transmission losses.

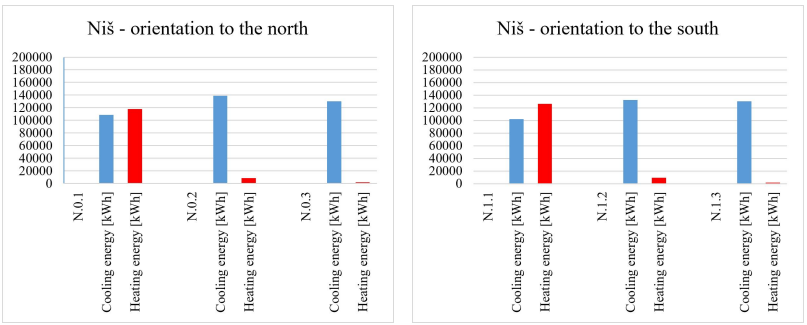


Figure 12. Analysis of the variations for Niš at the 0° (left) and 180° (right) orientation, Author

In Copenhagen (Figure 13) heating strongly dominates the basic variant, several times exceeding cooling, owing to the cold climate and the long heating season. Improving the insulation and windows markedly reduces heating while cooling rises but stays below the levels of warmer climates, and even in the most efficient variant heating remains an important component, which justifies strong insulation in cold climates. The change of orientation produces only minor differences, and improving the envelope clearly reduces the total energy demand, because the reduction in heating outweighs the rise in cooling. This unambiguous benefit of a well-insulated envelope in a heating-dominated climate is consistent with established bioclimatic principles, according to which minimising transmission losses is the primary strategy in cold regions [3, 4].

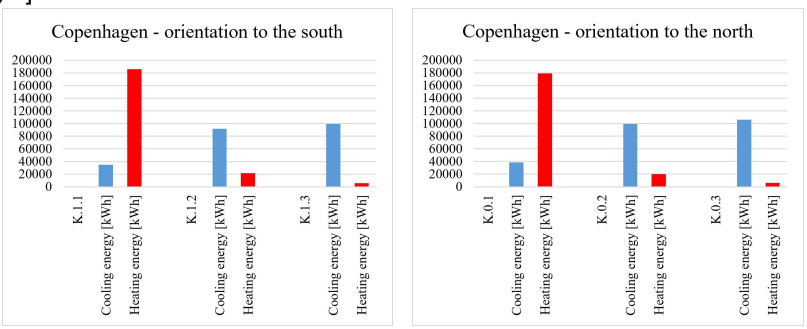


Figure 13. Analysis of the variations for Copenhagen at the 0° (left) and 180° (right) orientation, Author

In Athens (Figure 14) cooling dominates from the basic variant, several times exceeding heating. Increasing the insulation almost eliminates heating, but cooling remains very high and even rises slightly in the middle variant, decreasing only marginally in the most advanced one. Orientation has a more pronounced effect than in the other climates – at 180° the basic variant has noticeably lower cooling than at 0° – but increasing the insulation again raises cooling, confirming that in a warm climate insulation without protection against overheating can increase the cooling load. This agrees with studies of warm-climate design, which stress that controlling solar gains through external shading is more effective than envelope insulation alone for limiting cooling demand [11, 12], while the pronounced effect of orientation observed here supports the emphasis of Valladares-Rendón et al. [13] on combining a favourable orientation with façade shading.

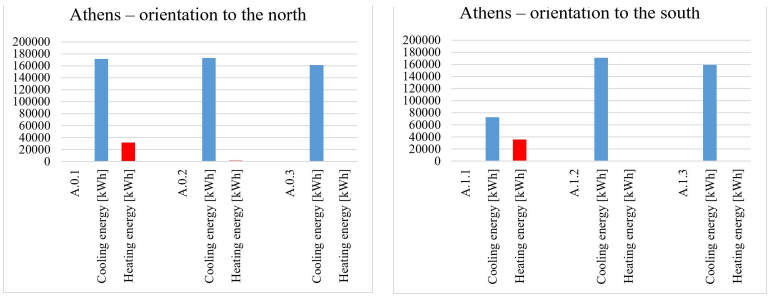


Figure 14. Analysis of the variations for Athens at the 0° (left) and 180° (right) orientation, Author

Comparing the basic variants for all three cities at both orientations clearly shows the influence of the climatic context: Copenhagen is heating-dominated, Niš is approximately balanced with a tendency towards cooling as insulation improves, and Athens is cooling-dominated in all cases. With improved envelopes the differences between the climatic zones grow: in a cold climate better insulation reduces total energy use, whereas in temperate and warm climates it increases the cooling demand, particularly with unshaded skylights. A comparable climate-dependence has been reported at the regional level for Serbian buildings, where horizontal shading elements significantly influenced the energy balance [14], confirming that envelope measures should be matched to climate and combined with solar control rather than applied uniformly.

Overall, the energy performance of a building does not depend solely on thicker insulation and better windows, but on harmonising these measures with the climate and with the control of solar gains. In cold climates a strongly insulated envelope effectively reduces total energy use, whereas in warm climates, without protection against overheating, it can have the opposite effect. Energy-efficient design therefore requires an integrated approach encompassing climate, orientation, envelope characteristics and passive solar-control measures.

6. CONCLUDING DISCUSSION

The analysis of the Visitor Centre within the Ćele Kula memorial complex shows that the architectural design, the arrangement of functional spaces, the envelope characteristics and the solar-control systems have a direct and measurable influence on the building's energy efficiency. Modelling in OpenStudio enabled a faithful reproduction of the geometry, openings, thermal zones and constructions, while simulation in EnergyPlus – with the appropriate climate data, temperature schedules and construction parameters – allowed the energy demand and heat gains to be assessed quantitatively across scenarios.

The simulations confirmed that the level of envelope insulation strongly affects heating and cooling, while orientation influences solar gains and losses, and the comparison of three climatic locations highlighted the building's adaptability and the importance of integrating climatic parameters into design. The carefully defined schedules, internal loads, infiltration and HVAC operation, together with the brise-soleil and roof openings, enabled a realistic full-year assessment of passive solar gains and overheating control. The study confirms that OpenStudio and EnergyPlus are a reliable

methodology for evaluating energy performance and supporting design decisions, capturing the interaction between architectural decisions, climatic factors and the building's modes of use.

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Research paper

PERFORMANCE-BASED DESIGN OF MODULAR SHADING CONFIGURATIONS FOR OUTDOOR THERMAL COMFORT

Aleksandra Tomić[1]

Abstract

Urban public spaces with limited natural shading can experience high thermal stress during hot summer periods. Modular shading systems can provide an adaptable solution. This study investigates how different spatial configurations of identical modular shading elements influence outdoor thermal comfort (OTC). A parametric workflow was applied to Katolička porta square in Novi Sad, Serbia. Three configurations (linear, centralized and scattered) were generated and OTC was calculated and evaluated using the Universal Thermal Climate Index (UTCI) for the hottest summer day. The objective was to minimize the average UTCI value within the shaded areas while maintaining the defined spatial constraints. The favourable configurations mitigated the average UTCI by 5.47% for the linear, 12.74% for the centralized and 4.49% for the scattered configuration. The centralized configuration achieved the greatest mitigation (4.203°C). The results show that the spatial arrangement of identical shading elements can influence their thermal performance. The proposed workflow provides a flexible approach for testing and optimizing shading configurations in different urban spaces.

Key words: *performance-based design, parametric design, outdoor thermal comfort, UTCI, modular shading system*

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1. INTRODUCTION

Increasing air temperatures and frequent heat events have intensified the need for climate-responsive design. High solar exposure in paved public spaces can increase heat stress and negatively affect outdoor thermal comfort (OTC) [1,2,3]. Shading is an effective mitigation strategy [4,5,6,7], while vegetation also provides cooling [8,9,10] but may be constrained by space, existing infrastructure and long growth periods. Architectural shading elements provide greater control over geometry and placement, while their form, orientation and dimensions can affect OTC [11,12,13,14]. Previous studies of vegetation also show that the number and spatial arrangement of shading elements influence OTC [15,16,17]. Urban geometry and shading conditions further affect OTC [18,19,20,21]. Thus, shading performance depends not only on the amount of shade but also on its spatial configuration. Parametric and evolutionary methods have been used to evaluate and optimize environmental performance in shading and urban design [22,23,24].

Despite the recognized importance of shading characteristics and spatial configuration for outdoor thermal conditions, a research gap remains in understanding how the spatial configuration of identical modular shading elements affects OTC. This provides a basis for investigating spatial configuration as an independent design parameter within a performance-based parametric workflow.

The research goal of this study is to evaluate how different spatial configurations – linear, centralized and scattered – of identical modular shading element influence OTC in a public square and to identify favourable layouts using a parametric workflow. The configurations are evaluated under hot summer conditions using UTCI performance evaluation and evolutionary optimization.

The study is guided by the following research questions:

RQ1: How do different spatial configurations of identical modular shading elements affect UTCI under hot summer conditions?

RQ2: Which of the tested configuration provides the greatest UTCI mitigation within the defined climatic and spatial conditions?

RQ3: Can a parametric evolutionary workflow support the identification of thermally favourable shading layouts?

2. METHOD FOR EVALUATING MODULAR SHADING CONFIGURATIONS

The proposed method was developed in order to evaluate how different spatial configurations of modular shading elements affect OTC. The workflow combines following steps:

- 3D modeling in Rhino 3D software, CAD program for 3D modeling.
- Parametric modeling in Grasshopper, visual programming tool in Rhino 3D.
- UTCI calculation in Ladybug, Grasshopper add-on for simulation analysis.
- Finding favourable configuration in Galapagos, an evolutionary algorithm.

2.1. 3D modelling

A simplified 3D model of the built environment was created to represent objects affecting the thermal conditions of the study area, including buildings and trees. Spatial information was obtained from OpenStreetMap (OSM) and Google Maps and further developed in Rhino 3D. Buildings were modelled according to their footprints and approximate height, while existing trees were represented as simplified 3D elements. This simplification reduces model complexity and computational load while retaining the main spatial features relevant to the analysis. The resulting 3D model provides the geometric basis for the generation of parametric modular shading configurations and their OTC analysis.

2.2. Parametric modeling and spatial configurations of shading modules

The modular shading system was created parametrically in Grasshopper, allowing the geometry and position of the modules to be controlled. The system consists of an equal number of identical circular shading modules, with the same dimensions and height, keeping the total shading area comparable across configurations.

Three spatial configurations were investigated: linear, centralized and scattered. In the linear configuration, modules are arranged at equal distances along a defined linear path. In the centralized configuration, they are grouped around a common central area, while in the scattered configuration, they are distributed across the available area. Module positions are controlled through parametric inputs. Grasshopper was also used to generate measurement points for the UTCI simulation within the shaded areas beneath the modules. This enables the same parametric workflow to generate and evaluate different spatial arrangements.

2.3. UTCI calculation

OTC was evaluated using the Universal Thermal Climate Index (UTCI) in Ladybug. The UTCI heat stress categories used for the interpretation of the results are presented in Figure 1.

