University of Niš
FACULTY OF CIVIL ENGINEERING & ARCHITECTURE

Serbian Academy of Sciences and Arts
Local Branch in Niš

SCIENCE TECHNOLOGY PARK NIS

sinarg 2025

International Conference

Synergy of Architecture & Civil Engineering

PROCEEDINGS

VOLUME 3

September 11 – 12, 2025

Science and Technology Park Niš, Serbia

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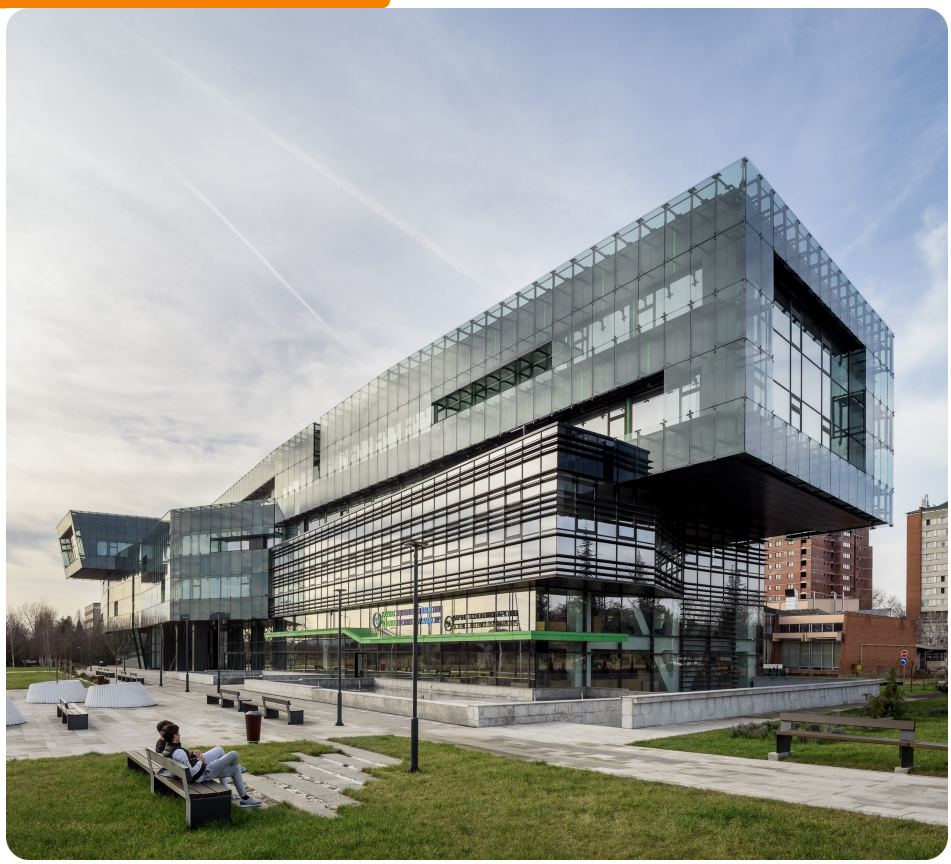
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PREFACE

The SINARG 2025 conference reaffirms its mission to foster a productive synergy between scientific research and practical application in architecture and civil engineering. At a time when the construction industry faces urgent challenges, ranging from sustainability and energy efficiency to resilience and digital transformation, SINARG provides a unique platform where theoretical inquiry directly informs practice. By creating a space for researchers, professionals, and practitioners to engage, the conference ensures that innovation does not remain confined to academic discourse, but instead contributes to tangible advancements in the built environment.

This year has marked an important milestone for SINARG. A total of 230 abstracts were submitted, demonstrating the conference's ability to attract a wide range of research interests and ideas. After a careful and rigorous review process, over 140 full papers have been accepted for publication in these proceedings. The international dimension of SINARG continues to grow. Authors from 15 countries contributed to this year's proceedings, highlighting the diversity and inclusiveness of the conference community. Equally significant is the work of the reviewers, who came from 30 countries and whose expertise and critical evaluation have ensured the scientific rigour and quality of the published contributions. This increasing global engagement confirms the international recognition of SINARG and gives us confidence that future editions will attract even broader participation from around the world.

The success of the conference depends, above all, on its authors. Their research represents the foundation upon which SINARG is built, and without their dedication and willingness to share knowledge, this gathering would not be possible. We extend our deepest gratitude to each contributor for advancing the dialogue on architecture and civil engineering, and for ensuring that SINARG remains a space of intellectual exchange and professional relevance.

We also acknowledge with sincere appreciation the support of our sponsors, whose commitment has made it possible to organize a conference without participation or publishing fees. Their investment in the advancement of science, education, and professional collaboration demonstrates the essential role of industry in fostering innovation. By supporting SINARG, our sponsors have strengthened the link between academic research and real-world practice. *Looking ahead, the Organizing and Scientific Committees are already preparing the ground for the next edition of SINARG. Building on the experience of 2025, the aim will be to expand international participation even further, strengthen cross-disciplinary collaboration, and continue positioning the conference as a key meeting point for both researchers and practitioners.*

The Editors sincerely thank all who have contributed to the preparation of SINARG 2025, authors, reviewers, sponsors, and organizers, for their indispensable roles in shaping the success of this conference. Together, we have created not only a collection of scientific papers but also a community dedicated to advancing knowledge and applying it in practice for the benefit of society.

Niš, September 2025

Editors

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Research paper

THE IMPORTANCE OF GREEN SPACES IN MODERN RESIDENTIAL DEVELOPMENT: ANALYSIS OF GREENERY IN MULTI-FAMILY HOUSING AREAS IN NIŠ

Anđela Stevčić[1], Vukašin Stefanović[2]

Abstract

Focusing on their existence and purpose in multi-family housing complexes, this study analyzes the significance of green spaces in urban environments, using the city of Niš as a critical case. Niš has experienced a continuous decline in green areas due to rapid urbanization and weak planning enforcement, which has negatively impacted residents. The lack of greenery causes numerous problems, including the urban heat island effect, poor air quality, and reduced community recreation spaces. It also addresses the challenges of implementing and maintaining greenery, emphasizing how investors frequently prioritize short-term financial gains over long-term environmental and social benefits. The methodology involves a review of relevant literature, an examination of successful international practices, an analysis of urban planning documents related to Niš, field observation, and an assessment of public institutions. This approach helps identify key factors shaping the presence and quality of green spaces in residential zones. It examines how urbanization in Niš, favoring building density over greenery, has resulted in insufficient integration of green infrastructure in new residential developments. Based on examples from abroad, such as Denmark's Green Mapping and the Netherlands' Operation Steenbreek, the paper proposes strategies for increasing and preserving green spaces in urban neighborhoods. These international models offer adaptable principles with potential for application in the context of urban planning in Niš. Finally, a comparative analysis of planning standards, supported by a mathematical evaluation of green space requirements and reflections on policy implications for Niš, reinforces the conclusion that policy interventions, stricter regulation, and community engagement are urgently needed. The findings underscore the importance of long-term environmental strategies, community involvement, and effective urban design to preserve and enhance green areas in residential zones, particularly in response to ongoing environmental degradation and worsening air quality in Niš.

Key words: *green spaces, multi-family housing, modern residential development, Urban planning, city of Niš, sustainable urban development*

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1. INTRODUCTION

With more than half of the world's population now living in cities, urbanization is recognized as one of the main themes of the twenty-first century, resulting in increased urban growth, environmental pressures, and a growing demand for sustainable solutions [1]. Due to population growth and ecological degradation, environmental concerns must be a priority in urban planning. Schumacher highlighted the risk of consuming environmental capital at a rate that exceeds nature's capacity to regenerate, thus threatening essential life support systems (E.F.Schumacher). In this sense, a city's environmental impact is greatly influenced by the way it is designed and function. Energy use in construction, transportation, and infrastructure contributes directly to environmental strain. Therefore, integrating sustainable practices into urban design is not optional but essential. As urban environments become increasingly dense and complex, the role of green spaces has expanded far beyond their traditional association with aesthetics and recreation. Multifunctional green networks in cities serve essential roles by offering leisure, visual appeal, and ecological benefits such as biodiversity support, stormwater management, and improved air and water quality. They also promote social cohesion, provide space for outdoor learning and local transport, and enhance property values and urban resilience. [2]. In response to these challenges, the integration of green spaces, trees, and environmentally conscious design within urban landscapes has gained increasing attention as a comprehensive strategy to enhance the sustainability of cities.

In the context of the city of Niš, the existing distribution and availability of green spaces expose several challenges. Protective greenery and forested land make up the majority of the total green area, indicating a small percentage of parks and public recreation areas. Moreover, the spatial distribution of green areas across the municipalities within Niš is markedly uneven, leading to disparities in access to urban nature among residents. The planning and construction of new multi-family housing units often neglect the integration of adequate green infrastructure, which undermines both environmental and social sustainability in rapidly urbanizing neighborhoods. In the sections that follow, a number of spatial analyses and chosen case studies will be used to further examine this situation, which is far from satisfactory.

This paper focuses on the present state and spatial distribution of green areas in the city of Niš, with particular emphasis on the availability and quality of greenery within newly developed multi-family residential blocks. The research investigates how green spaces are addressed in local urban planning documents, identifying both the regulatory requirements for minimum green coverage and the extent to which these provisions are implemented in practice. Additionally, selected examples of best practices from European cities are examined in order to highlight the environmental, social, and functional benefits of well-designed and systematically integrated green infrastructure. The methodology combines a review of relevant literature on the importance of urban green spaces with an analysis of spatial planning documents, as well as a comparative assessment of existing conditions in Niš. Through this comparative analysis, the study explores the potential for adapting and implementing foreign planning principles in the local context, taking into account the city's unique spatial, regulatory, and socio-economic limitations.The main aim of this research is to identify strategic solutions for improving the existing state of urban greenery in Niš. By evaluating the present situation and drawing insights from international examples, the paper seeks to support more sustainable and inclusive urban development, while also emphasizing

the ecological risks associated with continued neglect of green space planning in residential environments.

2. SIGNIFICANCE OF URBAN GREEN SPACES FOR RESIDENTS AND THEIR IMPACT ON THE ENVIRONMENT

The process of urbanization has significantly transformed the cityscape, leading to a reduction in green areas, an expansion of impervious surfaces, and alterations in urban microclimates [3]. In response to the growing demands of sustainable development, particularly within urban planning and the Architecture, Engineering, and Construction (AEC) sector, increasing emphasis is being placed on strategies such as the net-zero carbon approach and the Circular Economy model, both of which highlight the importance of urban green spaces in shaping resilient and sustainable cities [4].

Promoting awareness of the ecological, aesthetic, and economic values of green spaces supports the broader implementation of this concept in urban planning practices. The World Health Organization (WHO) recognizes the availability of green space as a public health indicator for sustainable cities and recommends a minimum of 9 square meters of green area per capita within a 15-minute walking radius [5].

In the following sections, the multifaceted significance of urban green spaces will be explored through their diverse roles within the urban environment:

- **Air quality**: Because of their role as natural air filters, trees and other vegetation in urban green spaces greatly improve air quality. By absorbing harmful pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and carbon dioxide (CO_2), and by releasing oxygen into the atmosphere, they help mitigate the adverse effects of urban air pollution. In addition, plants absorb toxic gases released from motor vehicle exhausts and industrial emissions, including sulphur dioxide (SO_2) and nitrogen oxides (NO_x), which are major contributors to urban smog and respiratory illnesses. In cities, pollution can take many different forms, such as solid particles, liquid droplets, and gases, and it is frequently accompanied by loud noises. The ability of urban greenery to reduce these pollutants, and even noise to some extent, is particularly relevant in densely populated environments where exposure to such conditions poses significant risks to human health, especially among vulnerable groups such as children and the elderly [6] [7].
- **Biodiversity**: Urban development rarely accounts for the ecosystems it replaces, often disrupting or even destroying them entirely. In this context, even in multi-family residential settings, urban green spaces are essential for preserving and improving biodiversity. These areas offer habitats for various plant and insect species, as well as for birds that have adapted to urban conditions. Green spaces support vital ecosystem services like pollination, water filtration, and soil stabilization by promoting urban biodiversity, and act as ecological corridors that enable species movement between fragmented areas, maintaining genetic exchange crucial for long-term resilience. However, integrating well-designed and connected green infrastructure, such as courtyards, greenways, and small-scale community gardens, can help counteract these effects and also serve as buffers between urban and natural systems. A functional green network, particularly one

composed of locally adapted and low-maintenance plant species, is key to enhancing ecological stability [8].