UTCI (°C)	Stress category
> +46	Extreme heat stress (EHS)
+38 to +46	Very strong heat stress (VSHS)
+32 to +38	Strong heat stress (SHS)
+26 to +32	Moderate heat stress (MHS)
+9 to +26	No thermal stress (NTS)
0 to +9	Slight cold stress (SCS)
-13 to 0	Moderate cold stress (MCS)
-27 to -13	Strong cold stress (SCS)
-40 to -27	Very strong cold stress (VSCS)
< -40	Extreme cold stress (ECS)

Figure 1. UTCI heat stress categories [25]

The location and meteorological inputs, including dry-bulb temperature, relative humidity, wind speed, direct normal radiation and diffuse horizontal radiation, were obtained from the EPW file for the study location. The analysis period, measurements points location and standing posture were specified according to the study objectives.

The 3D context shading included the surrounding buildings, trees and generated shading modules. This geometry was provided as context shading input to the Ladybug Solar Adjusted Temperature component together with the solar radiation data. Ground reflectivity was also specified as an input to this component.

The shading panels were modelled as geometric obstruction to direct solar radiation only. The radiative material properties, including solar reflectance, absorptance and logwave emissivity, were not explicitly assigned. The Solar Adjusted Temperature component was used to calculate mean radiant temperature (MRT), which was then used with the relevant meteorological parameters, as an input to the Ladybug Outdoor Comfort Calculator for the UTCI calculation. MRT was therefore used as an intermediate variable in the UTCI calculation rather than as a separate thermal comfort indicator.

For each shading configuration, UTCI values were calculated at parametrically generated set of measurement points to evaluate the OTC within the shaded areas. The same number of points was used for all configurations. The calculated UTCI values were first averaged over the analysed hours for each measurement point and then across all measurement points to obtain a single average UTCI value for each configuration.

2.4. Finding favourable shading modules layout

An evolutionary algorithm was applied in order to find favourable positions of the shading modules. Galapagos is a single-objective algorithm and it uses genes and a fitness value to search for a solution. The fitness value represents the objective that the algorithm aims to optimize, while genes are the input parameters that can be changed during the optimization process.

In this study, the fitness value was the final average UTCI, which was minimized using the *Minimize* option, with the maximum of 50 stagnant generations. Module positions were defined as genes, with their function adapted to each spatial configuration: for the linear configuration, the gene selects one of the predefined parallel lines; for the centralized configuration, it controls the position of the module group along the central axis; and for the scattered configuration, it controls the seed generating the spatial distribution. The same approach is applied separately to each predefined spatial configuration.

3. APPLICATION OF THE METHOD

3.1. Study area

The proposed method was applied to a real-world scenario at Katolička Porta (Catholic Port) square, Novi Sad (Serbia), shown in Figure 2.

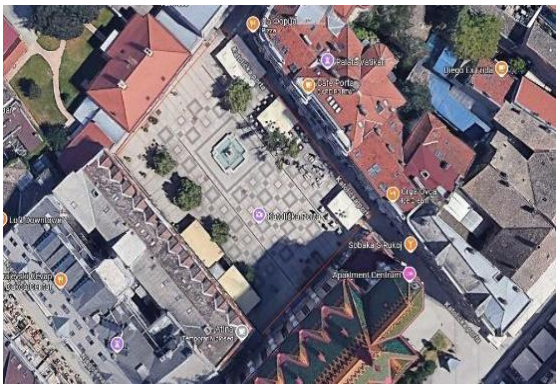


Figure 2. Katolička Porta square

The selected site is an open urban space used for pedestrian movement and outdoor stay, with limited natural shading and paved surfaces are exposed to summer solar radiation. It therefore provides a suitable case for testing different spatial configurations of modular shading elements.

3.2. Creating digital environment

A simplified digital environment was created for the analysis (Figure 3), including the surrounding buildings, the Catholic church and the existing trees. There is also a fountain located in the central part of the square. Its area was excluded from the available surface for panel placement. The resulting digital environment was used as the context for the parametric generation and calculation of the shading module layout.

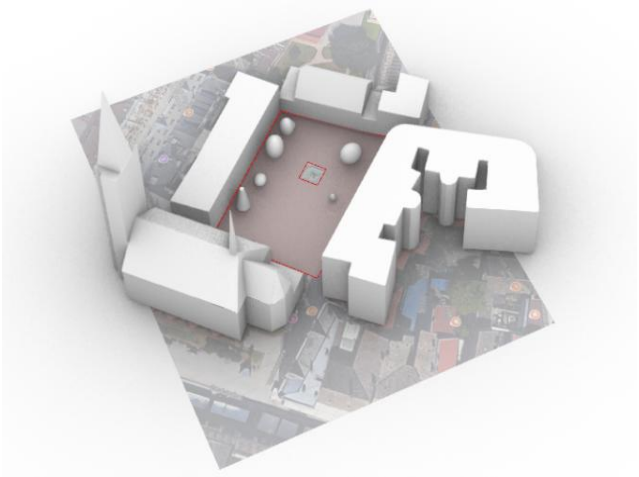


Figure 3. Digital environment of the study area

3.3. Parametric shading module configurations

Three spatial configurations of the shading modules were tested: linear, centralized and scattered (Figure 4).



Figure 4. Linear, centralized and scattered configuration

Each configuration consisted of seven identical circular shading panels, with a radius of 1.5m, positioned at a height of 4m. Their positions were controlled through parameters in Grasshopper and constrained to avoid intersections with existing trees, the fountain and the seating areas. The three configurations were analysed as separate scenarios for OTC analysis.

3.4. UTCI calculation setup

The UTCI analysis was performed for 7 July, representing the hottest summer day, over the period from 8-18 h. Meteorological data were obtained from the EPW file, while ground reflectivity was set to 0.350, representing a typical value for concrete surfaces. The surrounding buildings, trees and shading panels were included as context shading.

For each configuration, 35 measurement points were defined, with five evenly distributed points beneath each of the seven panels and positioned at pedestrian height (Figure 5). UTCI values were averaged across the analysed hours and measurement points.

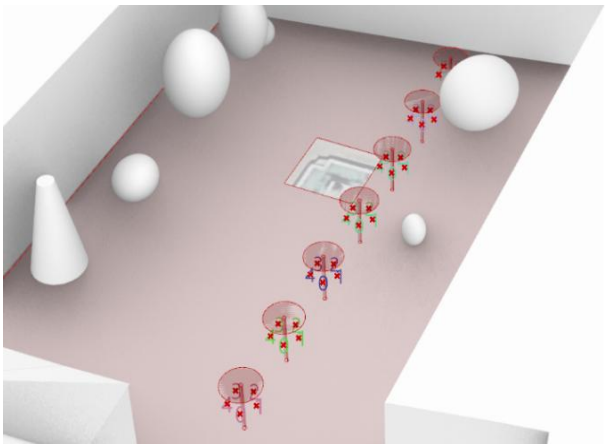


Figure 5. Example of measurements points distribution

For each minimized shading configuration, a corresponding unshaded reference condition was generated by removing only the shading panels, while retaining the same 35 measurement points and their coordinates. Thus, each shaded condition was compared with its corresponding unshaded condition at identical spatial locations. The measurement points differ between the shading configurations (linear, centralized and scattered), because the followed the respective minimized panel configuration, but remained unchanged within each shaded – unshaded comparison. This ensured that the observed

UTCI differences reflected the effect of the shading configuration rather than differences in measurement point locations.

The resulting average UTCI values were interpreted according to the UTCI thermal stress categories.

3.5. Finding favourable shading layout

Galapagos was used to identify favourable panel positions for each predefined configuration. Panel positions were defined as genes, while the average UTCI within the shaded areas was used as the fitness value. The objective was to minimize the average UTCI while maintaining the defined spatial constraints.

The resulting favourable configurations were then used for the final comparison of OTC with corresponding unshaded references.

4. RESULTS

The results show that all three shading configurations mitigated outdoor thermal stress, as indicated by the decrease in the average UTCI values compared with the corresponding unshaded condition (Table 1).

Table 1. comparison of OTC of unshaded and favourable shaded solutions

Shading configuration	Average UTCI – unshaded ($°C$)	Average UTCI – minimized ($°C$)	UTCI mitigation ($°C$)	Mitigation (%)	UTCI category - unshaded	UTCI category - minimized
Linear	32.880	31.080	1.800	5.47	Strong heat stress	Moderate heat stress
Centralized	33.000	28.797	4.203	12.74	Strong heat stress	Moderate heat stress
Scattered	32.422	30.966	1.456	4.49	Strong heat stress	Moderate heat stress

The unshaded values for the linear, centralized and scattered configurations were within the strong heat stress category, while all favourable shading configurations reached the moderate heat stress category.

The linear, centralized and scattered configurations achieved UTCI mitigation of 1.800 $°C$ (5.47 %), 4.203 $°C$ (12.74 %) and 1.456 $°C$ (4.49 %), respectively, with centralized configuration achieving the greatest mitigation. The favourable solution for each configuration is shown in Figure 6.

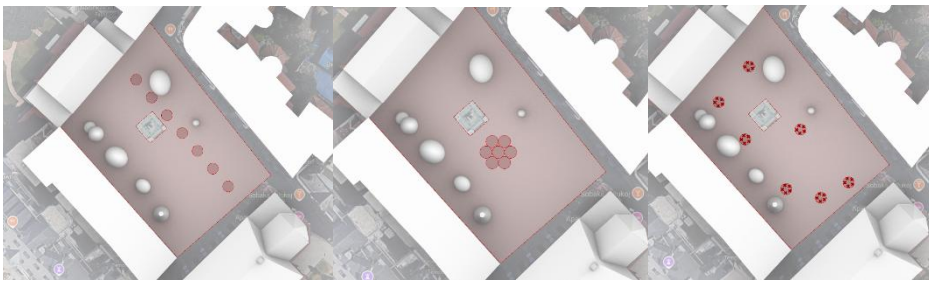


Figure 6. Favourable solutions for linear, centralized and scattered configuration

Although all three configurations resulted in a transition from strong to moderate heat stress, the magnitude of the mitigation differed. The centralized configuration provided the greatest UTCI mitigation, while the scattered configuration produced the smallest change. This indicates that the spatial arrangement affects the thermal performance of modular shading elements, even when their number, size and height remain constant. However, the shift to moderate heat stress in the linear and scattered configuration should be interpreted with caution. Their unshaded UTCI values were already close to the lower threshold of the strong heat stress category. Thus, relatively modest mitigation of 1.800°C and 1.456°C were sufficient to cross the category boundary. In contrast, the centralized configuration achieved a substantially larger mitigation of 4.203 °C, indicating a more pronounced thermal improvement rather than a mere boundary effect.

5. DISCUSSION

The results show that the parametric workflow can effectively evaluate thermal impact of different shading configurations. The centralized configuration achieved the greatest UTCI mitigation (12.74%), although the number, size and height of panels were identical among configurations. The more continuous and concentrated shaded area of centralized configuration resulted in greater UTCI mitigation compared with the more dispersed shadow patterns of the linear and scattered configurations. This indicates that spatial distribution of shading, not only the total shading area, influences OTC.

From a practical standpoint, this workflow is highly adaptable to other sites and shading geometries. Its parametric structure allows different module properties, spatial constraints and space layouts to be tested. The only requirements are the necessary weather data and spatial and geometric data of the study area.

6. CONCLUSION

This study explored how spatial configurations of identical modular shading elements affect OTC in a public square with limited natural shading. A parametric workflow was developed to generate and evaluate linear, centralized and scattered configuration under hot summer conditions. The results show that spatial arrangement influences OTC despite identical module number, size and height. The centralized configuration achieved the greatest UTCI mitigation, while the linear and scattered configurations achieved smaller mitigation. This confirms spatial configuration as an important design parameter for modular shading.

The proposed workflow supports the identification of thermally favourable layouts through parametric generation and environmental simulation. It can be adapted to different shading geometries and spatial constraints in other public squares, provided that appropriate weather data and sufficient spatial data are available.

This study is limited by the simplified representation of the environment and tree geometries that cast full shadow. In addition, the analysis was conducted for a single summer day. The shading panels were created as geometric obstruction to direct solar radiation. Consequently, the potential influence of material properties on OTC was not included in the analysis**.**

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Review paper

PRINCIPLES OF BIOCLIMATIC ARCHITECTURE APPLIED TO A FAMILY RESIDENTIAL BUILDING PROJECT ON A SLOPE – A CASE STUDY OF THE LOCATION OF KRAŠIĆI, MONTENEGRO

Marko Jeremić[1]

Abstract

The paper considers the application of bioclimatic principles in the design of a family residential building on a sloped terrain, using the example of the location in Krašići, Montenegro. The aim of the work is to analyze the ways in which the characteristics of the location, including the configuration of the terrain, climatic conditions, orientation and views towards the sea, influenced the formation of the architectural concept and the choice of bioclimatic solutions. The research was conducted using the case study method, through the analysis of project documentation and applied design principles. Natural ventilation, protection from solar radiation, green roof, use of solar energy, rainwater collection, underfloor heating and cooling, as well as the application of vegetation and local materials were analyzed in particular. The analysis shows that the connection of bioclimatic principles with the characteristics of the specific place enables an integral consideration of the functional, spatial and energy aspects of the object, where the configuration of the terrain and climatic conditions are the basis for the formation of design decisions.

Key words: *Bioclimatic architecture, Energy efficiency, Sloping terrain, Bioclimatic principles, Sustainable design*

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1. INTRODUCTION

Contemporary architectural practice is increasingly focused on designing energy-efficient and sustainable buildings that provide a high level of user comfort while reducing their environmental impact. In this context, bioclimatic architecture represents an approach that relates building design to the natural characteristics of the site, climatic conditions, and available resources. The application of passive strategies, such as appropriate orientation, natural lighting, and natural ventilation, can contribute to improving energy performance and reducing the need for active heating and cooling systems [1].

The bioclimatic approach involves adapting the architectural design to the specific characteristics of the site. In addition to climatic conditions, factors such as terrain configuration, site orientation, views, and the spatial context play an important role. Therefore, site analysis represents the basis for selecting appropriate design and bioclimatic strategies.

The subject of this paper is the analysis of the application of bioclimatic principles in the design of a single-family residential building at the site of Krašići, in the Municipality of Tivat, Montenegro. The aim of the paper is to identify and analyse the applied principles and their relationship with the characteristics of the site and design decisions, with particular emphasis on their expected contribution to thermal comfort, energy use, and the utilization of natural resources. The research is based on a qualitative analysis of the site and project documentation, establishing connections between the specific site conditions and the applied bioclimatic measures.

The contribution of the paper lies in the systematic analysis of the relationship between the characteristics of sloping terrain, design decisions, and the applied bioclimatic principles in a specific residential building. In this way, the paper highlights the possibilities of integrating interconnected bioclimatic strategies into the design of residential buildings in the Mediterranean climatic region.

2. METHODOLOGICAL APPROACH

The research is based on a qualitative approach and the case study method, applied to a single-family residential building designed for the site of Krašići, Montenegro. The descriptive-analytical method and qualitative analysis of the project documentation were applied by examining the site characteristics, identifying specific bioclimatic measures, and analysing their relationship with design decisions. Through the method of synthesis, the results were consolidated by establishing the relationship between site conditions, design measures, and their expected bioclimatic effects.

The analysis was conducted in three steps: (1) analysis of the climatic, topographic, and spatial characteristics of the site; (2) identification of the applied bioclimatic measures; and (3) qualitative assessment of their expected contribution to thermal comfort, energy use, and the utilization of natural resources. Given the qualitative nature of the research, the study does not include numerical energy simulations or

measurements of the actual building performance. Therefore, the analysed effects are interpreted as expected contributions of the applied design strategies.

3. LOCATION ANALYSIS

The designed single-family residential building is located in the settlement of Krašići, on the Luštica Peninsula, in the Municipality of Tivat, Montenegro (Fig. 1a and 1b). The settlement is situated on the coast of the Bay of Kotor and is characterized by a fragmented coastline, pronounced terrain slope, and direct contact with the sea. The planned development of the area is defined by the Detailed Urban Plan for Krašići [2].

a)  b) 

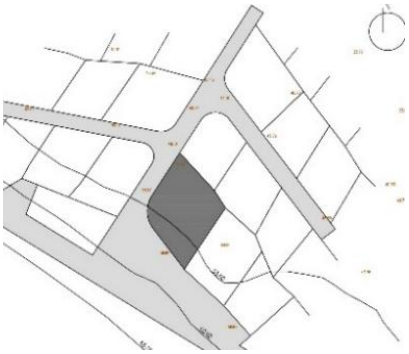
Figure 1a. Landscape of Krašići [3], Figure 1b. Location of the settlement of Krašići in relation to the map of Montenegro [3]

The Tivat area is characterized by a Mediterranean climate, with mild and rainy winters and warm, sunny summers. The mean annual temperature is approximately 15 °C, with approximately 2,446 hours of sunshine per year [4]. During winter, the prevailing wind is the bora (bura) from the northeast, while in summer the mistral (maestral) from the northwest is the most common, contributing to natural ventilation. The sirocco (jugo) is characteristic of the autumn and winter periods and is accompanied by increased precipitation. These characteristics provide a basis for the application of natural ventilation, daylighting, and summer overheating protection strategies.

The site is a corner plot with access to roads on two sides, while the terrain slopes downward from south to north, towards the coast (Fig. 2a). Pedestrian and vehicular access is organized from the northwest side (Fig. 2b). Due to the pronounced slope, the building was designed to follow the natural terrain configuration, with minimal earthworks and without creating significant artificial platforms.

The site orientation had a particular influence on the design concept. Although south orientation is generally recommended in bioclimatic design due to greater winter solar gains, the highest-quality views at the site are oriented towards the north, overlooking the Bay of Kotor. At the same time, the southern side is constrained by the elevated terrain. Therefore, the organization of the building is based on the integration of climatic conditions, terrain configuration, access, and the visual qualities of the site.

a)



b)



Figure 2a. Subject plot [author], Figure 2b. Situational solution [author]

4. DESIGN CONCEPT OF THE OBJECT

The design concept of the single-family residential building was developed based on an analysis of the natural and spatial characteristics of the site, with terrain configuration, orientation, access, and the quality of views representing the key factors in shaping the building. The concept is based on integrating functional requirements with the specific characteristics of the site and applying bioclimatic principles.

The pronounced terrain slope of approximately 4.5 m towards the north, where views towards the Bay of Kotor open up, conditioned the formation of the building as three functionally interconnected levels (B+G+1). Instead of creating a flat building platform and undertaking extensive earthworks, the building follows the natural terrain configuration, reducing the need for retaining structures and limiting intervention in the existing terrain. Access to the building and parking are organized from the northwest side, clearly defining the entrance zone. The spatial organization follows the functional division of the building: the basement level is partially embedded into the terrain and accommodates auxiliary and technical spaces, the ground floor contains the daytime zone with the living room, dining area, and kitchen, while the upper floor accommodates the night zone with bedrooms and associated spaces (Fig. 3a).

The daytime zone is oriented towards the north, overlooking the Bay of Kotor, establishing a direct visual and functional connection between the interior and exterior spaces. This orientation responds to the specific characteristics of the site, as the southern side of the plot is constrained by elevated terrain. Terraces and outdoor spaces are integrated into the architectural form, with the pool terrace at ground-floor level functioning as an extension of the daytime zone. The building is designed as a simple and compact form, using stone, wood, and light-coloured façade surfaces to establish a visual connection with the Mediterranean setting (Fig. 3b and 3c). Roof surfaces and systems for the utilization of renewable energy sources and stormwater management form part of the design concept, while their specific bioclimatic functions are analysed in the following section.

a)



b)



c)



Figure 3a. Basement floor plan, Ground floor plan, First floor plan [author], Figure 3a. and 3b. Three-dimensional view of the object [author].

5. ANALYSIS OF APPLIED BIOCLIMATIC PRINCIPLES

Based on the analysis of the site and the design concept, a set of interconnected bioclimatic principles was applied to the building, corresponding to the climatic and spatial characteristics of Krašići. The analysis includes natural ventilation and passive cooling, solar radiation protection, a green roof, the use of solar energy, rainwater harvesting, underfloor heating and cooling, as well as vegetation and material selection. Their application is examined through the relationship between specific design measures, site conditions, and their expected contribution to thermal comfort, energy efficiency, and the rational use of natural resources.

5.1. Principle of natural ventilation and passive cooling

Natural ventilation is achieved through the arrangement of façade openings, enabling natural air exchange throughout the interior spaces. Openings on opposite or interconnected façades allow air movement to be established, while the open organization of the daytime zone further facilitates airflow through the building (Fig. 4). This solution is particularly relevant during the warm period, when the prevailing mistral can be utilized for natural ventilation. During the night, when outdoor temperatures are lower, opening the façade surfaces allows part of the heat accumulated during the day to be removed. In this way, natural ventilation functions as

a passive cooling strategy that can reduce the need for active cooling. Its effectiveness depends on outdoor climatic conditions and the possibility of controlling the openings, which is why it is considered in combination with solar radiation protection [5].

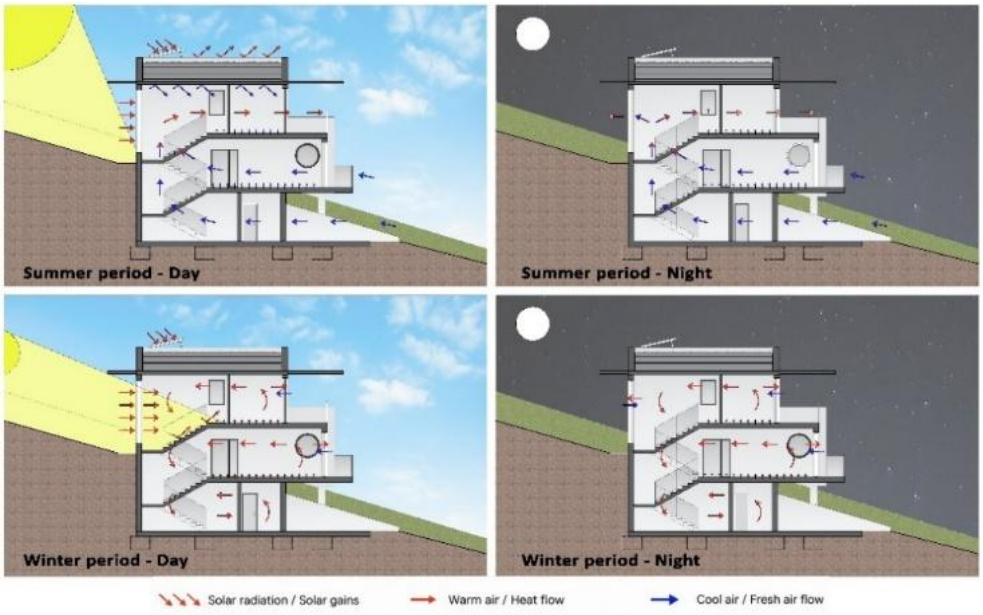


Figure 4. Hot-cold air flow patterns in summer and winter [author]

5.2. Principle of solar radiation protection

Solar radiation protection is achieved through horizontal canopies and overhangs integrated into the architectural volume of the building (Fig. 5a). Their role is to limit direct solar radiation entering through larger glazed surfaces, particularly during the warm period of the year, while maintaining the visual connection between the daytime zone and the outdoor space. The dimensions and position of the shading elements are related to the geometry of the openings and the seasonal position of the sun (Fig. 5b). During summer, when the sun is high in the sky, horizontal overhangs can reduce direct solar radiation, while their geometry allows greater solar penetration during periods when solar gains are desirable. In this way, solar protection represents an integral part of the building design rather than a subsequently added technical measure [6].