- **Urban heat islands**: The urban heat island effect, which occurs when cities have higher temperatures than neighboring rural areas because of the concentration of heat-absorbing materials and sparse vegetation, can be minimized partly by urban green space. Vegetation contributes to cooling through several complementary processes, including evapotranspiration, reflection of solar radiation, and shading. Through evapotranspiration, plants release water vapor into the atmosphere, using solar energy to convert water into vapor instead of heating the surrounding air, which helps lower ambient temperatures. Trees provide shade that limits solar penetration, reducing both the accumulation of heat on urban surfaces and the indoor heat gain in buildings, thereby decreasing the demand for artificial cooling and lowering energy use and waste heat emissions. In densely built areas, such as compact residential blocks in central urban zones, where sealed surfaces dominate and passive cooling is limited, these natural cooling mechanisms are especially valuable. By integrating greenery into such environments, cities not only alleviate heat stress and improve thermal comfort, but also contribute to strengthening overall ecological resilience [8] [9] [10].
- **Health benefits**: Urban greenery supports human health by encouraging physical activity, reducing the risk of cardiovascular disease, and contributing to lower stress and anxiety levels. Studies have shown a positive link between access to high-quality green spaces and increased physical activity, which directly supports heart health and lowers obesity risk. In particular, older adults can benefit from small-scale maintenance tasks or shared gardening in multi-family housing complexes, which not only improve mobility, strengthen muscles, and cardiovascular health but also foster social interaction and a sense of purpose. Mental health improves in green environments, where time in nature reduces stress and anxiety symptoms. Green spaces provide a peaceful and healing atmosphere that helps neutralize the stresses of noise, crowding, and rapid city life, even in densely populated urban neighborhoods. Although the relationship between urban greenery and allergies remains inconclusive, findings consistently support the idea that more intense and meaningful contact with natural spaces contributes to improved physical and psychological health [7] [11].
- **Social Interaction and mental well-being**: It has long been recognized that contact with nature has restorative effects, and numerous studies document the mental health benefits of green spaces. This reaction is often explained by the biophilia hypothesis, which suggests a natural human tendency to connect with nature. It causes a parasympathetic nervous system reaction that promotes relaxation. For example, a study in the United Kingdom using wearable electroencephalography (EEG) devices demonstrated how a short walk in a green space positively influenced brain activity associated with relaxation and restoration. Social interactions are important for mental health. A recent study in the Netherlands found a strong connection between the quantity and quality of greenery and perceived social cohesion, characterized by trust, shared norms, and a sense of belonging. The concept of "sense of place" and "place identity," shaped by both social and natural environments, further highlights the importance

of green spaces in fostering community ties. However, it's important to recognize that green spaces will only promote positive social and mental outcomes if they are perceived as safe and inviting, as proper management and maintenance are essential to ensure they remain conducive to social interactions. Residents in greener areas report less stress, stronger social ties, and greater well-being [6] [11].

- **Economic and Aesthetic Benefits**: Residential developments that incorporate well-designed greenery are significantly more attractive to potential buyers and investors. Aesthetic landscaping enhances the visual appeal of urban areas, increases property value, and contributes to a more pleasant and comfortable living environment. In addition to visual benefits, strategically placed vegetation can also reduce energy costs, making green design both desirable and economically efficient [8] [12].

Well planned and maintained green spaces enhance residential appeal, reduce environmental stress, and support social well-being and economic value. As cities face increasing challenges such as pollution and urban congestion, particularly in Niš, greater focus must be placed on integrating, managing, and monitoring greenery as a key component of urban development.

3. ANALYSIS OF GREEN SPACE PRESENCE IN MULTI-FAMILY HOUSING ZONES IN NIŠ

The actual condition on the ground frequently diverges from the planned project documentation, and the maintenance of existing green areas remains at an unsatisfactory level. As housing demand in the city center continues to rise, single-family homes are increasingly being replaced by small-scale multi-family buildings. These developments are typically carried out independently by individual investors, without coordination or the possibility for integrated planning of larger green areas. The transformation of single-family house plots into new residential buildings often occurs without adequate adaptation of supporting infrastructure or traffic systems. Even in cases where urban plans anticipate green spaces, the resulting open areas are minimal due to the limitations of small plots and the high cost of developing larger residential complexes. As a result, most private investors opt for smaller multi-family buildings that can fit within existing parcels. Furthermore, instead of restoring or enhancing existing green areas, infill construction [13] is increasingly occurring within previously planned residential blocks dating back to the socialist era, which were originally designed with generous green and open spaces.

This trend significantly reduces the amount of available greenery in areas that were once characterized by well-integrated communal outdoor environments. As a consequence, internal block greenery is often converted into construction land, leaving each resident with only 1.2 m² of green space, far below the defined urban planning standards of 20 to 40 m² per capita for urban areas and 9 to 13 m² per capita in residential zones [14].

3.1. Review of green space regulations in general urban plans of Niš

An analysis of general urban plans reveals that greenery within multi-family housing blocks is typically addressed only through the prescription of a minimum green surface

percentage per building plot. In the municipality of Medijana, the section titled *Building Rules* originally stipulates that at least 10% of a plot must be covered by green areas. However, the third amendments to the regulation introduce a more detailed approach, requiring that a minimum of 25% of the plot be designated as green space, of which 10% must be in direct contact with the ground.

The term green space is broadened to include several categories: one tree counts as 5.0 m² of green area; 50% of vegetated roof surfaces, green facades, and greenery above underground levels are included; while ground-level greenery is counted in full.

A similar revision was adopted in later amendments to the general plan for the municipality of Palilula, where the initially prescribed 10% green coverage was increased to 25%, following the same calculation principles as in Medijana. Across various plan phases in other municipalities, different thresholds are defined. For example, phase 3 of both Palilula and Crveni Krst requires 15% green coverage, while phases 1 and 2 of Crveni Krst demand 10%. In Palilula phase 2, the required percentage depends on the density: 10% for high-density and 15% for medium-density areas. In Pantelej, phase 1 prescribes 20% for high-density and 10% for medium-density zones, while phase 2 uniformly requires 15%.

These phases correspond to the proximity to the city center—phase 1 covers central urban areas, while phase 3 refers to peripheral or suburban zones, which reflects a spatial differentiation in green space planning priorities [15].

Notably, none of the examined plans provide clear mechanisms for the qualitative evaluation or long-term maintenance of green infrastructure, which may limit their effectiveness in achieving sustainable urban development goals.

3.2. Comparative analysis of older and new housing blocks in the municipalities of Medijana and Pantelej

The Monitoring Unit of the City of Niš conducted a comparative analysis of green space presence in both older and newly developed housing blocks within the municipalities of Pantelej and Medijana, aiming to identify shifts in the treatment of greenery over time.

In the case of Pantelej, 190 parcels representing older blocks were surveyed. These parcels collectively covered an area of 141,878 square meters, of which 78,079.88 square meters or 55.03 percent was recorded as green space. With 3,938 residential units in total and an estimated average household size of three persons, the total population was approximated at 11,814. This results in 6.61 square meters of green space per resident, falling short of the recommended 9 square meters per capita standard for residential areas. By contrast, the situation in newer blocks proved to be even more unfavorable, with only 9.33 percent of the total area allocated to green space. A total of 58 parcels, occupying 155,649 square meters, were analyzed, of which only 14,530.23 square meters was designated as green space. Using the same population estimation methodology, the calculated population was 12,705, resulting in just 1.14 square meters of green space per resident. An additional notable finding is the dramatic increase in the number of parking spaces, with 1,001 in older blocks compared to 2,437 in newer ones. Given that the total surface area of the old and new blocks is relatively similar, the data suggests a substantial portion of land has been allocated for parking, which appears to be a more economically attractive option for developers than green space, as parking units can be sold for profit.

In Medijana, 267 parcels forming older housing blocks were surveyed. These encompassed a total area of 848,725 square meters, with green space accounting for

291,242.20 square meters or 38.62 percent of the total. The estimated population for this area was 80,375, leading to a green space provision of 3.62 square meters per resident. Again, newer developments exhibit a marked decline in green area allocation. Analyzed data from 253 newer parcels covering 190,155 square meters shows that only 7,575.43 square meters or 3.98 percent consists of green space. Based on a projected population of 22,149, this results in a critically low ratio of just 0.34 square meters of green space per resident [16].

3.3. Review of residential buildings constructed in Niš in 2023 with emphasis on green space provision

The Republic Urban Planning Inspectorate carried out a field inspection in three cities in southern Serbia, one of which was the city of Niš. The inspection included all residential buildings designed for long-term occupancy, classified under categories B and V, that received occupancy permits in 2023. A total of 24 buildings were examined to determine the most frequent deviations from the established construction and site development regulations. These buildings are located in the municipalities of Medijana, Palilula, and Pantelej.

The built conditions were assessed in relation to regulatory standards concerning green space provision, parking availability, accessibility, intended function, and architectural appearance, as defined in the respective technical documentation. This study focuses particularly on identifying discrepancies between the planned and the realized conditions. The evaluation was based on site visits and visual observation. Among the parameters analyzed, the greatest deviations were noted in the area of green space provision, suggesting a widespread failure to meet the planned landscaping requirements.



Figure 2. Overview of Green Space Presence at 6 Residential Building Sites in Niš, source: Republic Urban Planning Inspectorate and author

As illustrated in the figures, the majority of observed sites are dominated by paved and concreted surfaces, while green areas are either minimal in size or entirely absent. In many cases, greenery is limited to narrow strips along the parcel boundaries, seemingly included only to formally meet planning requirements rather than to serve any meaningful purpose for residents. Such greenery is often perceived as highly unfunctional and contributes little to the overall quality of the space.

Moreover, even where green areas do exist, they are frequently neglected and poorly maintained, which further diminishes their potential environmental and social benefits. Unfortunately, only three examples were identified in which greenery was both properly designed and implemented in accordance with the approved plans, thereby demonstrating that well-planned and functional green space is achievable within contemporary residential development. However, in one of these rare cases, the greenery was fenced off, with restricted access for residents, raising concerns about the inclusiveness and actual usability of such spaces.

This discrepancy between planning documentation and execution suggests not only weak enforcement mechanisms, but also a prevailing prioritization of economic gain over the creation of livable and sustainable urban environments.

Table 1. Green Area Provision per Location: Planned vs. Actual Implementation

Location Number	Total Plot Area (m^2)	BCR (%)	Story Count	Planned Green Area (m^2)[3]	Realized Green Space
Location 1	652	59.4	G+4	65.5	0
Location 2	389	50	G+3	48.34	0
Location 3	783	49	G+6	88	0
Location 4	506	54.43	G+3	54	About 30%
Location 5	4555	42.95	G+6	568.75 (12.48%)	All green spaces were implemented during the first phase, as the remaining phases are still under construction
Location 6	584	60	G+3	65	65
Location 7	415	53.9	G+3	10%	Approximately 2 m^2 was not implemented
Location 8	340	48	G+3	11%	About 50%
Location 9	469	52.8	G+3	46.95	Approximately 5 m^2 was not implemented

The first part of this paper addressed the importance of green spaces and highlighted how, even at the planning stage, the amount of greenery allocated in urban development projects is generally insufficient. However, the field inspection reveals that even these limited green areas, as prescribed by planning documents, are often not implemented on site.

Overall, the situation in newly constructed residential areas is unsatisfactory, with a clear tendency to prioritize short-term financial gain over long-term quality of life for residents. This finding underscores the need for stronger monitoring and enforcement mechanisms to ensure that even minimal planning standards for greenery are actually realized in practice [17].

[3] If greenery in the project is indicated only as a percentage, it is recorded in the table accordingly.

4. PROPOSALS FOR IMPROVING THE EXISTING SITUATION IN THE CITY OF NIŠ

4.1. Integrating green spaces in urban planning: The role of Denmark's green map

In Denmark, the Green Denmark Map (Grønt Danmarkskort) is a key tool for preserving natural spaces and connecting larger ecological areas. It includes layers like the Biodiversity Map, which highlights habitats of endangered species, aiding municipalities in designating protected areas. Local authorities are responsible for incorporating these areas into planning, aligning with regional, national, and international goals.

The Green Map not only maps existing green spaces but also identifies potential areas for urbanization and ecological protection. This enables local authorities to integrate green corridors into urban development, enhancing sustainability and quality of life. While the Planning Act provides a framework, local governments make specific decisions on green space planning.

The system is vital for residential blocks, encouraging the integration of nature into urban life. Although the Planning Act does not directly address green spaces within residential blocks, the Green Map promotes their inclusion in new developments and revitalization projects. Projects like Aalborg's “good yards” illustrate how green solutions, such as rain gardens and green roofs, create multifunctional spaces that address environmental challenges and provide public recreational areas [18].

4.2. Greening paved residential areas: Education, participation, and social equity in operation Steenbreek in the Netherlands

In urban areas of the Netherlands, approximately 60% of private gardens are paved, contributing to biodiversity loss, poor water retention, and increased heat stress. Operation Steenbreek, established in 2015, aims to reverse this trend by encouraging citizens to replace pavement with vegetation. The initiative highlights the importance of education in promoting behavioral change and environmental awareness, particularly in residential settings where collective action can lead to visible improvements. Steenbreek functions as a national platform, bringing together municipalities, environmental NGOs, the Dutch state forest agency (Staatsbosbeheer), water boards, and provinces. While the foundation develops knowledge and communication strategies, municipalities implement local activities and engage directly with residents. Educational outreach is central to Steenbreek’s strategy. During the nationally coordinated Garden Week, municipalities and local partners organize workshops, neighborhood events, and symbolic actions like “tile-for-plant” exchanges. These activities inform citizens and foster social interaction, particularly in multi-family housing complexes.

Socioeconomic disparities influence access to and quality of urban greenery. Wealthier neighborhoods typically benefit from larger, biodiverse gardens, while disadvantaged areas often lack both green infrastructure and opportunities for contact with nature. This inequality particularly affects children, who are most likely to engage with nature in their immediate living environment. Thus, greening efforts in residential blocks contribute not only to ecological sustainability but also to environmental justice and social cohesion.

Operation Steenbreek shows how small garden changes can enhance biodiversity, climate resilience, and well-being. In residential areas, particularly in housing blocks where garden spaces are often limited in area and shared among residents, such interventions can be effectively advanced through a combination of education, municipal leadership, and active citizen participation [19].



Figure 3. Garden transformation: before and after greening, source: [19]

5. DISCUSSION AND CONCLUSION

In urban planning, the allocation of green spaces is essential for maintaining a healthy living environment. This section presents a mathematical model to evaluate whether 10% of a plot dedicated to green space is sufficient per resident in typical residential settings. The model assumes 50% plot coverage and a G+3 building height, reflecting common planning standards and maximizing permitted density, while remaining within the legal framework for open and green space provision.