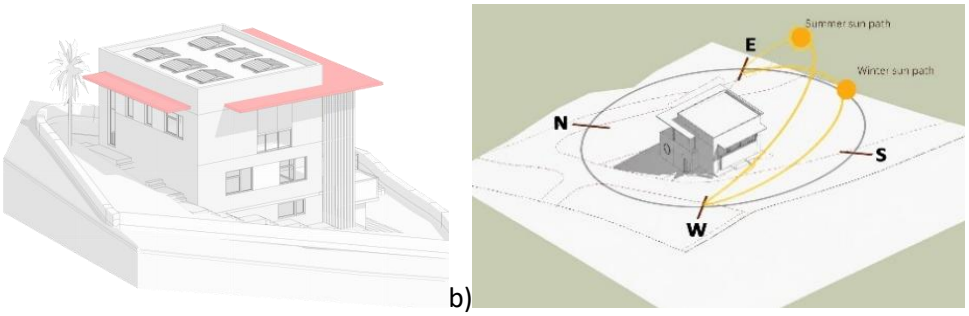
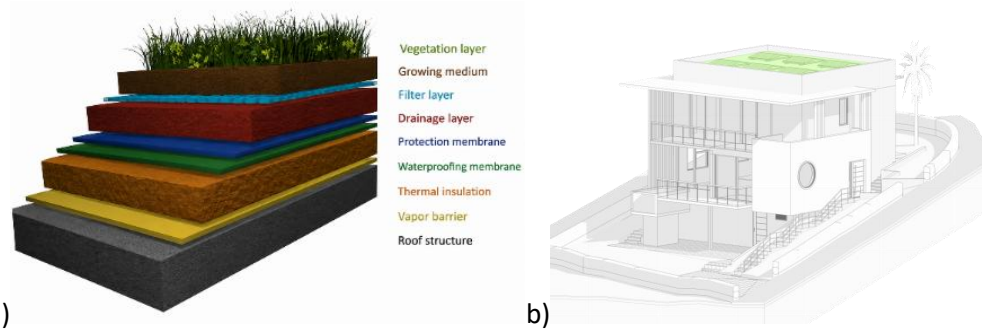


Figure 5a. Architectural elements - canopies and overhangs on the axonometric view of the building [author], Figure 5b. View of the movement of the Sun in summer and winter [author]

5.3. Principle of green roof application

A green roof with a vegetation layer is provided on the flat roof surface (Fig. 6a and 6b). The vegetation layer reduces direct heating of the roof surface and contributes to the thermal protection of the building, while the substrate and vegetation enable the retention of part of the atmospheric precipitation [7].

Under conditions of a pronounced site slope, the green roof also has an additional spatial function by visually connecting the building with the natural terrain. In this way, the roof contributes simultaneously to the thermal and hydrological performance of the building and to its integration into the landscape. Its application requires appropriate waterproofing, drainage, structural load verification, and regular maintenance.



a) b)

Figure 6a. Layers of the green roof [8], Figure 6b. View of the green roof on the axonometric view of the object [author]

5.4. Principle of solar energy utilization

Photovoltaic panels are installed on the flat roof surface, allowing the existing building surface to be used for electricity generation without additional land occupation. Their application is based on utilizing the high solar potential of the Mediterranean site.

The integration of the panels into the roof zone enables the connection of electricity generation with other bioclimatic measures applied to the building. System efficiency depends on the orientation and inclination of the panels, available solar radiation, and potential shading. Since annual electricity production was not calculated within the scope of the research, the contribution of the photovoltaic system is considered at the level of its design potential for the utilization of a renewable energy source [9].

5.5. Principle of rainwater harvesting and utilization

An underground cistern is provided for the collection of atmospheric precipitation and is connected to the roof surfaces of the building. The collected water can be used for irrigation of green areas and other purposes that do not require potable water quality

The system represents a simple means of reducing water consumption from the public water supply system and reusing atmospheric precipitation. Its effectiveness depends on the amount of precipitation, roof area, cistern capacity, and user demand. Within the project, the system is particularly relevant as a complement to the green

roof and vegetation, which together form part of an integrated approach to stormwater management [10].

5.6. Principle of underfloor heating and cooling

Underfloor heating and cooling is applied as an active complement to passive bioclimatic measures. The radiant system uses the large surface area of the floor for heat exchange and enables a more uniform distribution of temperature within the space, which can contribute to improved thermal comfort.

In the building under consideration, the system is combined with passive measures for solar radiation protection and natural ventilation. By reducing the thermal load through passive strategies, more favourable conditions are created for the operation of the active system. During cooling, control of floor surface temperature and indoor relative humidity is necessary to prevent condensation, making appropriate system regulation an important condition for its application [11].

5.7. Principle of vegetation and local material application

Vegetation is used as an element of both bioclimatic and landscape design of the site. Evergreen vegetation is planned on the northern side, while deciduous vegetation is planned on the southern part of the site. Deciduous vegetation provides shading during the warm period, while after leaf fall it allows a greater amount of solar radiation to pass through. In this way, vegetation can contribute to creating more favourable microclimatic conditions in the immediate surroundings of the building [12].

Stone and wood are applied as materials characteristic of the local context, together with light-coloured façade surfaces. Their selection contributes to the visual integration of the building into the Mediterranean context, while lighter surfaces can reduce the absorption of solar radiation compared with darker finishes.

5.8. Overview of applied bioclimatic principles and discussion

For the systematic presentation of the analysed principles, Table 1 shows the relationship between the bioclimatic principle, the specific design measure, and the expected effect.

Table 1. Overview of applied bioclimatic principles, design measures and expected effects

Bioclimatic principle	Application in the project	Expected effect
Natural ventilation and passive cooling	Arrangement of façade openings to enable natural airflow	Improved air exchange, heat removal, and reduced need for mechanical cooling
Solar radiation protection	Horizontal canopies and overhangs integrated into the building volume	Reduction of direct solar radiation and summer heat gains
Green roof	Flat roof with a vegetation layer	Reduction of roof surface heating, improvement of thermal performance, and retention of part of atmospheric precipitation

Solar energy utilization	Photovoltaic panels installed on the flat roof surface	Electricity generation from a renewable energy source and reduced dependence on grid-supplied energy
Rainwater harvesting and utilization	Cistern for collecting atmospheric precipitation from roof surfaces	Reduced water consumption from the public water supply system and reuse for irrigation
Underfloor heating and cooling	Radiant floor system for regulating indoor temperatures	More uniform temperature distribution and improved thermal comfort
Vegetation application	Evergreen vegetation on the northern side and deciduous vegetation on the southern part of the site	Shading and creation of more favourable microclimatic conditions
Local material application	Use of stone and wood combined with neutral light-coloured tones	Integration of the building with the local character and Mediterranean context

The analysis shows that the applied bioclimatic measures function as an interconnected system adapted to the climatic and topographic conditions of Krašići. Natural ventilation and solar radiation protection jointly contribute to controlling summer thermal loads, while underfloor cooling represents an active complement to the passive strategies. The green roof, vegetation, and rainwater harvesting connect the building with its immediate natural surroundings and contribute to more rational resource management, while photovoltaic panels enable the utilization of a renewable energy source. This demonstrates that the bioclimatic approach is not based on individual measures, but rather on their integration into the architectural concept. The specificity of the project lies in adapting the strategies to the site conditions. The northern orientation of the main daytime zone represents a compromise between solar requirements, terrain configuration, and the quality of views towards the Bay of Kotor. Although the study does not include numerical simulations or measurements, the analysis indicates the expected potential of the applied measures to improve thermal comfort and promote more rational use of energy and natural resources.

6. CONCLUSION

The analysis of the designed single-family residential building in Krašići showed that the climatic, topographic, and spatial characteristics of the site directly influenced the design of the building and the selection of bioclimatic measures. The integration of passive, active, and landscape strategies enabled the architectural concept to be aligned with the requirements of thermal comfort, energy efficiency, and the rational use of natural resources.

The case study demonstrates that bioclimatic design requires adaptation to specific site conditions rather than the application of universal solutions. In the analysed project, the northern orientation of the daytime zone represents a response to the terrain configuration and the quality of views, while potential climatic disadvantages are mitigated through other bioclimatic measures.

A limitation of the research is the absence of energy simulations and measurements of the actual building performance, meaning that the effects of the analysed principles can only be interpreted as expected contributions. Their quantitative verification represents an opportunity for further research.

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Research paper

TECHNICAL CRITERIA FOR LOW IMPACT DEVELOPMENT RETROFIT OF SPORTS GROUNDS IN THE CITY MUNICIPALITY OF MEDIJANA, NIŠ

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Abstract

Outdoor sports grounds can keep their sporting function and still help to manage stormwater. Methods for choosing sites for low impact development (LID) measures are written for city blocks or catchments. They rarely deal with the technical limits of sports surfaces or show where site data are missing. This paper defines technical criteria for the preliminary assessment of sports grounds for LID retrofit. The assessment is not a design. It shows how much potential a site has, how much of that rests on verified evidence, and which surveys are still needed. Seven criteria cover the playing surface, the court area, the local slope and run-on from surrounding areas (inflow of runoff onto the surface), the usable edge or subsurface space, the external impervious area that could be connected, the overflow route and the maintenance condition. Each criterion has fixed anchors for scores 1 to 5 and a stated minimum evidence for a verified score. Ownership, accessibility and operating regimes are left to the final decision stage. All criteria are treated as equally important, so no weighting is applied. Every score is marked verified or not verified, and the result is reported as the mean score S, the share of verified criteria E, and the interval $[S^{-}, S^{+}]$ that the unverified criteria still allow. The criteria are demonstrated on two 40 × 20 m school courts in Medijana, Niš, one with a sealed mineral surface and one with an acrylic surface. They score 3.29 and 3.14, but only 29 % of the criteria are verified at either site, so the intervals overlap and neither court can be called the better one. For an illustrative 40 mm event, assumed runoff-volume reductions are 16.0 m^3 and 12.8 m^3 at Schools 1 and 2; these are indicators, not measured storage capacities.

Key words: *low impact development, sports grounds, technical criteria, field evidence protocol, stormwater retrofit*

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1. INTRODUCTION

Urban development seals natural ground and increases both the volume and the peak of stormwater runoff. Low impact development (LID), sustainable drainage systems (SuDS) and similar approaches manage rainfall where it falls [1–3]. Outdoor sports grounds suit such measures well: they are spread across the city, usually publicly managed, and large enough to store or treat runoff while still in use for sport [4]. However, a sports ground is not ordinary open space. Playing quality, user safety, surface durability and continuous use decide which measures can be considered at all.

Published LID site-selection methods work at the scale of plots, sub-catchments or urban blocks, and their criteria are mainly environmental, social and hydrological [5–7]. They do not address the technical limits of sports surfaces. Li et al. [8] used a hydraulic model with expert judgement to compare LID options inside one sports centre, but only as design variants at a single site. What is missing is a simple, repeatable procedure for one facility that respects the sports surface, separates preliminary potential from proven feasibility, and makes missing site data visible.

The aim of this research is therefore to: (1) define technical criteria, evidence rules, and eligibility conditions for a reproducible preliminary assessment and ranking of sports grounds, particularly in situations with incomplete local data; and (2) develop a technically feasible retrofit concept for sports grounds compatible with the sports surface, focusing solely on engineering and technical solutions without addressing urban planning or dual-use considerations. Ownership, accessibility, operating regimes, maintenance responsibility, demographic justification and the wider urban context are therefore not assessed here. They belong to the final decision stage, in which planners and facility owners take part.

Two school courts demonstrate the criteria. They come from a 2023 field inventory of 38 outdoor sports and recreational facilities in Medijana, compiled by the authors after earlier stormwater studies of the same area [9,10]. They are examples only, not a representative sample, and no ranking of the full inventory is given here. The criteria will be applied to all 38 facilities in a separate study.

2. TECHNICAL CRITERIA AND EVIDENCE RULES

Figure 1 shows the whole procedure and marks the parts defined and demonstrated here: the eligibility check, the seven criteria, the evidence rules, the reporting of the result and the conditional retrofit concept. Ranking of the full inventory and the design-stage investigations lie outside it.

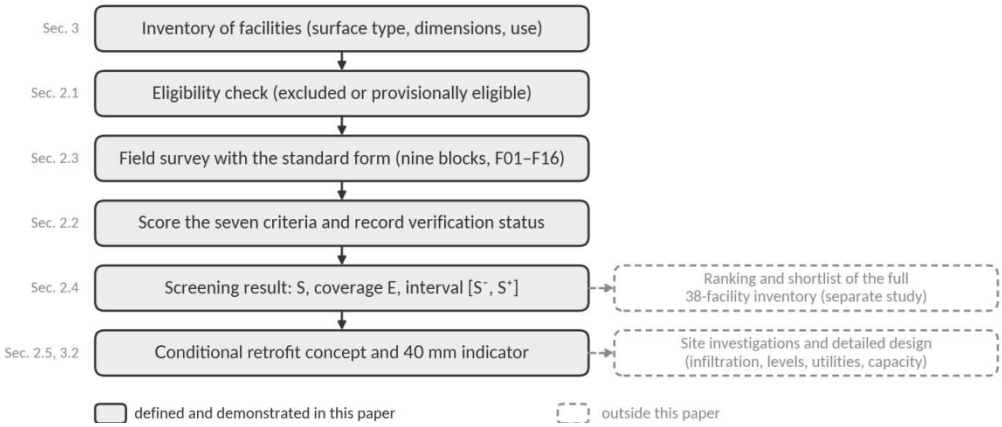


Figure 1. The preliminary assessment procedure and the parts covered here. Source: authors.

2.1. Eligibility check

The eligibility check decides whether a facility can be scored at all. A facility is excluded only when a confirmed site condition makes every realistic retrofit concept impossible. If some conditions are unknown, the facility is provisionally eligible and is scored; the unknowns are recorded and checked later. A constraint that rules out one concept excludes that concept, not the facility. Groundwater depth, bearing capacity, buried utilities, receiving-system capacity and sports-surface compliance are design-stage checks.

2.2. The seven technical criteria

Seven criteria, labelled P1 to P7, describe a facility from an engineering point of view. Table 1 gives the anchors and the minimum evidence for a verified score.

P1, surface conversion opportunity. P1 records how easily the playing surface can be made permeable. A sealed mineral surface, concrete or asphalt, scores highest, because it can be replaced by a permeable sports surface without changing the sport. Acrylic and polymeric surfaces score one step lower, artificial turf and modular tiles lower again, natural turf lowest. P1 depends on the type of surface only; its condition is recorded separately, because condition decides whether the concept replaces the surface or keeps it.

P2, core playing-surface area. P2 is the area of the court itself, from measured dimensions and not from a plot boundary. It sets the upper limit of the rainfall volume the facility can handle.

P3, local slope and run-on. P3 combines the slope of the court and its surroundings with any runoff arriving from outside. Each condition is scored separately and the lower score is used. A flat court with no external run-on is easy to drain and to build storage under; a steep court, or one receiving uncontrolled runoff, is not.

P4, usable edge or subsurface space. P4 records where a bioretention strip, a trench or a buried tank could be placed. Only continuous usable width counts; obstacles, mature trees and machine access are recorded and reduce the score.

P5, external impervious area that can be connected. P5 is the ratio $r = A_{ext}/A_{court}$ between the external impervious area that could realistically be led onto the facility and the court area. A high ratio increases the hydrological benefit, but also the storage needed and the risk of polluted inflow.

P6, overflow and hydraulic connectivity. P6 records whether water above the storage volume can leave the site safely. The highest score needs a confirmed route and a confirmed receiving point. If no safe overflow is possible at all, this is a site-level exclusion under Section 2.1, not a score of 1.

P7, maintenance and operating condition. P7 records ponding after rain, the cleaning regime of the existing gullies and any record of clogging. Permeable systems fail mainly through clogging [11], so a known maintenance problem lowers the score.

Two rules keep the scoring unambiguous. Where the anchors are nested, the highest fully supported category applies. Where a criterion combines two conditions, each is scored separately and the lower score is used. Two observers with the same measurements should therefore choose the same category.

All seven criteria are treated as equally important and no weighting is applied. At this stage the evidence is too incomplete to justify weights, and the message is carried by the coverage and the interval, not by a small difference between mean scores.

Table 1. Score anchors and minimum evidence for the seven criteria; Section 2.2 explains what each criterion measures

Code	Score anchors (5 → 1)	Minimum evidence for a verified score
P1	5 sealed mineral (concrete or asphalt); 4 acrylic or polymeric; 3 artificial turf or modular tile; 2 natural turf; 1 non-standard or protected construction	Inventory record and a photograph of the surface. The binder need not be identified: concrete and asphalt share score 5.
P2	5 ≥ 4,000 m²; 4 1,500–3,999 m²; 3 800–1,499 m²; 2 400–799 m²; 1 < 400 m²	Measured dimensions, or a plan that can be trusted.
P3	Slope: 5 ≤ 2 %; 4 > 2–5 %; 2 > 5–8 %; 1 > 8 %. Run-on: 5 none; 4 minor and manageable; 2 significant; 1 severe and uncontrolled. 3 = not verified	Three longitudinal and three transverse slope measurements, and the direction of surface runoff.
P4	5 usable width ≥ 3 m in at least two zones, or a confirmed open subsurface area; 4 one continuous strip ≥ 2 m; 3 one strip 1–2 m, or not verified; 2 one strip 0.5–1 m; 1 no continuous strip ≥ 0.5 m	Measured length and usable width of each zone, with obstacles and machine access. Buried utilities remain a design-stage check.
P5	$r = A_{ext}/A_{court}$: 5 $r \geq 2.0$; 4 $1.0 \leq r < 2.0$; 3 $0.5 \leq r < 1.0$, or not verified; 2 $0 < r < 0.5$; 1 $r = 0$, confirmed	A sketch of the catchment, its approximate area and a realistic connection route.

Code	Score anchors (5 → 1)	Minimum evidence for a verified score
P6	5 confirmed safe route and receiving point; 4 receiving element identified and connection plausible with minor works; 3 not verified; 2 only major or off-site works possible; 1 severe unresolved constraint	The receiving point, the route and the levels. A proven impossibility is a site-level exclusion, not a score of 1.
P7	5 documented low risk; 4 routine maintenance and no record of ponding; 3 not verified or mixed evidence; 2 documented ponding or clogging; 1 documented high risk	An operator record, repeated observation, or evidence collected after rain.

For P3 and P5 to P7 the value given to an unverified criterion equals one of the verified categories; the two are told apart by the verification status in the field record and by the coverage *E* of Section 2.4.

2.3. Field evidence and verification

A standard field form is used so that different observers record the same things. It has nine blocks: header data; surface, dimensions and use; slope profiles and runoff direction; edge and subsurface zones G1 to G4; external impervious sub-areas C1 to C4; drainage elements D1 to D4; use regime; maintenance and ponding records; and a closing summary with the score and status of each criterion and the two main unknowns. Sixteen coded photographs, F01 to F16, are taken at every facility, so that the same views always exist. Zones, sub-areas and elements are numbered on a site sketch, so every measurement and photograph can be located. The complete form is supporting material.

A criterion counts as verified only when the evidence places it in one anchor category with certainty. A photograph of a green strip proves that space exists, but not its usable width. Partial observations stay in the record and count as not verified. This avoids false precision and keeps the result repeatable.

2.4. How the result is reported

The screening score S_i of facility *i* is the mean of the seven criterion scores:

$$S_i=(1/n)\sum_j p_{ij} \quad (1)$$

where $n = 7$ is the number of criteria and p_{ij} is the score of facility *i* for criterion *j*, on the scale 1 to 5. A criterion that is not verified is given the value 3. This is a central assumption and not a safe one: it can be too high for a poor site and too low for a good one. The evidence coverage E_i is the share of verified criteria:

$$E_i=n_V/n \quad (2)$$

where n_V is the number of verified criteria and $n_M = n - n_V$ the number that are not verified. The bounds replace every unverified criterion by its worst and by its best possible value:

$$S_i^{-}=(1/n)\left(\sum_{j\in V_i} p_{ij}+n_M\right)\ ;\ S_i^{+}=(1/n)\left(\sum_{j\in V_i} p_{ij}+5n_M\right) \quad (3)$$

The result is therefore not a single number but the eligibility status together with *S*, *E* and [S^-, S^+]. Because the scale runs from 1 to 5, the interval width is always 4(1 − *E*): the lower the coverage, the wider the interval.

2.5. Retrofit concept and 40 mm indicator

After scoring, the type and condition of the surface select a conditional retrofit branch. A sealed mineral surface near the end of its life can be replaced by a permeable sports surface over an open-graded reservoir layer, with an underdrain and a safe overflow; one that is still serviceable keeps its surface and receives edge collection or subsurface storage. A serviceable acrylic surface is kept and connected to edge interception, pretreatment and then storage, reuse or bioretention. Artificial turf needs checks of the drainage build-up and infill containment; natural turf suits root-zone storage with controlled drainage. Permeable systems need a planned cleaning regime [11], and the final design must meet the standards for water infiltration and sports surfaces [12–16].