5.1. Mathematical analysis of green space requirements

Assumptions and Initial Conditions:

Plot size: Let the total plot area be denoted by A (in square meters).

- The building plan occupies 50% of the plot, so the area of the building footprint (Ab) is:

$$\mathrm{Ab} = 0.5\mathrm{A} \tag{1}$$

- Green space allocation (Ag): 10% of the plot is designated for green spaces, so the area of green space is:

$$\mathrm{Ag} = 0.1\mathrm{A} \tag{2}$$

- Building structure: The building has 4 levels (including the ground floor and three additional stories).
- Average living space per resident: The average living space per resident is 20 m².
- Required green space per resident: It is assumed that each resident requires 9 m² of green space.

Mathematical Formulation:

1. Total residential area:

Since the building has 4 levels, the total residential floor area (Ares) is:

$$\mathrm{Ares} = 4 \times \mathrm{Ab} = 2\mathrm{A} \tag{3}$$

2. Number of residents:

The number of residents N is calculated by dividing the total residential area by the average living space per resident:

$$\mathrm{N} = \frac{\mathrm{Ares}}{20} = \frac{2\mathrm{A}}{20} = 0.1\mathrm{A} \quad (4)$$

3. Green space per resident (G):

The green area available per resident is:

$$\mathrm{G} = \frac{\mathrm{Ag}}{\mathrm{N}} = \frac{0.1\mathrm{A}}{0.1\mathrm{A}} = \frac{0.1}{0.1} = 1\mathrm{m}^2 \quad (5)$$

The model shows that allocating 10% of the plot area to green space results in approximately 1 m² of green space per resident (as shown in equation (5)). This amount is significantly lower than the required 9 m² per resident, indicating that 10% green space allocation is insufficient for maintaining a healthy and sustainable living environment.

This analysis clearly demonstrates that, in typical urban development scenarios, the proposed green space allocation does not meet the minimum requirements for residents. This finding highlights the need for increased green space in residential areas to support both environmental and health standards.

5.2. Concluding reflections

An integral part of sustainable residential development is the improvement of urban green spaces. In the face of climate change, rising urban temperatures and declining air quality, greenery in multi-family housing areas contributes to environmental balance, supports biodiversity, and enhances both physical and mental well-being. These spaces absorb carbon dioxide, help regulate temperature, improve air quality, and promote social interaction, ultimately increasing the quality of life in urban settings.

The analysis of residential blocks in Niš reveals a noticeable decline in greenery, especially when comparing older blocks with newer ones. While the older developments tend to have more generous green areas, newer ones often lack adequate planning for vegetation, despite the opportunity to do so. This is especially evident in a decline in ecological benefits and a reduction in tree coverage. Although minimum biologically active areas are formally required, enforcement is inconsistent and often insufficient. Furthermore, the lack of harmonized standards and effective monitoring tools makes it difficult to track the condition and development of urban greenery, while existing strategies often remain unimplemented. Strengthening monitoring and encouraging practical initiatives are key steps forward.

While European cities increasingly adopt integrated strategies to expand and preserve urban greenery, Niš continues to face challenges in both planning and implementation. What is especially concerning is that even in newly developed neighborhoods, where there is potential to plan and allocate green areas more effectively, green spaces are frequently overlooked. Improving this situation requires more than just better urban policies. Educational programs and active community involvement are essential for building a shared sense of responsibility for urban greenery. Citizens need to understand their role in addressing climate change, while decision makers should recognize that investing in green infrastructure is an investment in public health, environmental stability, and long term urban sustainability. If cities are to remain livable for future generations, maintaining and increasing urban greenery is imperative.

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Preliminary report

THE CITY AS AN INVENTION FOR THE FUTURE

Dejan Milivojević[1], Dragana Stamenić[2]

Abstract

At the turn of the century, more precisely in 2005, the World Congress of Architects was held in Istanbul under the theme A Celebration of Cities. A vast number of ideas from around the world, translated into drawings and texts, testifying to the optimistic spirit of architects and urban planners. The presence of Zaha Hadid, renowned for her avant-garde concepts and realizations, contributed to the affirmation of the Congress's idea, which was focused on the urban society of the 21st century. This year marks the 20th anniversary of that event. It is quite difficult to assess where we stand today in relation to the plans and ideas presented back in 2005. It is worth recalling that the Grand Prix was awarded to the project Milano il centro intorno. Milan serves as an example through which we can discuss to what extent urban planning visions have become reality. In this note, we will present the most significant achievements of the new urban centers in Milan: City Life, Porta Nuova, Garibaldi, and Isola. Our goal is to critically examine the these contemporary accomplishments in the fields of planning, urbanism, and architecture. Such an overview allows for a more comprehensive perspective on the crisis of civilization on one hand and the inspirations and utopian visions of architects on the other.

Key words: *UIA 2005, Milano, City Life, Porta Nuova, crisis of urban society*

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1. INTRODUCTION

One of the key issues recognized by urban planners in the second half of the 20th century was the question of the city's identity. In response, new planning strategies emerged that sought to preserve historical heritage, adapt to local contexts, and encourage greater public participation in shaping urban environments. The work of *Rob Krier* played a significant role in this shift, emphasizing the importance of traditional urban morphology and the quality of public space [1]. *Kevin Lynch* focused on exploring how people perceive and interact with cities. Rather than viewing cities as rationally constructed wholes, he proposed understanding them as multilayered urban structures filled with meaning, emotions, and relationships. At the heart of this space is the individual - not as a passive user of pre-defined urban solutions, but as an active participant in shaping their living environment [2].

Theoretical framework established by Henri Lefebvre in his seminal 1970 work, *The Urban Revolution* is particularly important. His call for a reversal of urban planning practices centers on activities oriented "not toward the traditional man, but toward the human being, newly observed and newly created—the man of urban society that is being formed" [3]. He was particularly critical of what he termed *urban implosion*. Lefebvre critiques industrial space as homogeneous, rationally planned, and strictly zoned—where the spatio-temporal structure is uniform. He contrasts this with a *differential space/time*, in which “each place and each moment exist only as part of a whole, through contrasts and oppositions that simultaneously connect them to, and differentiate them from, other places and moments” [3]. According to Lefebvre, urban life cannot be reduced to the city’s functional aspects, such as transportation, infrastructure, and rational urban parameters. Rather, it must encompass the full spectrum of citizens’ needs. Within this context, he underscores the phenomenon of alienation. In articulating his urban vision, Lefebvre distinguishes between places, territories, events, centers, corridors, isotopies, heterotopias, utopias, homogeneity, and difference. These conceptual distinctions highlight the imperative for urban planning and architectural practice to continuously engage with the deeper meanings and lived experiences embedded in space. We must recognize that *the right to the city*[3] stands as one of the most significant contributions of his philosophy.

2. UIA WORLD CONGRESS 2005

The beginning of the 21st century was marked by a sense of optimism and hope for the advancement of humanity. An intensified global effort toward environmental recovery has introduced key concepts tailored to the demands of the new millennium: sustainability, ecology, accessible education, technological progress, poverty eradication, gender equality, and more. In honor of the new millennium—and as an homage to the previous one—avant-garde, high-cost structures began emerging around the world. In London alone, projects such as the *Millennium Footbridge* (Norman Foster), the *Millennium Dome* (Richard Rogers and Mike Davies), and the *Millennium Wheel* (a team of architects) were constructed. The entire planet was imbued with optimism, as collaboration and mutual understanding flourished across borders.

[3] 1968. *Le Droit à la ville*, Paris: Anthropos (2nd ed.); Paris: Ed. du Seuil, Collection "Points"

In this spirit, the UIA World Congress of Architects was held in 2005 in Istanbul. The Congress organizers launched an international competition titled *Celebration of Cities*, initiated by the International Union of Architects (UIA) in June 2003. Confronted with the reality that more than half of the global population lives in urban environments and that poorly regulated urbanization continues, the architectural profession sought to initiate a dialogue between citizens and their social, aesthetic, physical, and economic environments. Once again, the fundamental question was raised: *What is a city?* It was emphasized that many existing cities often fail to communicate effectively and directly with the needs of their inhabitants. The competition was designed to encourage spatial interventions that would address both specific urban environments and universal issues of urban life. The aim was to propose models for improving local lifestyles, with special emphasis on sociological categories such as solidarity; psychological aspects like creativity; ethical values such as multiculturalism and gender equality. It was evident that extravagant and financially demanding solutions were not expected. Rather, the aim was to promote innovative and thoughtful approaches that embraced simplicity, functionality, accessibility, and public interest. Competition participants were informed that their projects could focus on the improvement of historic city centers, large residential complexes, substandard settlements and suburban areas [4].

2.1. Grand Prize for Milan

By decision of the professional jury, the Grand Prize of the international competition was awarded to the project by an Italian team of architects from Milan, titled *Reuniting Milan*. The authors of the project were Maurizio Marzi, Giorgio Morini, Marcello Ganassini, Francesca Scianna and Yewande A. Omotoso. The Milan project focuses on the transformation of the surrounding the Milan ring road–an infrastructural section 20 kilometers long and 40 meters wide, covering a total area of approximately 12,000 hectares. The ring road encircles the historical core and the inner urban area of the city, while simultaneously creating a physical divide that separates Milan into two spatial entities: Milan within and Milan beyond the ring. The authors proposed a concept aimed at re-establishing both spatial and symbolic integration between these two urban segments. They envisioned a wide pedestrian zone located between the dual carriageways, lined with rows of trees and equipped with modular urban furniture. The symbolic reconnection of the two sides—suggesting the reunification of previously separated parts of the city—was articulated through the pavement design, which took the form of a giant zipper. This paved surface was intended for pedestrians, cyclists, and scooter users. The proposal stood out for its simplicity, while also offering the possibility of transforming the ring road into a unique urban belt—not one dominated exclusively by vehicular traffic, as is currently the case [5] (*Figure 1*).

Unfortunately, the award-winning idea of the Milanese architects was never realized. On the other hand, another urban area, visible in the plan as a composition of white volumes encompassing the fairground complex and the *CityLife* zone, was successfully implemented. In close proximity lies another ultra-modern mixed-use urban and architectural complex known as *Porta Nuova, Garibaldi e Isola*—marked with a circle on the map (*Figure 1*). These two urban complexes are of exceptional significance, not only for the urban evolution of Milan and Italy but also within a broader European and global context.

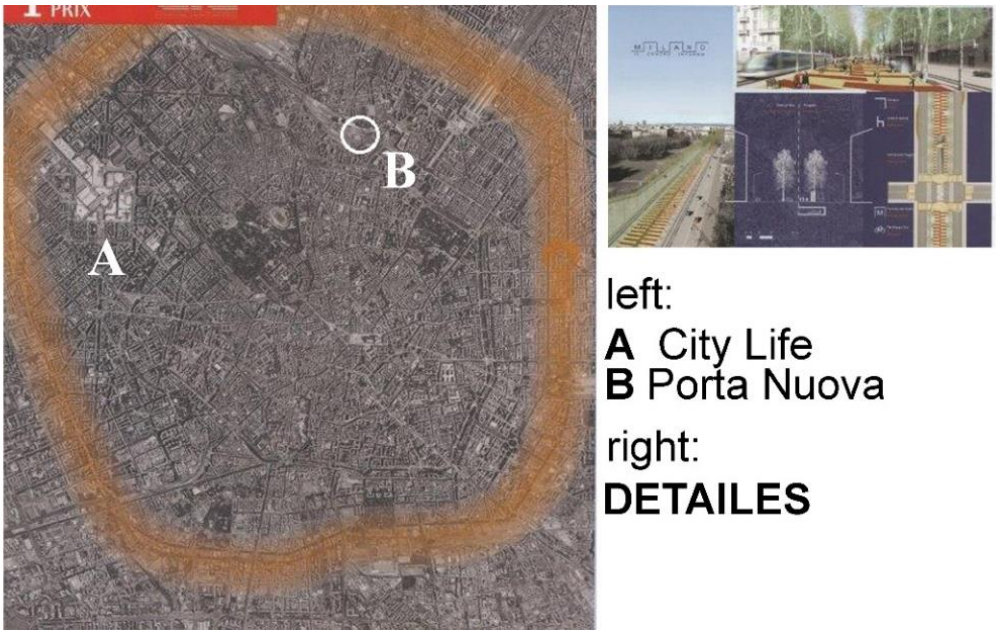


Figure 1. Milano il centro intorno UIA 2005.

3. MILAN AS A STAGE FOR 21ST-CENTURY ARCHITECTURE

Most Italian cities are open-air museums. This abundance of heritage has, in a way, overshadowed the significance of Italian architecture of the 20th and 21st centuries. Italy is rarely perceived as an environment open to extravagant and ultra-modern architectural and urban compositions. However, this perception does not reflect the reality, particularly in recent decades, during which cities such as Rome, Milan, Naples, Turin, and Genoa have become centers of numerous innovative urban-architectural interventions. The distinctiveness of architecture in Italy lies, among other things, in its cultivated respect for context. It seems that, in Italy, extravagant architectural forms within the built environment are almost considered taboo. Contemporary Italy appears somewhat isolated from the ideas of a new, anti-historical and anti-traditional reality. Fabio Severino discusses this phenomenon in his column *Ricominciamo sognare* ("Let Us Begin Dreaming Again"). He criticizes the citizens of Italian cities, stating that they dream little—if they dream at all. He highlights the need for the city to become the bearer of its own vision of development, with its identity and character. Citizens, led by a City mayor and professional teams, should cultivate an atmosphere that encourages visions of a peaceful and cohesive future. He offered particular praise to the then-mayor of Milan, under whose leadership the city became more open, more cheerful, and oriented toward its own renewal, in which the imperative *"I have, therefore I am"* (*Ho quindi sono*) had lost some of its former harshness. Numerous international events hosted in Milan contributed to this new spirit of optimism and progressiveness [6].