An illustrative event runoff volume shows the scale of the task:

$$V=P\cdot A\cdot C/1000 \quad (4)$$

where *V* is the runoff volume [m³], *P* the rainfall depth [mm], *A* the court area [m²] and *C* a dimensionless event runoff coefficient. The comparison depth of 40 mm is close to the mean of the highest daily rainfall recorded in each month at the Niš station [17]; it is not a design storm with a return period. Before the retrofit, *C* = 0.90 for the sealed mineral court and *C* = 0.85 for the acrylic court. After it, the central values are *C* = 0.40 for the permeable reservoir branch and *C* = 0.45 for the retained surface with storage or reuse, with conservative and optimistic values of 0.55 and 0.20, and 0.60 and 0.30. These are assumed values, not measured performance. The assumed runoff reduction is also expressed as an equivalent depth over the court, $d = (C_{before} - C_{after})\cdot P$. Multiplying by the court area gives $\Delta V = d\cdot A/1000$. Here *d* is an equivalent runoff-reduction depth, not a storage depth; Δ*V* is an indicative runoff reduction, not a measured capacity. It is the volume to infiltrate, reuse or store. The calculation excludes the unverified external area of P5. Temporary storage only delays discharge unless water is infiltrated or reused.

3. DEMONSTRATION ON TWO SCHOOL COURTS

The 2023 inventory recorded the identity, dimensions, use and surface type of each facility; the scoring protocol was written afterwards. A targeted survey of the two courts was therefore carried out by I. Ilić on 4 August 2026 with the standard form. The weather was dry and sunny and, according to the observer's record, about ten days had passed since the last rain. There was no operator interview and no independent weather record. The surface and the visible drainage elements could therefore be

documented, but ponding behaviour, maintenance history, levels and the external catchment could not.

The courts are OŠ „Učitelj Tasa“ (School 1) and OŠ „Duško Radović 3“ (School 2). Both are 40 × 20 m (800 m²) courts for futsal and handball at public primary schools. They share area, sport and type of owner and differ only in surface type, which isolates the effect of P1. School 1 was recorded as concrete; the photographs do not prove the binder, so the surface is described as sealed mineral pavement. This does not change P1, because concrete and asphalt share the same anchor. School 2 has an acrylic or polymeric surface.



Figure 2. Targeted survey of 4 August 2026: unpaved edge strip at School 1 (F05) and gully D1 at the paved edge of School 2 (F06). Photographs by I. Ilić.

3.1. Scores and what they mean

The survey verified the surface group and court dimensions at both sites and confirmed active school use. It also produced two partial observations: gully D1 next to the paved edge of the acrylic court, and an unpaved strip around the sealed mineral court (Figure 2). Neither verifies P4 or P6, because usable widths, levels, route, capacity, buried utilities and tree roots were not established. P3 and P5 were not measured, and P7 needs observation after rain or a maintenance record. No site-level exclusion was found, so both facilities are provisionally eligible. Table 2 gives the scores and the evidence status.

Table 2. Scores and evidence status at the two facilities

Criterion	School 1	School 2
P1 Surface conversion	5 – sealed mineral (verified)	4 – acrylic (verified)
P2 Court area	3 – 800 m² (verified)	3 – 800 m² (verified)
P3 Slope and run-on	3 – not verified	3 – not verified
P4 Edge or subsurface space	3 – not verified (partial, F05)	3 – not verified (partial)
P5 External impervious area	3 – not verified	3 – not verified
P6 Overflow and connectivity	3 – not verified	3 – not verified (partial, F06)
P7 Maintenance condition	3 – not verified	3 – not verified

Criterion	School 1	School 2
Eligibility	provisionally eligible	provisionally eligible
Result: S; E; [S^-, S^+]	3.29; 28.6 % (2 of 7); [1.86, 4.71]	3.14; 28.6 % (2 of 7); [1.71, 4.57]

Two of the seven criteria are verified at each site, so the coverage is 28.6 % and each interval is 2.86 wide. The difference between the mean scores is 0.14 and comes only from P1, so the intervals overlap almost completely. The result does not show that School 1 is the better site, only that the criteria give higher conversion priority to a sealed mineral surface than to a serviceable acrylic one.

Because no weights are used, the result depends on no weighting judgement. Weights introduced later could not change the order either: the courts differ on one criterion only, so the difference keeps that criterion's sign for any positive weights. The two-site demonstration therefore cannot test how well the criteria separate facilities; that needs the full inventory.

3.2. Conditional concepts and the 40 mm indicator

Table 3 gives the concept for each court and the 40 mm indicator. The unresolved checks are similar at both sites: slope and levels, edge width and tree roots, groundwater and buried utilities, and a safe overflow route. School 1 also needs its surface material and remaining service life; School 2 needs the invert and capacity of gully D1, the external catchment, and sports-surface compliance. Both courts have the same area, so the difference between the reductions comes only from the assumed coefficients; the indicator shows an order of magnitude, not which facility is better. Gully D1 proves that a receiving element exists, not that a working connection is possible, and the unpaved strip shows space but also mature trees and their roots. The criteria turn both observations into tasks for the next survey, not into favourable scores.

Table 3. Conditional retrofit concepts and the illustrative 40 mm indicator

Facility	Conditional retrofit concept	40 mm indicator: V before/after; reduction; equivalent depth
School 1	Near renewal: permeable sports surface over an open-graded reservoir, with underdrain and safe overflow. Still serviceable: keep the surface and add edge or subsurface storage.	28.8 / 12.8 m³; 16.0 m³, 56 % (39–78 %); 20 mm over 800 m² = 16.0 m³ per event
School 2	Keep the acrylic surface; edge interception and pretreatment; subsurface storage or reuse under the adjacent paved or open area; bioretention if green space is confirmed.	27.2 / 14.4 m³; 12.8 m³, 47 % (29–65 %); 16 mm over 800 m² = 12.8 m³ per event

4. DISCUSSION

In the demonstration, one dry-weather visit left the evidence coverage (the share of verified criteria) at 28.6 % at both sites. Verifying P3 and P4 alone would raise it to 57.1 % and narrow the interval from 2.86 to 1.71, so the criteria also show which survey work reduces uncertainty fastest.

Compared with general LID site-selection methods [5–7], this procedure works at the level of one facility and deals with the technical limits of sports surfaces. It is deliberately limited to engineering questions; ownership, accessibility, operating regimes and the wider urban context are decided later, with planners and owners. The main limitations are the ordinal scale, the offsetting of a low score by high scores on other criteria, and the two-site demonstration; the illustrative 40 mm runoff-volume calculation is a simple indicator and does not model storage routing or peak flow.

5. CONCLUSIONS

Technical criteria were defined for the preliminary assessment of outdoor sports grounds for LID retrofit: seven criteria with fixed anchors and a stated minimum evidence, a two-level eligibility check, a nine-block field form with sixteen coded photographs, the central value 3 for an unverified criterion, and joint reporting of the mean score, share of verified criteria and uncertainty interval. No weighting is used, so the result depends only on the criteria and the evidence behind them.

The criteria were demonstrated on a matched pair of 40 × 20 m school courts. The mean scores are 3.29 and 3.14, but only 28.6 % of the criteria are verified at either site and the intervals overlap almost completely, so the difference reflects the type of surface, not proven site quality. For the illustrative 40 mm event, assumed runoff-volume reductions are 16.0 m^3 and 12.8 m^3 at Schools 1 and 2; they are indicators, not verified storage capacities.

The proposed procedure is a screening and evidence-management tool, not a site-selection or design model. Its output is a documented list of checks and a conditional retrofit concept that keeps the sporting function. Ownership, accessibility, operating regimes and maintenance responsibility remain planning decisions. The output partly matches the data required by the EPA Storm Water Management Model (SWMM) [20]: it identifies area, surface, slope, contributing impervious area, outlet and LID location; width, infiltration, roughness, network geometry and LID-layer parameters require design-stage data. Further work will apply the criteria to all 38 facilities, with more than one observer, locally calibrated thresholds and an AHP weighting [18] agreed by a multidisciplinary panel [19], followed by hydraulic and sports-surface design at the shortlisted sites.

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Research paper

MAPPING HISTORICAL CHANGES IN CURVE NUMBER VALUES IN THE TOPLICA BASIN USING SCS-CN BUILDER

Nikola Đokić[1]

Abstract

Land use and land cover (LULC) changes can alter infiltration conditions and surface runoff potential within a river basin. Because CN provides an integrated measure of how land-cover and soil conditions influence runoff generation, this study examines its spatio-temporal variation in the Toplica River Basin from 1990 to 2018. For this purpose, historical LULC conditions were represented using CORINE Land Cover datasets for 1990, 2000, 2006, 2012, and 2018, which were accessed and spatially extracted through Google Earth Engine. The original CORINE classes were processed in the author-developed SCS-CN Builder QGIS plugin and automatically reclassified into seven generalized LULC classes. These maps were combined with the HYSOGs250m hydrologic soil group dataset and SCS TR-55 CN values for average antecedent moisture conditions (AMC II) to generate spatially distributed CN2 maps. Mean CN2 values and percentage changes relative to 1990 were calculated for seven sub-basins. The results show no substantial basin-wide changes, although the spatial pattern was not uniform. Percentage changes ranged from −1.88% to +0.89%, with the largest decrease recorded in downstream sub-basin S7 between 2000 and 2006. The findings highlight the value of sub-basin analysis and confirm the applicability of the SCS-CN Builder for semi-automated and reproducible CN mapping.

Key words: *SCS-CN, Curve Number, LULC change, QGIS plugin*

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1. INTRODUCTION

Land use and land cover (LULC) changes can affect basin hydrology by altering infiltration, surface retention, and runoff generation. The Soil Conservation Service Curve Number (SCS-CN) method is widely used for event-based direct runoff estimation because of its simplicity and limited data requirements [1,2], representing the combined effects of land cover, soil type, hydrological condition, and antecedent moisture conditions through the Curve Number (CN) [3].

Previous studies have successfully combined the SCS-CN method with GIS and remote sensing to assess the hydrological effects of LULC change [4–7].
However, CN mapping commonly involves several manual procedures, including LULC reclassification, raster alignment, CN assignment, raster calculations, and zonal statistics. Repeating these steps for multiple time periods can be time-consuming and may introduce inconsistencies.

To simplify and standardize this process, the author developed the SCS-CN Builder plugin [8], a QGIS-based tool for semi-automatic and reproducible CN mapping that integrates LULC, hydrologic soil group (HSG), and basin data within a single workflow. The present study focuses on CN2 values, representing average antecedent moisture conditions.

The aim of this study is to analyse spatio-temporal changes in CN2 values in the Toplica River Basin from 1990 to 2018, with emphasis on their spatial distribution and mean values across seven sub-basins, while demonstrating the applicability of the SCS-CN Builder for repeated and reproducible CN mapping.

2. METHODOLOGY

2.1. Study area

The study area comprises seven sub-basins of the Toplica River upstream of the Doljevac hydrological station, delineated according to seven hydrological stations of the Republic Hydrometeorological Service of Serbia [9] (Figure 1).