3.1. Milan and the Subtle Transformations of Historic Urban Space

Several projects stand out for their value in revitalizing old Milanese buildings through new purposes. One such example is *L'Ansaldo Base*[4], opened in 2016 in Milan as a space for cultural progress, established through the renovation and reconstruction of a building considered as a significant monument of industrial archaeology. A similar concept underlies *Fondazione Elpis*[5], a space intended for exhibitions, interdisciplinary laboratories, installations, and innovative projects. Originally, in the 19th century, the building served as a laundry facility; today, thanks to the vision of Marina Nissim, it has become a meeting point for young artists from different cultures. The center's themes are dedicated to contemporary social challenges, including migrations, climate change and cultural tensions [7].

In addition to cultural venues, social centers designed for broader groups of citizens are also of particular interest. One such example is the project *Cascina Case Nuove – il progetto di riqualificazione per un nuovo hub sociale*[6], initiated by the *Terzo Luogo Foundation* in collaboration with the City of Milan. The project envisions the development of a comprehensive social complex in the San Siro district, on Alessandro Paravia Street. The plan involves the revitalization of dilapidated rural houses and the construction of new pavilions. With an investment of nearly 10 million euros, the goal is to create a gathering place for people of all generations and nationalities, offering programs that encourage creativity and social interaction. The existing area is to be transformed into an open social square, a local hub toward which the surrounding community will naturally gravitate. The center is structured around three functional units: a multimedia library, a creative space for children, and a creative zone for all age groups. The project promotes principles of collaboration, dialogue, and coexistence [8]. These examples illustrate the implementation of ideas promoted by the UIA 2005 Competition, emphasizing inclusivity, cultural diversity, and the reactivation of forgotten spaces through new functions. They confirm the sensitivity of Italian architects to context and the contemporary social need for spaces that encourage dialogue and creativity.

3.2. Milan: New Centers

In 2015, Milan hosted the World exhibition EXPO, under the theme *"Feeding the Planet, Energy for Life."* Organizing such a complex event required comprehensive preparations involving all sectors of the city–from administration to architectural and urban planning. That year also served as a period for evaluating the success of the transformations Milan had undergone in the preceding decades. Many projects initiated in the late 1980s and 1990s were finally completed. Two ambitious and expensive urban complexes, *CityLife* and *Porta Nuova*, whose development began in the early 2000s, were finalized. In the previous period, the city had grown uncontrollably and hypertrophically. Like many other European cities, its expansion was largely driven by economic interests. The rapid growth resulted in localized infrastructural shortcomings and encroachments on agricultural land. Taking all of this into account, architects, urban planners, and the city administration have recognized the Milan area as one holding potential for balanced growth and the implementation of the principles of

[4] https://base.milano.it/en/casabase/
[5] https://fondazioneelpis.org/en
[6] https://www.wrp.polimi.it/cascina-case-nuove/

sustainability. A key imperative for the future is the responsible use of natural resources and energy, as well as respect for the architectural heritage that shapes the inhabited space.

Milan has also faced challenges such as the progressive abandonment of certain parts of the city, urban decay, and the pressures of globalization. Professor Valente accurately pointed out that the city's reconstruction must recognize the paths, routes, and developmental flows that preserve the continuity of the city, while also respecting the logic of a certain spatial homogenization. Architects and urban planners are encouraged to direct their visions toward new perspectives in urban design. In this process, fundamental urban analysis should be place-oriented [9]. When comparing the transformations of two major Italian cities – Turin and Milan – *Simone Cola* observes that both cases involve a deep re-evaluation of developmental directions and methods. In Turin, transformation was strongly influenced by public initiatives, whereas in Milan, it was marked by large private investments that did not solely pursue profit. Milan occupies a unique place in the economic, political, cultural, and social context that is difficult to compare with any similar example within the country. Italian critics often emphasize that while the country has many architects – including highly skilled ones – there remains an unfulfilled potential to adequately valorize the wealth of knowledge rooted in its history and culture [10]. Milan's development has been guided by a series of master plans throughout the 21st century. Since the early 2000s, the city's comprehensive plan has been continuously reviewed and reorganized in a positive manner. The outcomes of these plans are being monitored, and the situation is now almost entirely consolidated. Although the city remains anchored to its institutional and administrative boundaries, it is evident that its developments resonate on both regional and international levels. Since 2013, the international scene has seen the emergence of the *Ri-formare* project—an educational and research initiative that has been well received. Promoted by the *Politecnico di Milano*, specifically the *School of Architecture* and *Società Edilizia Privata*, along with the *Agricultural Department of the City of Milan*, the project involved passionate participation from students and professors [11].

A series of notable projects have been implemented in Milan, undoubtedly supporting the creation of new centers and architecture emblematic of the 21st century. One such example is the *Museo delle Culture di Milano*[7] (David Chipperfield), which repurposes a former industrial warehouse complex located on the edge of the greater central area of Milan. Another prominent project is the new headquarters of the *Fondazione Feltrinelli*[8], designed by the architecture studio Herzog & de Meuron, whose form and landscaping innovatively explore architectural contextualism. The path of Milan's transformation is clearly articulated in the project by Rem Koolhaas / OMA,[9] who designed the new *Fondazione Prada* headquarters, located in a former industrial area near the historic city's core, close to the important territorial axis *Corso Lodi*. Numerous other contemporary interventions exist, both on pre-existing structures and undeveloped sites, such as the new *Bocconi University Campus*[10] (SANAA), which spans 35,000 square meters along the city's ring road [11].

[7] https://davidchipperfield.com/projects/mudec
[8] https://www.herzogdemeuron.com/projects/327-porta-volta-fondazione-feltrinelli/
[9] https://www.oma.com/projects/oma-amo-for-with-prada
[10] https://www.archdaily.com/975778/new-urban-campus-for-bocconi-university-sanaa

3.2.1. Porta Nuova Garibaldi and City Life

We can state that Milan is undergoing a continuous process of transforming formerly neglected urban zones into dynamic, multifunctional spaces, thereby enriching its historical core with new layers of urban identity. The emergence of new mental, formal, functional, and commercial elements reveals multiple "Milans" within the city. This is evident both in architectural form and spatial organization. The role of green areas in Milan's newly developed urban centers notably diverges from that of traditionally conceived parks with geometric layouts.

3.2.1.1. Porta Nuova Garibaldi

The ***Porta Nuova*** project covers 290,000 square meters in the heart of Milan, and is today considered one of the most significant examples of contemporary architecture and urban planning in Italy. Initially conceived as a synthesis between the neighborhoods of Brera, Isola, and Repubblica, this space was designed through the collaboration of renowned architectural firms: Studio Pelli Clarke Pelli Architects, Kohn Pedersen Fox, and Boeri Studio. Through landscape design and architectural expression, these teams succeeded in establishing a strong identity for the area. The space is unified by a network of pedestrian passages leading toward *Piazza Gae Aulenti*, the central aesthetic and organizational element of the composition *(Figure 2*). The piazza is a circular elevated platform featuring three reflecting water surfaces. The square is partially covered with perimeter canopies, offering shade and defining its spatial character. The ground level accommodates various commercial functions, retail spaces, and hospitality venues, while the majority of the more attractive programs are located on the underground floor. The plaza is surrounded by three glass towers of varying heights, arranged in accordance with its circular geometry. The focal point of their composition is the spiral-shaped pinnacle of the tallest tower—*Torre Unicredit*[11]. Adjacent to the complex is a low-rise building that underscores the regulation of the surrounding street, *Via Fratelli Castiglioni*. Continuing along this axis stands the *Unipol Tower*[12], a commercial building of distinctive geometry, completed in 2023. On the plaza, facing *Viale Luigi Sturzo*, two low-rise buildings have been constructed, one of which is the *Uni Credit Pavilion*, designed by Michele De Lucchi studio[13]. The structure, realized in timber construction, is a monovolume of free form. On one side, it comprises a ground floor and three upper levels, while on the opposite side, the height is reduced to a ground floor with a gallery. The form of the pavilion is inspired by the shape of a seed and, according to the architect, "symbolizes the unity of nature and the people who live and work here" [12].

The materialization and design of the pavilion completely diverge from the surrounding architectural context. It is intended for various social and cultural events, such as meetings, conferences, congresses, exhibitions, performances, and seminars. Immediately adjacent to the pavilion is the *East Office Building*[14], designed by architect Mario Cucinella. The building is conceived as two geometrically pure volumes. The one with an elipsoidal plan features a transparent laminated timber grid that acts as a membrane, detached form the building's main mass. The other volume is a solid cube made of exposed concrete. The contrast between the characteristics of the applied materials is dedicated to exploring potential

[11] https://pcparch.com/work/porta-nuova-garibaldi-and-unicredit-headquarters
[12] https://www.mcarchitects.it/progetti/headquarters-gruppo-unipol
[13] https://divisare.com/projects/367152-michele-de-lucchi-tom-vack-unicredit-pavilion
[14] https://www.asingegneria.com/en/collaborazioni/e3-east

syntheses between the natural and the artificial. The interior space is flexible and adaptable, suitable for office or commercial purposes. The transparency of the building emphasizes the connection between exterior and interior, forming a unified spatial environment. The building's position and form carry a strong urban and symbolic value, evoking the notion of a gateway: next to the basement level, a broad staircase leads up to the elevated plateau of *Piazza Gae Aulenti*.

The architecture of the entire complex is heterogeneous—formally, conceptually, and materially. There are pronounced vertical dissonances within the composition, while the horizontal regulation remains rigid and well-defined. The square has placed many of its essential functions underground, thereby largely losing the traditional role of the Italian *piazzetta*, which has been replaced by spectacular architectural gestures and corporate presence. Nevertheless, within the broader urban ensemble—which includes a pleasantly landscaped area extending toward the Isola district—a balanced atmosphere of contemporary Milan emerges. A particular contribution to the space is made by the residential complex *Bosco Verticale*[15], a project by the Boeri Studio, internationally recognized as a paradigm of sustainable architecture. Its balconies host 480 medium-sized trees, 250 small trees, 14,000 ground-covering plants, and 5,000 shrubs. This part of Milan also accommodates the office towers of numerous corporations, collectively generating the impression of capital that relentlessly reshapes the city's identity, transforming it into a metropolis of power, design, and extravagance. Milan boldly promotes new traditions of urban form and urban life—traditions that are, at times, subject to debate.



Situational plan for Porta Nuova and Isola



Skyscraper UniCredit



Piazza Gae Aulenti



Piazza Gae Aulenti under ground

Figure 2. Legend: 1.Piazaa Gae Aulenti; 2. UniCrdit; 3. Edificio di Piuarch 4. Unipol Tower; 5.UniCredit Pavilion; 6.East Office Building; 7.Piazza Alvar Alto; 8.Biblioteca degli Alberi; 9. Bosco Verticale. Photos from Private archive.

[15] https://www.stefanoboeriarchitetti.net/en/project/vertical-forest/

3.2.1.2. City Life

Another radically modern urban area has been realized in Milan: the *City Life* complex. This urban entity was constructed in the vicinity of the former Milan Fairgrounds, which remained active until 2005. The zone now occupied by CityLife, approximately two-thirds of the overall site, is bounded by the city's highways and has a shape close to a square. As one of the most ambitious urban and architectural interventions in Milan, CityLife can be regarded as a competitor to the *Porta Nuova* complex, with which it shares similar aspirations in terms of redefining contemporary urban identity. While Porta Nuova represents a high point in the architecture of the early 21st century, CityLife in certain aspects takes the concept a step further. The projects within this complex were designed by internationally acclaimed and influential architects—Zaha Hadid, Arata Isozaki, Daniel Libeskind and Bjarke Ingels. Their skyscrapers, grouped around *Piazza Tre Torri*, have become iconic symbols of contemporary Milan and a reference point within the global discourse of architectural production.

The complex CityLife is located relatively close to the historic city center and enjoys a more favorable position compared to Porta Nuova. It is open to its surroundings, not confined by dense urban fabric, and is characterized by a spacious, landscaped, and gently sloping green terrain. At its highest point lies *Piazza Tre Torri*, irregular in shape and distinct in character. The buildings that surround the square are arranged freely, without strict geometric alignment, emphasizing the openness of the space. The square transitions seamlessly into *Parco Tre Torri*, ensuring the continuity of the city's green belt. *Piazza Tre Torri* was designed by Oe Works Studio, while *Parco Tre Torri* was designed by Gustafson Porter. The entire area is free of vehicular traffic, which has been redirected to three large underground parking facilities. CityLife spatially and visually connects to the existing traditional Milanese blocks, which are clearly defined and geometrically structured. The main compositional axis extends from *Viale Ezio* toward *Piazza Tre Torri*, forming a broad promenade that leads across the *Fontana delle Quattro Stagioni* to *Piazza Elsa Morante*. To the left of this piazza is the residential complex designed by Daniel Libeskind[16], while to the right stands the housing block by Zaha Hadid[17]. From this perspective, a view opens up to the elevated platform of *Piazza Tre Torri*, which rises approximately seven meters above the surrounding access level The platform is perforated in three locations, allowing natural light and ventilation to reach the lower levels. This layered and carefully articulated spatial sequence reflects the ambition to reinterpret the classical principles of representative urban space through the lens of 21st-century urbanism and architecture (*Figure 3*).

The three aforementioned towers rise above the elevated plaza of the square. These are the *Torre Allianz*[18], designed by Arata Isozaki in collaboration with Andrea Maffei Architects; the *Generali Tower*[19], designed by Zaha Hadid; and *PWC Tower*[20] („Il Curvo"), authored by Daniel Libeskind. These office skyscrapers prominently represent the corporations that financed their construction—an unambiguous display of prestige. All three towers feature glass façades, yet differ significantly in form. *Torre Allianz* is characterized by restrained elegance, reflecting rational functionalism and the precision of Isozaki's approach. The *Generali Tower*, with its spiraling, sculptural form, expresses the dynamism and formal

[16] https://libeskind.com/work/citylife-residences-parcel-ii/
[17] https://www.zaha-hadid.com/architecture/city-life-milano-residential-complex/
[18] https://isozaki.co.jp/archives/projects/allianz_tower/
https://www.google.com/search?q=Andrea+Maffei+Architects+tore+Aliance+Milano
[19] https://www.zaha-hadid.com/architecture/citylife-milano/
[20] https://libeskind.com/work/central-tower-c/

freedom inherent to Zaha Hadid's architecture. Libeskind's tower is formally more complex, distinguished by pronounced curves and diagonals that defy the orthogonal logic of most contemporary office buildings. *Torre Allianz* was the first to be completed and was well received by both the professional community and the general public, being described as follows: *"The presence of the highly prominent Torre Allianz by Arata Isozaki—visible, yet never imposing, subtle and restrained, partially inspired by the Pirelli Tower—has undoubtedly played and will continue to play a leading role in shaping the city's skyline"* [21][11].



Figure 3. Legend: P. Piazza Tre Torri; 1.Tore Allianz; 2.Tore Generali; 3.PwC Tower; 4. Zaha Hadid residential complex; 5. Libeskind residences.- Photos from Private archive.

CityWave, designed by *Bjarke Ingels Group (BIG)*, represents the final phase of Milan's CityLife redevelopment and is set to be completed in 2026. Envisioned as the northeastern gateway to the district, the project consists of two symmetrical posted office buildings connected by a 140-meter-long photovoltaic timber canopy, forming one of the largest urban rooftop solar installations in the world. According to the idea, the approach to the Piazza Tre Torri and the City Life complex is wide open and clear**.** CityWave will be the first office building to achieve a *'beyond zero impact'* standard, powered entirely by renewable energy sources. The system integrates sustainable technologies such as photovoltaic panels, rainwater harvesting, and thermal use of groundwater. These innovations are expected to reduce energy consumption by approximately 45% compared to standard office buildings.[22]

Piazza Tre Torri is organized on two levels. Although the plaza incorporates openings that allow natural light to reach the underground spaces, the atmosphere gives the impression of enclosure and coldness. This feeling is further reinforced by the sparse greenery. The most attractive features are located underground, which is the inverse of a traditional urban setting. The interiors are designed in a uniform style, creating an atmosphere that more closely resembles an airport terminal than an urban public space. There is a lack of intimacy. The residential blocks by Zaha Hadid and Daniel Libeskind are innovative in form. Hadid's design subtly uses soft, curved lines to create a composition where the ensemble of buildings is perceived as a fleet of ships. This impression is enhanced by the white façade cladding, wooden details, and the geometry of the window openings. The block functions as

[21] Maria Vittoria, **Milano viaggia verso il future** in *Milano Architettura La citta e l' EXPO*, Milano (2015): 24
[22] https://www.dezeen.com/2025/04/11/citywave-big-milan-construction-photos/

a continuous monovolume, with the height gradually increasing from *Piazza Elsa Morante* toward the perimeter of the complex. In contrast, Daniel Libeskind's urban layout for the residential buildings appears more fragmented and spatially dynamic. Instead of a compact whole, his buildings form two separate groupings, with a green space between them. The focal point of his composition is a freestanding tower. The architectural forms are characterized by sharp planes, which seem to have been cut with a scalpel and then rejoined to create complex volumes. The result is a strong visual expression of dynamism and movement, although compared to Hadid's architecture, there is less refinement and subtlety in the form.

4. CONCLUDING REMARKS

As researchers approaching Milan from an external perspective, we are aware of our limitations in fully perceiving all the layers of this city's urban phenomenon. Our understanding is primarily based on available documentation and direct experience with its most representative contemporary urban-architectural interventions. A series of critical questions arises: Has Milan, as a multi-coded and distinctly recognizable, and economically powerful metropolis, succeeded in realizing an urban revolution that opens avenues for reflection on needs, aesthetics, techniques, technologies, art, and 21st-century urban lifestyles (particularly those of *Generation Z*)? Has Milan responded to the vision outlined by the UIA in 2005? Can we trace future-oriented thinking, rooted in 20th-century conceptual frameworks, within the contemporary city? These questions invite both intimate and subjective answers, grounded in personal experience, yet they also demand confrontation with broader urban paradigms—specifically those of the postmodern and global-corporate eras. In this paper, we have examined several significant interventions in the physical and mental fabric of Milan. Within the CityLife and Porta Nuova developments, we observe the convergence of presumed values such as contemporary architectural fashion, engineering excellence, cultural vitality, and professional humanism. There is an undeniable sense of comfort and ease when resting on the gently contoured terrain of CityLife Park, safely removed from vehicular traffic and direct environmental pollution. However, the decision to place some of the most attractive programmatic content underground raises spatial and experiential concerns. Porta Nuova and Piazza Gae Aulenti reflect a similar design logic, though the latter suffers from high building density and a notable lack of green spaces. Nevertheless, the presence of *Biblioteca degli Alberi* and the area's strong pedestrian connectivity with its urban surroundings affirm Piazza Gae Aulenti as a necessary and impactful intervention.

Today, Milan presents itself as a rational and efficient metropolis. The municipality demonstrates strong financial capacity, with significant investments directed toward both profitable and non-profitable construction initiatives. The city administration, alongside its citizens, has clearly expressed a commitment to creating a contemporary urban environment and a readiness to support visionary projects that aim to shape the city's future. It is important to emphasize that art, creativity, innovation, ongoing education, and the creation of spaces for quality leisure time are all fully aligned with the spirit of the 2005 UIA Congress. Milan boasts a modern metro system and a compact urban structure, enabling strong connectivity between key urban nodes. Nonetheless, challenges remain in bridging the divide between central and peripheral parts of the city—an issue clearly reflected in the distribution of public

facilities and metro infrastructure. Although metro lines have been extended since 2005, the *Reuniting Milan* project, developed by award-winning Milanese architects, continues to hold significant symbolic and functional potential, serving as an example of the integration of collective spaces, green areas, and major transportation routes. Finally, we ask the question if the ideas of post-war architects and futurists have left a lasting impact on contemporary understandings of urban transformation. The visions that emerged from concrete spatial challenges and efforts to meaningfully reshape the existing city have materialized in the phisical environment. The postmodern era particularly emphasized the idea of returning to the city, fostering context-driven architectural thinking, reaffirming the significance of traditional squares, and critically reassessing the typology of the urban block. In the case of Milan, the subject of this research, it is evident that postmodern principles remain present and relevant in contemporary transformations within the historical city center. A strong departure from traditional urban forms and the incorporation of futurist traditions can be seen in the shaping of new urban focal points. Yet, contemporary architects have taken a step further. These new urban centers are like a room filled with distorted mirrors. A new reality—or just “one more object”? In either case, they demand renewed intellectual, theoretical, technical, and practical engagement.

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Research paper

DESIGN AND IMPLEMENTATION OF GREEN ROOFS: A CASE STUDY IN NIŠ

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Abstract

Green roof is one of the elements of green infrastructure to compensate for the loss of green areas in urban areas, due to increasingly intensive urbanization and the need to build on existing undeveloped areas. There are different types of green roofs, from extensive to intensive, which differ in the type of vegetation planted on them, access options, functions that can be performed on them, etc. They play an important role in preventing and mitigating the negative impacts of climate change, as well as the occurrence of heat islands in the most populated urban areas. Their implementation was common in the world at the end of the 20th and beginning of the 21st centuries, however, Serbia is only at the beginning of the development of this modern practice. The paper lists the characteristics of green roofs, their types and methods of application. The paper focuses on a case study in the city of Niš, on researching their implementation.

Key words: *Green roof, Extensive green roof, Intensive green roof, Design of green roof, Niš*

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1. INTRODUCTION

We are witnessing the constant various challenges that the world is facing due to climate change and increasing urbanization. According to data, it is predicted that urbanization will reach approximately 83% in 2030 [1]. Also, it is a significant fact that cities occupy only 3% of the Earth's surface, but account for 60-80% of global energy consumption, 75% of global carbon emissions and more than 60% of resource use [2]. Urbanization is recognized to the greatest extent in them - in areas that are the most populated and in which the problem of degradation of natural landscapes, especially open spaces that are used for construction purposes, is recognized [2]. This is automatically reflected in the appearance of urban heat islands. Also, in addition to the fact of excessive energy consumption, the fact that air pollution is at a high level in Serbia is also extremely important. There is a possibility, through an interdisciplinary approach, to respond to the mentioned challenges through new solutions adapted to nature and the space where they are implemented. One of the solutions or answers is the creation of new green areas by introducing various elements of urban green infrastructure (UGI).

Many cities in the world are already striving towards a solution and creating conditions for a better, healthier life by defining plans for creating sustainable cities, eco-cities, precisely by implementing the elements of UGI. It promotes integrated spatial planning by identifying multifunctional zones and incorporating habitat restoration measures and other connectivity elements into various land use plans and policies, such as connecting peri-urban and urban areas. Multifunctionality provides a wide range of environmental, economic and social benefits.

In Serbia, according to the General Regulatory Plan that was valid in the earlier period, it was necessary to maintain or create a minimum of 10% of green areas that are in contact with the ground on the plot. According to the latest version, the percentage of green areas was increased to 25%, of which 10% of the plot area is under green areas in direct contact with the ground [3]. Green areas mean all green areas, including high greenery, green roofs, greenery above underground floors. In this connection, one can see the increasingly frequent appearance of one type of UGI in projects for the construction of new buildings. It is a green roof (GR).

The paper briefly mentions the main characteristics of the GR and presents its main typology. The aim of the work is to research design and implementation of GRs in the city of Niš. Although there are more than 10 examples of GR implementation on top of buildings in the city, the paper selected an analysis of a total of 6 examples of practice, divided into three public buildings and three residential buildings. The main criteria for selection were: year of construction no older than 10 years, location in the city center or wider, an equal number of residential and public buildings and selection of extensive and intensive examples of GRs. The paper, by analyzing a case study of six selected GRs in the city, expects to answer the following questions: 1) Are GRs exclusively planned and implemented on newly constructed buildings or is there a case on old buildings as well?; 2) On which buildings are intensive GRs more often designed, and on which extensive ones?; 3) What is the current state or appearance of the implemented GRs - are they adequately maintained?

2. GREEN ROOF – TERM, STRUCTURE AND CHARACTERISTICS

GR represents one of the effective solutions for the implementation of green spaces when one of the main problems is the lack of free green spaces in the urban core. This is supported by the information that roofs make up almost 20-25% of the total urban area [4], that is, about 32% of the horizontal surface of built-up areas [5]. The application of GR has recognized numerous benefits, most of which relate to the provision of different

categories of ecosystem services, including support services, supply services, regulatory and cultural services (MA, 2005). Therefore, its application advantage is reflected in the positive impacts it has from the ecological, economic and social [6] aspects.

2.1. Structure and typology of green roofs

A GR consists of several components/layers including vegetation (plants), substrate, filter layer, drainage material, waterproofing, root barrier, thermal insulation, vapor barrier and roof structure [7]. Depending on the desired results and financial possibilities, as well as the duration of implementation, the concept and number of components or layers during implementation may vary. However, each component plays an important role in the functioning of GRs and it is not desirable to eliminate it at the same time. The type of each GR component depends primarily on the geographical location where it is implemented [7].

There are two basic types of GRs, depending on the future purpose, type, number and size of greenery, i.e. the thickness of the substrate in the layers of the roof: intensive and extensive GR. Depending on the desired results and financial possibilities, the concept and number of components or layers during implementation may vary, however, each component plays an important role in the functioning of GRs and it is not desirable to cancel it during the same. The type of each GR component depends primarily on the geographical location where it is implemented. The basic division of GRs is into intensive and extensive GR.

- **Extensive green roofs**

Extensive GRs, depending on the roof structure on which they are installed, can be flat or sloping. They are characterized by a thin substrate layer (less than 15 cm), lower costs, light weight and minimal maintenance [7]. Therefore, the advantage of extensive GRs is reflected, among other things, in that they can be installed on almost all roof structures of any building because they have a low specific weight. Also, they do not require an irrigation system. This type of GR supports plant species that have a small root system and can easily withstand high temperatures and drought.

- **Intensive green roofs**

Intensive GRs are almost identical to the natural habitat of plants on the ground, that is, they represent a landscape-architecturally designed garden on the roof of the building [8]. They are characterized by a thick layer of substrate (20-200 cm), a wide selection of plants, a high degree of maintenance and greater weight [7]. A wider selection of plants refers to shrubs and taller plants from 50cm to 4m. The thickness of the substrate layer depends on the desired vegetation that will be planted on the roof. The cost of construction as well as the cost of maintenance is very high compared to other types of GRs. This type of GR requires the most maintenance, constant fertilizing and watering is necessary. For watering, i.e. irrigation, it is recommended to collect rainwater, which is later, after collection, absorbed in the soil. Intensive GRs can contain all the same elements as classic green areas - paths, furniture, lighting, various garden-architectural elements such as pergolas, walls and the like. Judging by the mentioned facts, it can be said that such GRs provide a complete possibility of relaxation, recreation and at the same time socialization in addition to the visual-aesthetic impact on the environment.