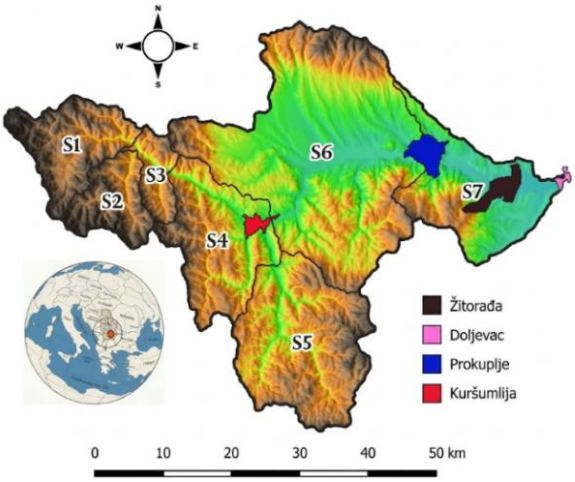


Figure 1. Toplica river basin with seven analysed sub-basins (S1–S7) and major settlements.

The basin is characterized by pronounced geomorphological heterogeneity, with Kuršumlija, Prokuplje, Žitorađa, and Doljevac as the major settlements.

2.2. Methodological workflow

Historical CORINE Land Cover maps for 1990, 2000, 2006, 2012, and 2018 were obtained and spatially extracted for the Toplica River Basin using Google Earth Engine (GEE). The datasets were subsequently processed using the SCS-CN Builder to generate spatially distributed CN2 maps by integrating LULC and HSG information with the adopted CN parameterization. Finally, mean CN2 values were calculated for each of the seven analysed sub-basins.

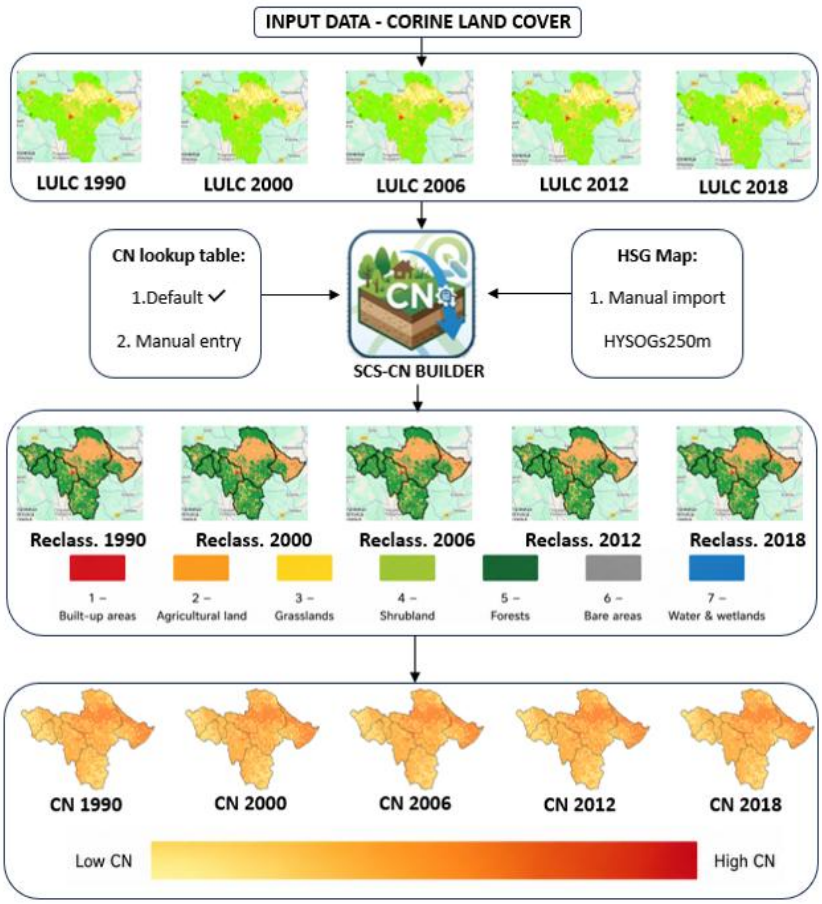


Figure 2. Methodological workflow of the SCS-CN Builder for historical Curve Number mapping in the Toplica River Basin.

The input datasets, CN parameterization procedure, plugin workflow, and subsequent analysis of CN changes are described in the following sections.

2.3. Input data

The spatial input data included CORINE LULC maps for 1990, 2000, 2006, 2012, and 2018, the HYSOGs250m HSG dataset, and vector boundaries of the seven sub-basins

(Table 1). The year 1990 was used as the reference period for assessing subsequent CN changes.

HYSOGs250m represents soil infiltration characteristics through standard HSG classes A–D and dual classes (A/D, B/D, C/D, and D/D). Since spatial information on artificial drainage was unavailable, dual classes were assigned to HSG D according to their undrained condition. The sub-basins were delineated from the 30 m Copernicus DEM using hydrological stations of the Republic Hydrometeorological Service of Serbia as outlet points, enabling the future use of observed discharge data for model calibration.

LULC and HSG data were provided to the plugin as GeoTIFF rasters and sub-basin boundaries as a polygon vector layer. The current SCS-CN Builder implementation requires raster LULC and HSG inputs.

Table 1. Spatial input datasets used in the analysis

Dataset	**Data type**	**Spatial Resolution**	**Temporal Coverage**	**Source**	**Purpose**
CORINE Land Cover	Raster	100 m	1990, 2000, 2006, 2012 and 2018	[10]	LULC input and automatic reclassification into seven generalized land-cover classes
Global Hydrologic Soil Groups – HYSOGs250m	Raster	250 m	2017	[11]	Representation of hydrologic soil groups A, B, C and D for CN parameterization
Sub-basin boundaries	Vector	/	/	Author-prepared dataset	Spatial delineation of the seven analysed sub-basins and calculation of zonal statistics

2.4. CN parameterization

The original CORINE classes were automatically reclassified by the SCS-CN Builder into seven generalized LULC classes using the same classification scheme for all analysed periods. Their correspondence with the original CORINE classes is presented in Table 2.

CN2 values representing average antecedent moisture conditions (AMC II) were assigned according to the standardized SCS TR-55 lookup tables [13], based on combinations of generalized LULC classes and HSG categories A–D (Table 2).

Table 2. CN lookup table used for CN parameterization

LULC code	Generalized LULC class	Corresponding CORINE classes	SCS TR-55 category	CN_A	CN_B	CN_C	CN_D
1	Built-up areas	111–142	Dense residential / highly developed urban area	77	85	90	92
2	Arable agricultural land	211–223; 241–244	Row crops, straight row, good condition	67	78	85	89
3	Grasslands/pastures/ meadows	231; 321	Pasture/grassland / range, fair condition	49	69	79	84
4	Shrubland/transitional vegetation	322–324	Brush, fair condition	35	56	70	77
5	Forests	311–313	Woods, fair condition	36	60	73	79
6	Bare, sparsely vegetated and unproductive area	331–335	Bare soil / newly graded areas	77	86	91	94
7	Water bodies and wetlands	411–423; 511–523	Open water assumption	98	98	98	98

Since CORINE Land Cover does not provide information on hydrologic condition, representative conditions were adopted from the SCS TR-55 CN tables reproduced in the HEC-HMS Technical Reference Manual [14]. For each raster cell, the corresponding LULC and HSG classes were combined to assign the appropriate CN2 value. These assumptions can be modified when more detailed local information is available.

2.5. SCS-CN Builder

The SCS-CN Builder [8] is a QGIS-based plugin developed to automate and standardize CN mapping by integrating raster alignment, CN assignment, and zonal statistics within a single workflow. Before CN assignment, the 250 m HSG raster was automatically aligned to the 100 m CORINE LULC grid using GDAL Warp/Reproject with nearest-neighbour resampling to preserve the categorical HSG values. The resulting CN2 maps therefore had a spatial resolution of 100 m.

The plugin allows users to define the input datasets, CN lookup values, and output settings, enabling adaptation to different datasets and study areas.

2.6. Analysis of CN changes and runoff response

To quantify the changes in mean CN2 values through time, the percentage difference for each analysed year was calculated relative to the reference year 1990. The calculation was performed separately for each of the seven sub-basins using the following equation:

$$\Delta CN\% = \frac{CN_t - CN_{ref}}{CN_{ref}} \times 100\% \quad (1)$$

where *ΔCN%* represents the percentage change in the mean CN2 value for a given sub-basin, CN_t is the mean CN2 value of that sub-basin for the analysed year *t,* and CN_{ref} is the corresponding mean CN2 value for the reference year 1990. Positive values indicate an increase in mean CN2, while negative values indicate a decrease relative to the reference condition.

To illustrate the hydrological effect of the largest observed CN2 change, direct runoff depth was additionally estimated for S7 using the standard SCS-CN relationship:

$$Q = \frac{(P-I_a)^2}{P-I_a+S}, P > I_a \quad (2)$$

where

$$S = \frac{25400}{CN} - 254, I_a = 0.2S \quad (3)$$

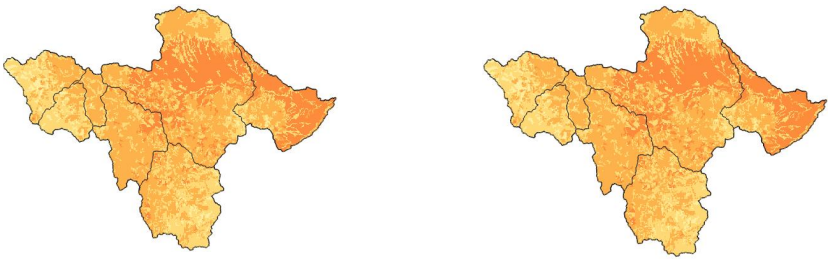
where *Q* is the direct runoff depth (mm), *P* is rainfall depth (mm), *S* is the potential maximum retention (mm), and I_a is the initial abstraction (mm). Runoff depths were calculated for rainfall depths of 50, 75, 100, and 125 mm using the S7 mean CN2 values for 2000 and 2006.

3. RESULTS

3.1. Spatio-temporal distribution of CN values

The spatiotemporal distribution of CN values was analysed for the reference year 1990 and for the subsequent historical periods 2000, 2006, 2012 and 2018. These maps illustrate how the spatial distribution of runoff potential changed over time as a result of observed LULC changes within the Toplica River Basin.

Figure 3 illustrates the spatiotemporal distribution of CN2 values for the selected historical periods. High CN values generally indicate areas with lower infiltration capacity and higher runoff potential, while lower CN values correspond to areas with higher retention and infiltration capacity.



1990 (reference) 2000

Figure 3. Spatio-temporal distribution of CN2 values in the Toplica River Basin for the reference year 1990 and for the subsequent historical periods 2000, 2006, 2012 and 2018

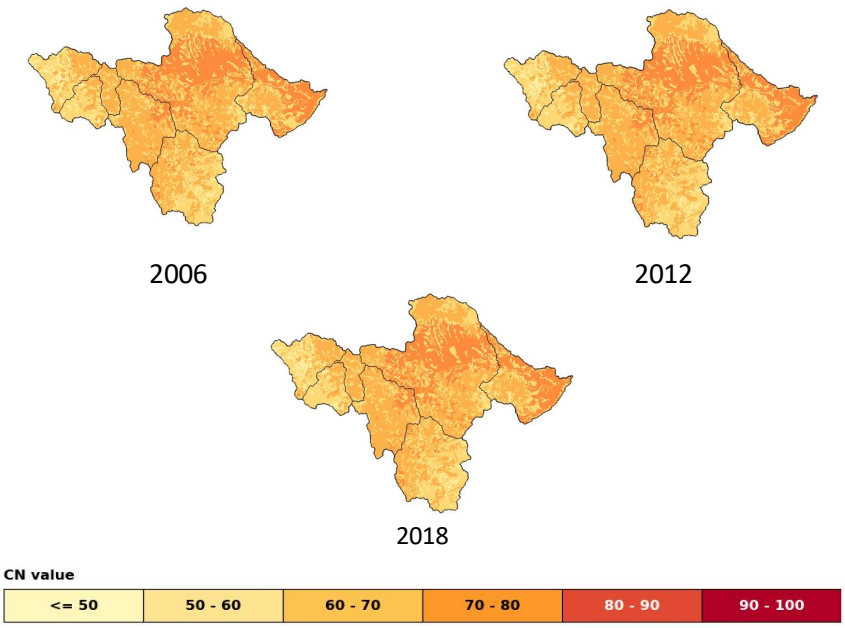


Figure 3. Continued

The spatial CN2 pattern remained relatively stable from 1990 to 2018, with only limited local changes. The highest values were generally observed in the downstream sub-basins S6 and S7**.**

3.2. Mean CN values by sub-basins

Mean CN2 values were calculated for each sub-basin to quantify temporal variations in runoff potential (Table 3).

Table 3. Mean CN2 values by sub-basins for the analysed periods

Basin ID	Area (km^2)	Year				
		1990	2000	2006	2012	2018
S1	173.25	65.87	65.90	65.65	65.30	65.28
S2	113.14	63.91	63.99	64.27	64.48	64.47
S3	63.66	71.33	71.33	71.40	71.41	71.38
S4	262.08	73.54	73.52	73.53	73.53	73.50
S5	371.03	68.13	68.11	67.98	67.93	67.92
S6	801.94	75.99	75.96	75.80	75.71	75.71
S7	272.47	78.28	78.27	76.81	76.87	76.91

Mean CN2 values were highest in S6 and S7 and lowest in S1 and S2. Temporal changes were generally small, with the most pronounced decrease observed in S7, from 78.28 in 1990 to 76.91 in 2018. A comparison of the generalized LULC classes for 2000 and 2006 provides a clear explanation for this decrease.

Within S7, approximately 36.38 km^2 changed from arable agricultural land to shrubland/transitional vegetation, representing the dominant land-cover transition

during this period. Accordingly, the total area classified as arable agricultural land decreased from 178.28 to 137.28 km², while shrubland/transitional vegetation increased from 7.46 to 42.12 km². Since shrubland/transitional vegetation is assigned lower CN2 values than arable agricultural land in the adopted parameterization, this transition provides a plausible explanation for the observed decrease in mean CN2 in S7.

4. DISCUSSION

Historical LULC changes produced limited but spatially non-uniform variations in mean CN2 values. The largest decrease occurred in S7 between 2000 and 2006, from 78.27 to 76.81 (−1.46 CN units; −1.87%), coinciding with the dominant transition from arable agricultural land to shrubland/transitional vegetation, which has lower assigned CN2 values. This indicates that CN2 changes depend not only on the extent of LULC change but also on the type of land-cover transition. Although CN2 slightly increased in S7 after 2006, its 2018 value remained approximately 1.75% below the reference value. Changes in the remaining sub-basins were generally small, demonstrating that basin-wide averages may conceal more pronounced local variations.

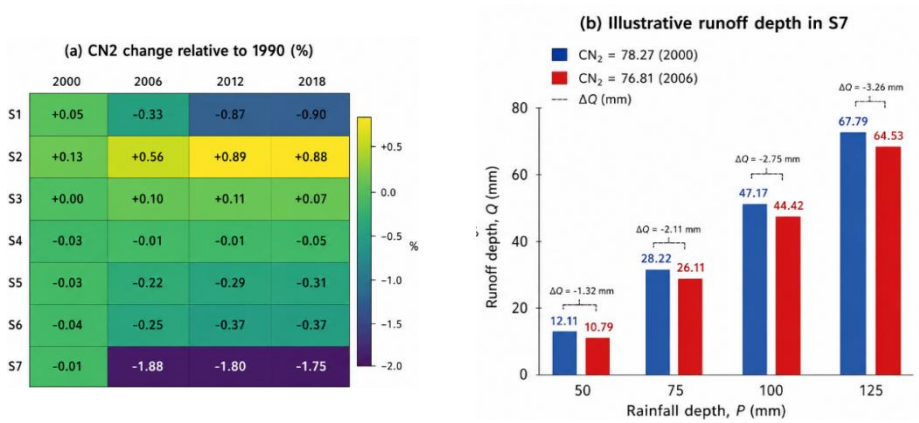


Figure 4. Historical changes in mean CN2 values and their hydrological implications: (a) percentage changes by sub-basin relative to 1990; (b) illustrative runoff-depth response in S7 for the observed CN2 change between 2000 and 2006.

The hydrological significance of the S7 change was further illustrated through runoff-depth calculations (Figure 4b). For hypothetical rainfall depths of 50, 75, 100, and 125 mm, the 1.46-unit decrease in CN2 reduced estimated runoff by approximately 1.32, 2.11, 2.75, and 3.26 mm, respectively. Thus, even relatively small changes in CN2 may produce measurable differences in event runoff. However, these calculations represent sensitivity to the observed CN2 change and should not be interpreted as direct estimates of changes in flood magnitude.

The relatively small CN2 variations should also be considered in relation to the spatial characteristics of the input data. Although CORINE LULC was processed at 100 m raster resolution, CLC status layers have a minimum mapping unit of 25 ha, meaning that small or fragmented land-cover changes may not be fully represented. Consequently, CN2 variations approaching approximately one CN unit should be interpreted cautiously.

Overall, the results suggest that historical LULC changes between 1990 and 2018 did not substantially alter basin-wide runoff potential within the SCS-CN framework. Nevertheless, this relative stability does not imply unchanged flood risk, which also depends on rainfall characteristics, antecedent moisture conditions, and other hydrological factors not analysed here. The observed differences among sub-basins support local-scale monitoring of future LULC changes. In addition, because the current SCS-CN Builder assigns CN values based on LULC and HSG combinations without explicitly accounting for terrain slope, optional slope-adjustment procedures represent a potential direction for further plugin development [15,16].

5. CONCLUSION

This study applied the author-developed SCS-CN Builder plugin to analyse historical changes in spatially distributed CN2 values in the Toplica River Basin from 1990 to 2018. The plugin enabled a transparent, semi-automated, and reproducible workflow while retaining user control over the input data, CN lookup values, and output settings.

The results of this study indicate the following:

1. The Toplica River Basin did not experience substantial changes in mean CN2 values during the period from 1990 to 2018.
2. The observed changes in CN2 values were not uniformly distributed across the basin, indicating spatially differentiated effects at the sub-basin level.
3. Relative to the reference year 1990, the percentage changes in mean CN2 values ranged from −1.88% to +0.89%.
4. The most pronounced change occurred in S7, where CN2 decreased sharply between 2000 and 2006 and remained below the 1990 value in 2018.
5. The illustrative runoff analysis showed that the observed 1.46-unit CN2 decrease can produce measurable differences in event runoff depth, although these should not be interpreted as direct changes in flood magnitude.
6. Basin-wide averages may conceal more distinct local variations, confirming the importance of sub-basin-scale analysis.

From a water-management perspective, the relative stability of CN2 suggests that historical LULC changes were not a major driver of changes in basin-wide runoff potential during the analysed period, while the observed sub-basin differences emphasize the importance of local-scale monitoring.

Future development of the SCS-CN Builder may include optional slope-adjustment procedures to account for terrain effects in steep basin areas. Future research will focus on applying projected LULC scenarios to assess potential changes in CN values and runoff potential in the Toplica River Basin.

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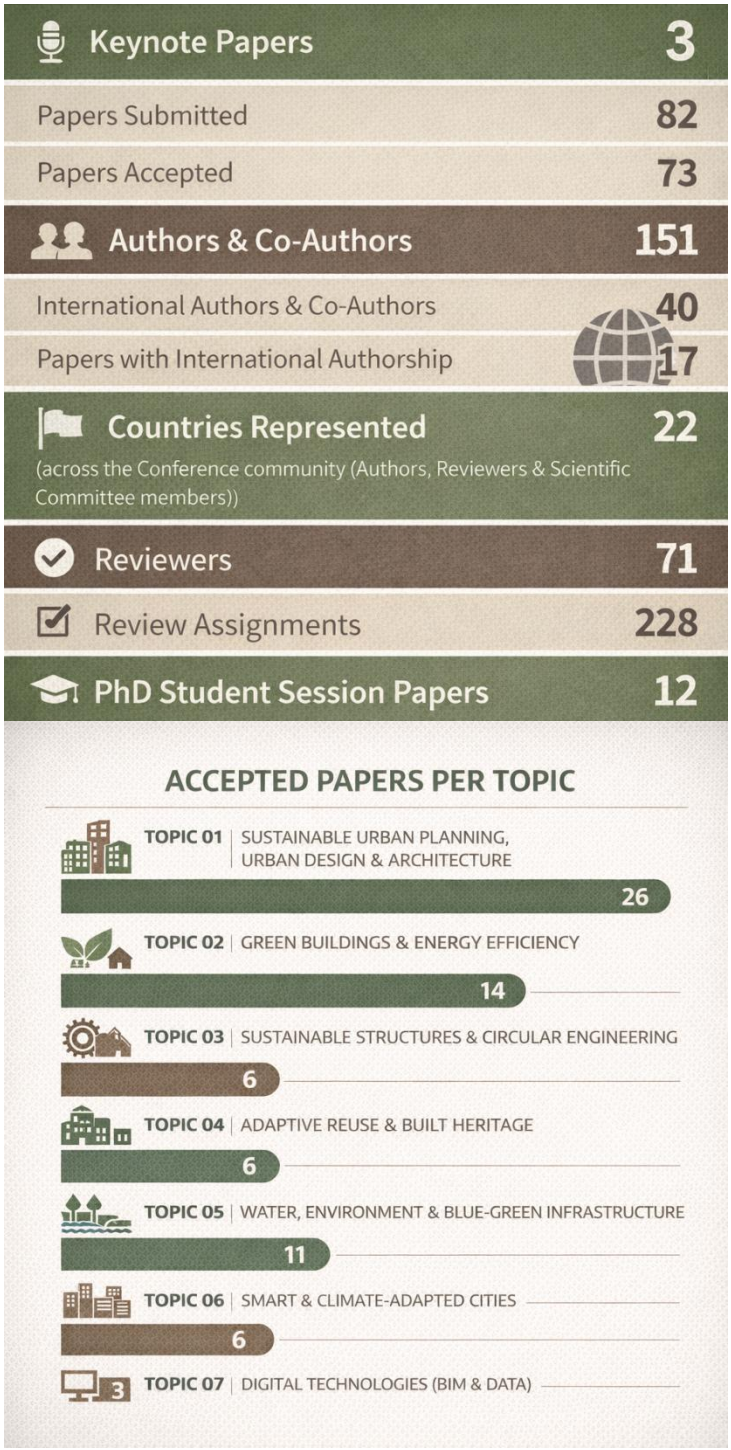
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