2.2. Advantages of applying green roofs

The application of GRs enables regulatory services: 1) rainwater collection and its infiltration - control of the quantity of rainwater runoff [7]; 2) improving the quality of rain runoff; 3) reducing the temperature [9]; 4) mitigation of the heat island effect; 5) reducing

the negative impact of noise [10]; 6) improvement of air quality [11]; 7) improvement of microclimatic conditions, support services: improvement of biodiversity [12], supply services: 9) application of urban agriculture and cultural services 10) recreation and education [13].

In addition to the greening of facades, the greening of roofs is, in the context of structural improvement, the only sustainable measure that also has visual significance. The visual impression itself is directly related to the increase in the market value of the real estate within the facility where it was implemented, which represents a significant value from an economic point of view. The most significant economic benefits at the building level refer to savings in energy consumption to achieve thermal comfort, extended life of the roof structure [2] and the use of GRs for the development of agriculture.

Social benefits are primarily observed with intensive GRs, which, among other things, are designed as passable and accessible to people for various types of activities. Their existence and use affects the improvement of people's physical activities and healthy lifestyle. GRs can be used for the study of flora and fauna, and therefore it can be concluded that it has a role in the mentioned sphere of education. Also, they can be rearranged by introducing adequate furniture in the park areas on the tops of the buildings with the possibility of use throughout the day. Therefore, GR serves to create additional usable area on top of a building.

3. APPLICATION OF THE GREEN ROOF - A CASE STUDY IN NIŠ

The city of Niš, which is the third largest city in Serbia in terms of size and number of inhabitants, was selected for the case study. In the continuation of the work, a total of six residential and public buildings where GRs have been implemented so far are presented.

3.1. Business building, Vizantijski Boulevard

As part of the wider city center, a GR has been installed on top of a public building on Vizantijski Boulevard in Niš (Figure 1). It is a P+3 storey building that is the center of three companies - Dualsoft, UFC Holding and KAPAPROJEKT. The last, third floor, as well as the roof of the building, belongs to the company KAPAPROJEKT.



Figure 1. Marked location and view of the object, Google maps, Author's archive

The facility was built and officially opened in March 2023, when the GR on top was implemented. Considering the location where it was built, from the top there is an impressive view of the surrounding greenery and the river Nišava. In the initial phase of the project, there was no greenery on the roof but, In one of the following phases, it was decided to implement an extensive GR on the top of the building. Of the total roof area of 471.25m^2, 86.38m^2 was selected for green space (Figure 2a). The urbanscape greening system produced by KnaufInsolation was chosen (Figure 2b). Its features are numerous and it is distinguished by its innovation, light weight, simple installation, high water retention capacity, etc. In particular, the choice was a modular roof in cubes, which is recommended for smaller square footage and all elements of which, except for the

anti-root membrane, are delivered in cubes measuring 50x50cm. The layers of the selected GR consist of: 1) basic roof structure; 2) waterproofing; 3) urbanscape anti-root membrane; 4) urbanscape drainage system; 5) urbanscape green roll substrate and 6) urbanscape cover with sedum mix (Figure 2c).

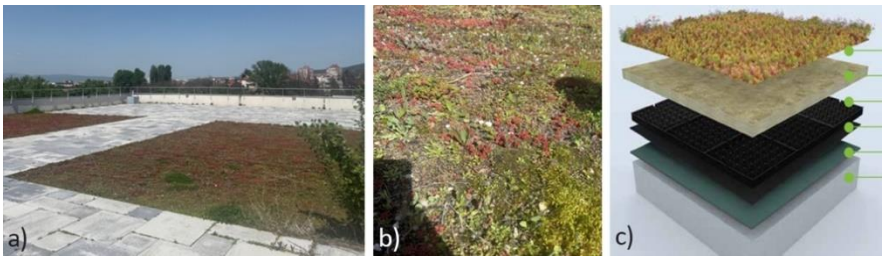


Figure 2. (a), (b) Current appearance of the GR (April 2025), (c) KnaufInsolation system - view of the roof layers, (a), (b) Author's archive, (c) https://knauf.com/sr-RS/

The original idea was to place planters on the roof with planted thuja trees that will be irrigated with a drip system. However, it was not an ideal solution. Most of the thuja trees dried up, and the rest were transplanted in the garden that belongs to the parterre landscaping around the building (Figure 3a). Also, the greenery on the roof is not maintained in the best way, it has also sprouted along the perimeter of the roof, along the linear gutter that extends to the other end of the roof (Figure 3b) and among the succulents (Figure 3c).



Figure 3. (a) Dried thuja in planters; (b) Weeds along a linear drain; (c) Weeds among succulents, (a), (b), (c) Author's archive

3.2. Science and Technology Park, Aleksandra Medvedeva Street

The Science and Technology park in Niš was built and opened in 2020. It is located in the immediate vicinity of the technical faculties, at the location Gradsko polje, on Aleksandra Medvedeva Street (Figure 4). The facility consists of a basement, ground floor and three floors intended for young researchers and innovative companies. The premises in the building are mainly offices, multifunctional halls and amphitheatres for holding larger gatherings such as various conferences and scientific meetings.



Figure 4. Marked location and view of the object, Google maps

On the third floor of the building, on the edge of the terrace, as well as on the roof, an attempt to implement GR is visible, which is designed in terms of the selection of layers, as an extensive roof, and in terms of purpose and use, as an intensive GR (urban

furniture has also been installed). Including the terrace and roof, the greenery covers an area of 930 m^2. Figure 5 shows the condition of the roof during the implementation of greenery (Figure 5a) and the current condition (Figure 5b). It can be seen that the maintenance is not at an enviable level, that there is no greenery except in the planters, where thujas are planted. One of the main mistakes that resulted in the current look is choosing and placing silt instead of substrate. In these situations, the material can pass through the textile and flood the accumulation drainage panels. The plan is to transform this surface soon, but this time with the selection and placement of appropriate layers.

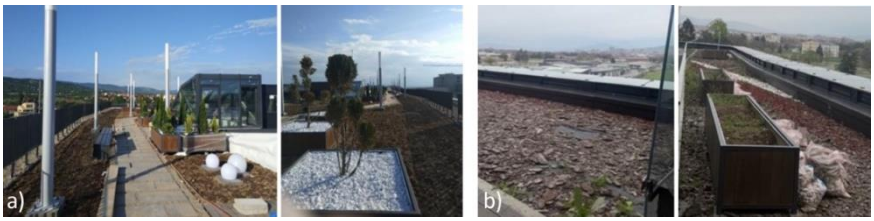


Figure 5. Current appearance of the GR (April 2025), Author's archive

3.3. Annex of the Faculty of Electonic Engineering, Aleksandra Medvedeva Street

The last selected example of the implementation of a GR on a public building is located next to the previous one, within the complex of technical faculties. It is a multi-purpose slat built as an annex of the Faculty of Electronics in 2020 (Figure 6).



Figure 6. Marked location and view of the object, Google maps, https://www.gradnja.rs/visenamenska-lamela-elektronskog-fakulteta-nis-teking/

In order to achieve greater sustainability and the life cycle of the building as well as the impact of the building on the environment, the flat roof was designed as an extensive GR on its impassable part. The greenery was designed on two surfaces, in a total area of 400 m^2.The flat terrace is made of the following layers - green layer of soil with plants, drainage layer Sarnavert Aquardrain 550, FPO membrane Sarnafil TG 66 thermal insulation HPS 20cm, vapor barrier Sarnavap 5000E, concrete layer for fall, reinforced concrete slab, extension mortar [14]. Similar to the previous example, after analyzing the current state, it is concluded that the maintenance is not at an enviable level (Figure 7).



Figure 7. Current appearance of the GR (May 2025), Author's archive

3.4. Residential and business building, Nemanjića Boulevard

The newly built building at the end of Nemanjića Bulevard in Niš is a residential and business building with Po1+Po2+8 floors (Figure 8). On the roof of the building, on the 9th floor, a GR was designed and built on a gross area of 0.12 ha.

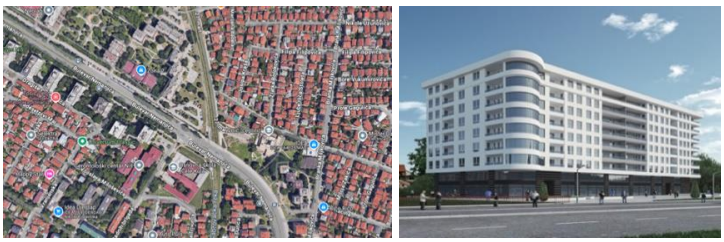


Figure 8. Marked location and view of the object, Google maps

The idea for the implementation of the GR was to provide tenants with an oasis of peace and greenery within the roof garden, from where an impressive view of the entire city is offered. One of the wishes of the investor of the building was that by greening the top floor, the building would be further tucked away and isolated from negative influences. By greening and planting numerous species of plants, the GR also provides a new place for the creation and development of biodiversity, a new place for birds and insects. Of course, primarily a space was created for the building's residents to meet and relax.

Of the total roof area of 1200 m^2, 800-900 m^2 is covered with sedums, while the rest is made up of paths. The BioPixel system was selected and more than 30,000 different plant species were planted (Figure 9). The growth of plants, ie the formation of a green cover, is ongoing. Extensive vegetation as well as ornamental grasses and ferns were selected for planting.



Figure 9. Presentation of the GR implementation, https://www.zelenikrov.rs/

At the moment, a more intensive development of vegetation on the surface of the roof has begun, as shown in the following photos (Figure 10).



Figure 10. Current appearance of the GR (April 2025), Author's archive

3.5. Residential and business complex Planet Residence, Blagoja Parovića Street

Planet Residence represents a newly built residential and business complex in Niš, located in Blagoja Parovića street (Figure 11). The complex is made up of 13 floors that make up the residential part of the building, the mezzanine, ground floor and

underground garage, which include public spaces and a parking space. The structure of the apartments ranges from studios to penthouses. On the first floor, above the mezzanine, as part of the residential part, there is a courtyard intended exclusively for tenants. The yard is designed as an intensive GR and covers an area of 2800 m^2.

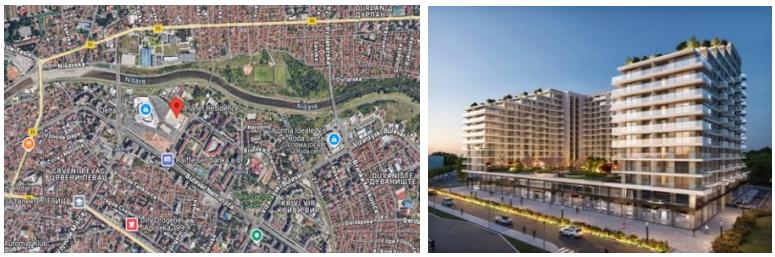


Figure 11. Marked location and view of the object, Google maps

The implementation of the GR took about half a year, which included all the steps from the pictures below (Figure 12). The first step was to mark the exact positions where the paths will be and where the greens will be. Accordingly, a drainage layer was installed in the form of drainage-accumulation panels filled with natural gravel. A geotextile was placed over it, on which a layer of crushed stone was later sprinkled. Behaton was intended for the trails. Large planters were placed in positions where high greenery was planned. The tall greens are carefully raised with a sizer. Also, in addition to tall greenery, low and medium-high greenery was also raised in the form of various types of plants that were planted around the planters and along the perimeter of the yard, next to private gardens. Due to the deadline for the implementation of the project, but also according to the recommendation of the landscape architects who participated in the implementation, instead of the traditional planting of grass, grass in the form of sod was installed. With a sufficient number of people participating in the trimming and laying of sod, the area was completely greened after one day. The green areas are irrigated using a drip irrigation system and using jet grass sprinklers.

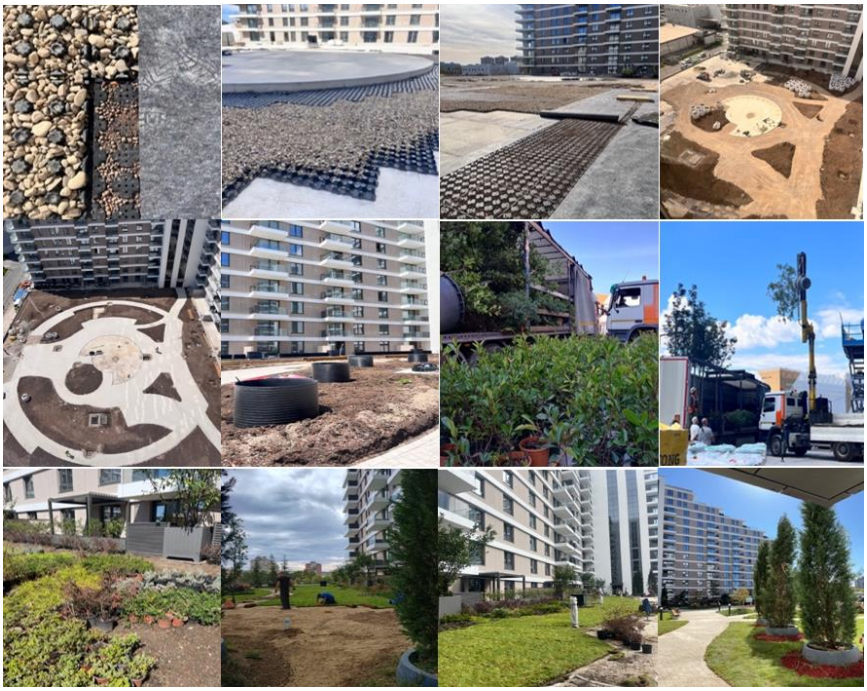


Figure 12. GR Implementation Steps (March 2024 - Sept. 2024), Author's archive

The following species were selected for the greenery planted as part of the GR: Lavender, Liriope muscari, Tiarella, Pennisetum little bunny, Spiraea golden carpet, Evonimus beucom, Verbena bonariensis, etc. Finally, the appropriate furniture was selected and installed. Benches and bins for small waste have been placed in the area intended for the building's tenants to gather, strengthen their relationships and relax. In the central part, there is a children's play area that includes swings and a large slide. Lighting is installed in the form of small reflectors positioned in planters that illuminate the treetops and in the form of columnar elements arranged around the perimeter of the paths. White quartz sand was placed along the entire length of the paths, and mulch was sprinkled around the planters (Figure 13)..



Figure 13. Current appearance of the GR (March 2025), Author's archive

3.6. Residential and business building, Vojvode Tankosića Street

The residential and commercial building in Vojvode Tankosića Street, located in a residential block with a high density of housing in Niš, is another example of a building with a GR on top. The construction of the building was completed in 2015 (Figure 14).



Figure 14. Marked location and view of the object, Google maps, Author's archive

Forty-four residential units, two business units and an underground garage are provided for in the project terms of reference. It was designed without bay window overhangs towards the street, with a composition of a dominant white cube with window openings in the living rooms. The structure of the apartments ranges from one- and two-bedroom apartments. The roof of the building intended for intensive use by the tenants, for relaxation and their gathering, is enriched with greenery on an area of about 100m2. The focus was primarily on the selection of low and medium height greenery in the form of turf and bushy plants. The project also provides for the arrangement of the main path and the fence on the roof (Figure 15). It is adequately maintained.

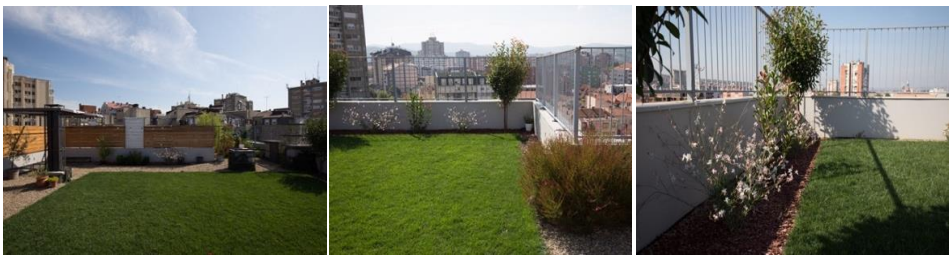


Figure 15. Appearance of the GR after implementation, Author's archive

4. DISCUSSION

During the analysis of the case study in the city of Niš, it is primarily noted that GRs are slowly becoming a practice during the design. The question arises whether awareness of the benefits of green areas on buildings has increased or whether the progress is solely a consequence of the introduction of new regulations, i.e. an increase in the percentage of required greenery on the plot where the building is being built. It was also determined that the planting of greenery was carried out immediately after the construction of the buildings, so that examples exist exclusively in new construction. Most of the GRs presented in the paper are designed as extensive in terms of layer selection, and intensive in terms of purpose and use. Tall greenery is planted in planters that are later placed on the roof.

By analyzing the buildings given in the paper, it is clearly observed that green covers are installed on both residential and public buildings The paper lists three public buildings with green covers - the Science and Technology Park on Aleksandra Medvedeva Street, the Annex of the Faculty of Electronics at the same location and the building where Kapa Projekt is located, on Vizantijski Boulevard. Other three objects are residential&business buildings in the city core. The use of various systems was observed for the implementation of GRs on the analyzed buildings. The choise depends on the completion date of the works, the cost of the system, and the plants that need to be installed.

Although most of the analyzed green areas date back no more than a decade, it is noted that some of them have not been adequately preserved and treated. These examples are observed exclusively on the roofs of buildings that are for public purposes, which is interesting given that in terms of layers they are designed as extensive GRs that are simpler and less frequently maintained. The Table 1 also provides insight into the fact that intensive roofs are more often designed on residential buildings in order to create additional space for residents to gather and relax.

Table 1 - Analysis of all objects with GR selected in the work

No.	Location In Niš	Use (public / residental)	Year (construction)	GR Type (intensive / extensive)	Current state (green-good / red-not good)
1	Vizantijski Boulevard	Public	2023	Extensive	
2	Aleksandra Medvedeva Street	Public	2020	Extensive / Intensive	
3	Aleksandra Medvedeva Street	Public	2020	Extensive	
4	Nemanjića Boulevard	Residential	2024	Intensive	
5	Blagoja Parovića Street	Residential	2024	Intensive	
6	Vojvode Tankosića Street	Residential	2015	Intensive	

5. CONCLUSION

The application of GRs in city centers is considered a sustainable measure to improve the condition, microclimate and living conditions, especially in areas where there is a constant appearance of construction and occupation of free open areas. Also, the advantages that GRs provide at the level of the facility, from the economic and aesthetic side, have been observed, and are reflected in saving and energy consumption,

increasing the market value of facilities, visually more attractive appearance of the facility, as well as extending the life of the existing structure.

More frequent design of GRs has been observed since the previous decade. The first conclusion is that the application of GRs has so far been recorded only on newly built buildings. The reason for this data is primarily the fulfillment of the minimum % of greenery on the plot. It is necessary to raise citizens' awareness of all the aforementioned advantages that vegetation on flat roofs provides and to open the issue of greening existing, built buildings in Niš. If the owners and tenants of existing buildings decide to take this step, it would be necessary first of all to examine the load-bearing capacity and condition of the current existing structure and materials on the roof, as well as the selection of an appropriate GR system and possible strengthening of the existing structure. For future projects that would relate to already existing buildings, a better option would be the implementation of extensive GRs due to the ease of installation.

Another conclusion after analyzing the case studies in Niš is that residential buildings are more often designed with intensive GRs intended for the activities of tenants of the buildings on whose roofs they are located, while public buildings are designed, in this case, exclusively with extensive GRs. However, it is necessary to note that some roofs, due to the selection of layers and types of plants planted during implementation, are considered extensive, but their very purpose and the existence of other elements such as paths and furniture make them intensive. One such example is the GR on the Science and Technology Park in Niš

The conclusion and also the answer to the third question in the paper, based on the analysis of the case study in the city, is that the current state of GRs on residential buildings is much better than the condition on public buildings. One of the possible reasons for the current unenviable appearance of GRs is the need to save money when installing greenery and the choice of lower-quality materials. Such decisions lead to long-term damage to buildings.

Analyzing the previous examples, it is important to note that after the implementation of GRs on a building, adequate maintenance is necessary. Greenery on roofs does not require daily maintenance and watering. It only needs to be watered a few times a year to prevent it from falling into winter hibernation.

Observing other buildings in the city of Niš, which according to the design have a GR on top and realizing that it has not been implemented, it is concluded that there is insufficient control and verification of completed works in the city during the technical acceptance of the building. During the inspection of the performed state, it is necessary to take a detailed look at all segments of the project. Therefore, a special appeal has been made to strengthen controls during the technical acceptance of the building as a main measure for the well-being of all.

ACKNOWLEDGMENTS

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Research paper

RESTORATION OF THE SOUTH GATE AT THE ROMAN CASTRUM TIMACUM MINUS

Igor Bjelić[1], Goran Radosavljević[2], Bojana Ilijić[3]

Abstract

The late antique site of Timacum Minus near Knjaževac (eastern Serbia) has been archaeologically investigated for almost 50 years. At the end of the nineties of the last century, a gate was discovered on the southern rampart of this Roman castrum, which was protected by two towers on its eastern and western ends. The gate and towers were built using large pieces of stone, so massive granite was used in the foundation parts, while the ground part of the towers, together with the gate itself, was built from polygonal hewn blocks (ashlar). The wall of one of the towers provided valuable information about the architecture of the gate itself and its towers. However, already during the excavation, it was noticed that the mentioned wall had a five-degree lean from the vertical axis towards the north, which is why there was a danger of it falling over. In three campaigns, a project was created and conservation and restoration works were conducted on the gate itself, its towers, and its surroundings, which saved the 1700-year-old monument. The paper presents a project carried out in cooperation with three institutions, which led from the endangered state of the monument of our cultural heritage to a tourist attraction that is now presented to the scientific, professional, and general public.

Key words: *Restoration, Timacum Minus, Late Antique Architecture, Roman Castrum*

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1. INTRODUCTION

Timacum Minus is a late-antique archaeological site, located near the village of Ravna, 8 km north of the small town of Knjaževac in Eastern Serbia. In Roman times, it was on the main road which connected the town of Lissus on the Adriatic-Ionian shore (modern Lješ in Albania) and the towns of Bononia and Ratiaria on the Danube (modern Vidin and Arčar in Bulgaria). Between these towns, there were many towns (Ulpiana, Naissus) and smaller Roman fortresses and settlements [1, 2]. Timacum Minus was one of them, and it consisted too of a Roman military fortress (lat. castrum) and a nearby civil settlement. The first data about it is related to the stay of the cohort *I Thracum Syriaca* during the 1st century. Back then, this fortification consisted of wooden earthen ramparts. From the middle of the 2nd century until the end of the 3rd century, a special territorial military unit – *cohort II Aurelia Dardanorum*, was situated in it. During the 4th century, *Pseudocomitatenses Timacenses Auxiliarii* resided in the castrum. From the second half of the 4th century, castrum and the settlement were under periodical attacks by the Goths and the Huns. Goths attacked in 378, while the Huns got a final stroke in 445, after which the castrum and the settlement never recovered [3, 4].

The first systematic excavations of Timacum Minus began thanks to the efforts of Petar Petrović, the head of the Institute of Archaeology in Belgrade. Back in 1975, he started with the archaeological research on the site Kuline near the village of Ravna. He identified this site as the castrum Timacum Minus mentioned in Tabula Peuntengeriana, the famous map from the Roman period. One of the main goals of the excavations was to define the perimeter of the castrum area. In that sense, walls and towers on the western rampart have been investigated, as well as some towers on the northern rampart. The excavations have been followed with the simultaneous conservation of the walls' masonry.

2. THE STATE OF THE EXCAVATED SOUTH GATE

The first archaeological excavations of the South Gate were conducted in 1997 [5]. It consisted of the Gate passage itself and two almost rectangular towers on both sides of the passage - one on the west and the other one on the east side (Figure 1.). Soon after the initial investigations of the gate, first deformations and cracks emerged. However, after the excavations, there was no conservation work for more than two and a half decades. The Institute for the Protection of Cultural Monuments in Niš was responsible for this site and this institution asked for a new project cycle after two decades. That meant new revision archaeological excavations would have to be conducted so the Institute of Archaeology in Belgrade and the Homeland Museum of Knjaževac concluded a new joint project for the excavations of this site in a period from 2019 until 2023 [6, 7][4]. Three phases of the gate have been discovered (Figure 2.). The first phase of the walls (from the 2nd century) is done using the pebbles in a hot lime mortar both at the foundation as well as at the aboveground level. The second phase (from the 3rd century) is the most representative. Large monolithic ashlars of sandstone (among which some were polygonal in shape) and spolia – ancient gravestones (Figure 3.) have been used for its aboveground construction. These ashlars are connected by hot lime mortar. At the foundation level, huge granite stones, pebbles and hot lime mortar

[4] The leader of joint project is PhD Sofija Petković, Principal Research Fellow from the Institute of archaeology in Belgrade.

were used. The third phase (from the IV century) can be noticed by the walls which are made by the combination of several rows of pebbles and other types of stones and rows of bricks, as usual for this period.



Figure 1. The excavated South gate of Timacum Minus from the South side (the photo of I. Bjelić)

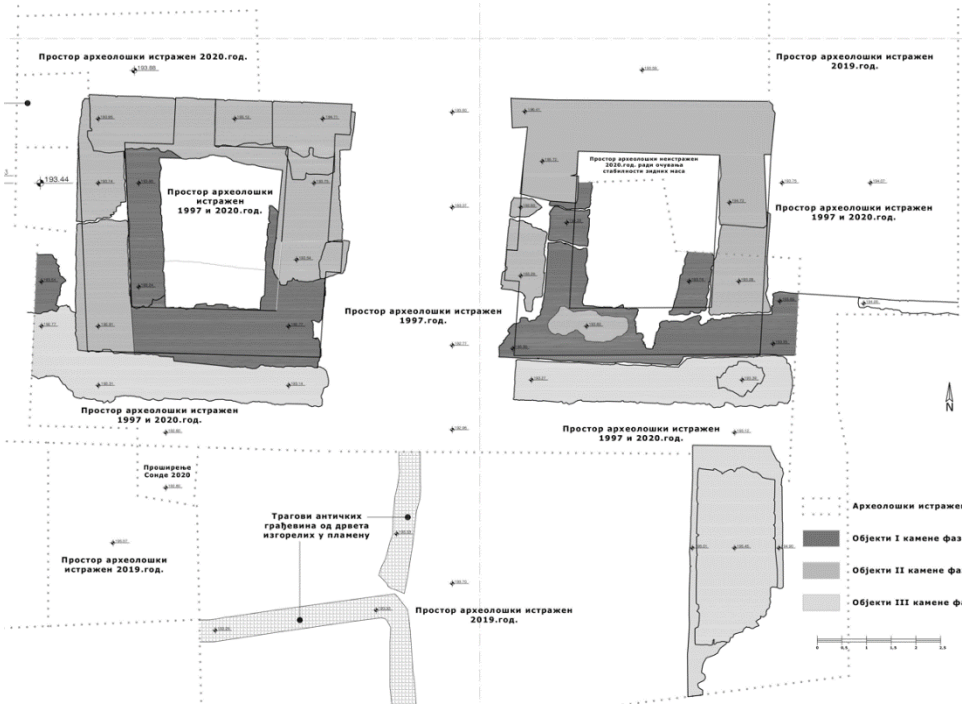


Figure 2. Plan of the excavated state of the South gate of Timacum Minus (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

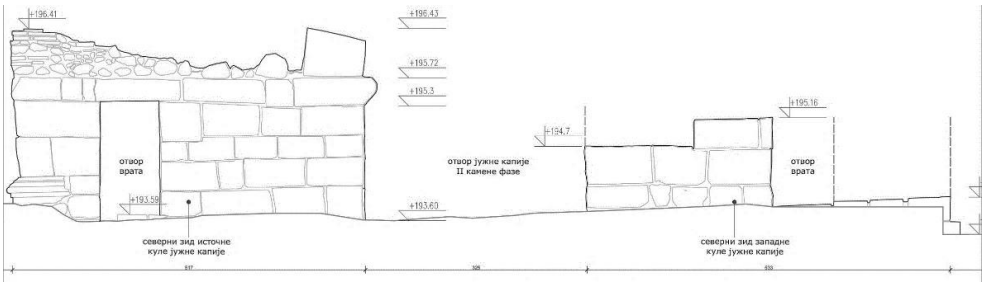


Figure 3. North façade of discovered South gate of Timacum Minus (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

Deformations of the excavated masonry structures have become more visible in the meantime – the whole north wall tilted towards north, numerous cracks emerged, and the most distinctive one was on the architrave beam above the tower door (Figures 3 - 5). These structural failures indicated that a danger from a final collapse have become more plausible, and that there is a need for an intervention from a civil engineering point of view at the foundation level.

There were other problems on which project addressed. The north wall of the east tower is 3m high in a preserved state, while its south wall was noticed only at the foundation level, at the depth of 1,5m below the threshold of the tower's door. The difference of 4,5 m was at the distance of 4,7m which corresponded to the length of the tower itself. Beside this, at the site, three phases of masonry are preserved, but not in a whole at all positions (lengths) of the walls.

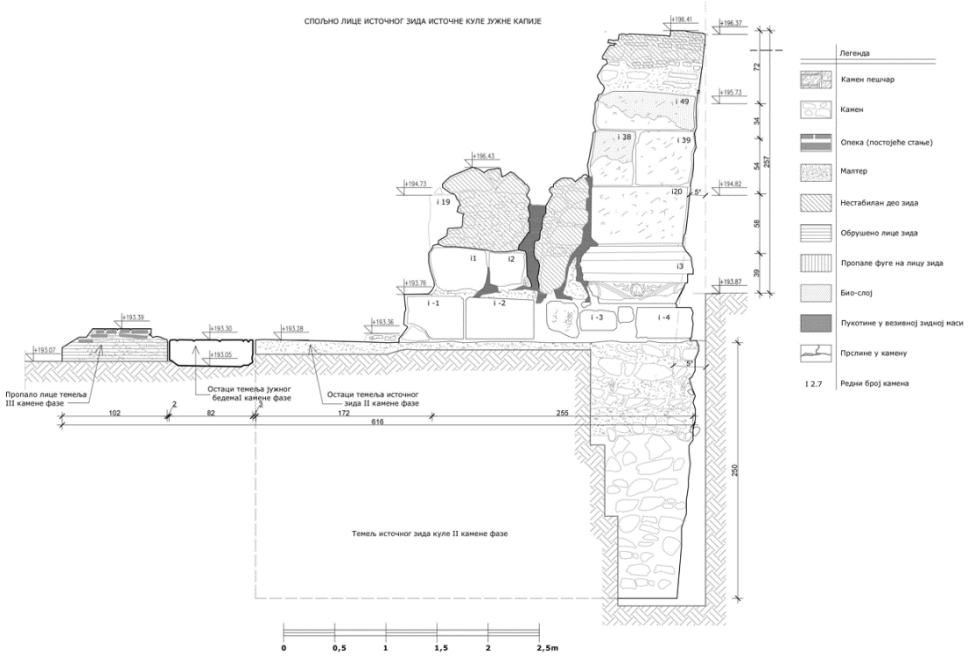


Figure 4. East façade of the East tower of the South gate of Timacum Minus (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

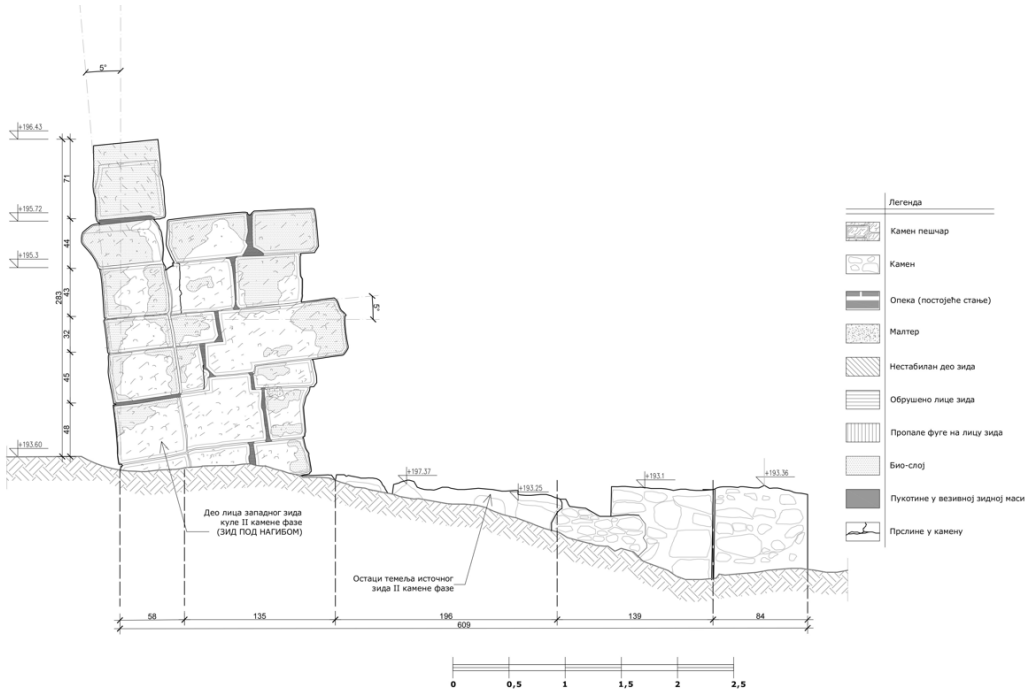


Figure 5. West façade of the East tower of the South gate of Timacum Minus (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

3. METHODOLOGY

One of the most important principles in the conservation of masonry walls at archaeological sites is that an architect-conservator shouldn't project the amount of masonry that would jeopardize the original masonry, the original state, and the shapes that are excavated. On the other hand, we got most of the elements for the reconstruction of one of the arches above the Gate itself, since there was an abutment preserved at the original level and the first ashlar (voussoir) at the springing level of this arch. This specially shaped stone had an upper edge cut under the angle, which was close to the center of the arch. All the differences between the heights of the preserved walls had to be reconciled in the sense that a state of presentation should be clear to any visitor who would come to this site. However, reconciliation between the heights was a hard task since the three phases of masonry (from the II, III, and IV centuries) are at some positions in very close proximity.

4. RESULTS

The Ministry of Culture of the Republic of Serbia has financed the new project for the restoration of the gate, and the Homeland Museum of Knjaževac was the investor. Project under the name: *Preliminary design for restoration works on the southern gate with the tower towers at the archaeological site of Timacum Minus*, has been done by the Institute for the Protection of Cultural Monuments in Niš. Three architects participated in it: Goran Radosavljević (Senior conservator from the Institute for the Protection of Cultural Monuments in Niš), Mile Veljković (retired conservator from the Institute for the Protection of Cultural

Monuments in Niš), and Igor Bjelić (Research Associate from the Institute of the archaeology in Belgrade). The architects from the Institute for the Protection of Cultural Monuments in Niš defined the methodological approach of restoration and the applied materials, while a Research Associate Architect from the Institute of Archaeology defined the shapes of the restored walls.

The first level of the project is intended to bring back the original shapes of the excavated monument state. It meant that the axis of the north wall of the east tower must be at the right (vertical) angle. In that sense, for the needed interventions on the foundation level, we consulted several experts: Nenad Šekularac from the Faculty of Architecture in Belgrade as well as Dragan Zlatkov and Predrag Petronijević from the Faculty of Architecture and Civil Engineering in Niš. The first expert suggested that the structure of the tilted north wall should be restored at the vertical angle above the ground level by using the grid net of wooden beams from both sides of the wall. Thus, a crack would be opened between the foundation level and the aboveground part of the wall, which would be then filled with special connecting masses for dilatation (made by company Sika or Mapei). The original foundation should be reinforced by reinforced concrete beams, which would take a huge part of the loading of the aboveground structures. The point of view of other experts was a traditional one, where all the aboveground structures of the wall would be first dismantled in a process, that involved recording each of the sandstone ashlars from the wall. A new strip foundation from reinforced concrete would be set in the mass of the original foundation. After that, the old ashlars would be set on their old prerecorded positions. The Institute for the Protection of Monuments in Niš agreed with the second proposition since the first complex method had never been applied on the territory of the Institute's jurisdiction, and there was a great possibility that extra financial resources would be needed for it.

In the restoration approach, we observed the Gate at the wider plan of castrum Timacum Minus. Plans for presentation shaped the previous excavating approach, so the edges of the archaeological trench were defined at a distance of min 5m from the remains of the Gate to avoid water residues around the discovered walls. We count on that the Gate will be the future starting point for the gathering of the visitors groups at the site. Therefore, the terrain around the gate should be as flat as possible, without traces of archaeological trenches nearby. Also, according to that fact, all the walls should be visible above the ground level, including those which at the moment of excavation were preserved only at the foundation level. That was the case with those on the south edges of the towers. Nothing of the foundation structures should be exposed to climate change.

As we pointed out earlier, there was a great difference (4,5 m) between the north and south walls of the east tower, so we decided to make the west and east walls stepped in a way that these acted as abutments starting from the south to the most preserved north wall of the East tower (Figure 6.).

One of the most important artistic elements of the Roman Gate is the arch above its passage. The cornice on the abutment level marked the starting point – the so-called impost for the arch – it was preserved on the north wall of the east tower. Besides this, the specially carved stone (ashlar) – voussoir of the arch was preserved *in situ* (in an original state and position). That voussoir was the first ashlar within the structure of the arch – the so-called springer. The outer and inner curved edges of that ashlar – extrados, and intrados, determined the position of the center point of curvature of the arch. However, the upper bed edge of the voussoir was under the angle that pointed at another center by which a

stonemason marked the beds between separate voussoirs of the arch. This second center was higher than the first one (Figure 7.). From the data presented here, we decided there were enough elements for the restoration of the arch. The mass of the wall above the arch could theoretically be defined according to the remains next to the springer.

There was a great question about whether the north wall of the west tower should be restored and on which level (proposed levels of restoration are marked in dark and light tones in Figure 8.). The same question applied to the whole west tower. The response to this question depended on a decision on whether we have enough elements for the restoration of the arch above the Gate. Since the arch should be restored, the north wall of the west tower, which played a role as another abutment of the gate 'arch, should be restored too. At this stage of the project, there was also a question about whether a whole north wall of the west tower should be shaped as a symmetrical replica of the north wall of the east tower (proposed light tone in Figure 8.) or whether the level of restoration should be limited only to the section of the wall, which played a role as the abutment of the arch (proposed dark tone at Figure 8.)?

To distinguish the phases, but simultaneously not lose the appearance of the Gate as a whole, we had to have whole units of restored walls from each of the phases, but in a way where the state of presentation would be clear for the understanding by any visitor. To make a clear presentation of the already complex order of chronological phases and the number of walls in a small space, we decided to make the west tower a symmetrical structure to the east tower (light grey shade in Figure 8, Figure 9.).

According to the project presented here, the works on the restoration of the Gate were conducted in three campaigns. Institute for the Protection of Cultural Monuments in Niš was controlling the process, and the company "Mitre Tasić doo" from Smederevo did works on the site as a construction contractor (Figure 10.).

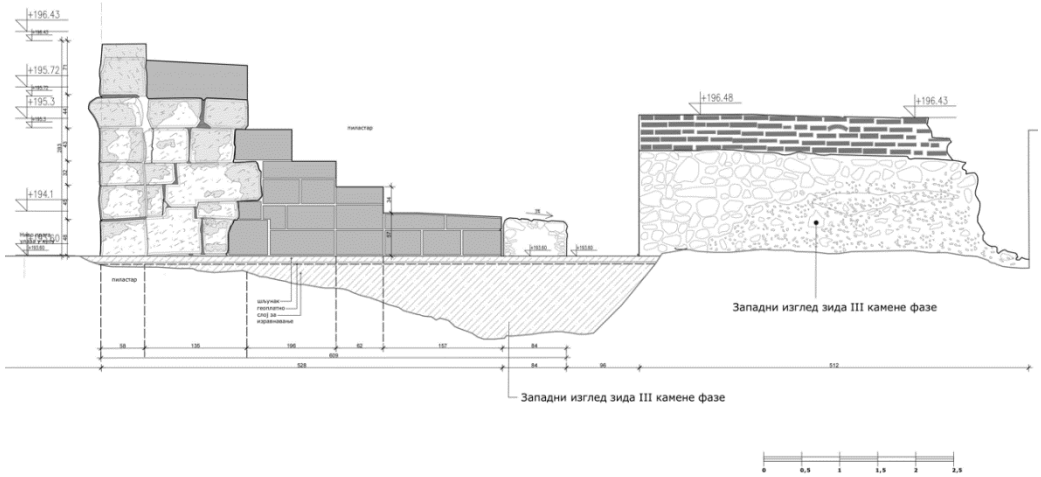


Figure 6. West façade of the East tower and the wall from the fourth phase according to the project of restoration (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

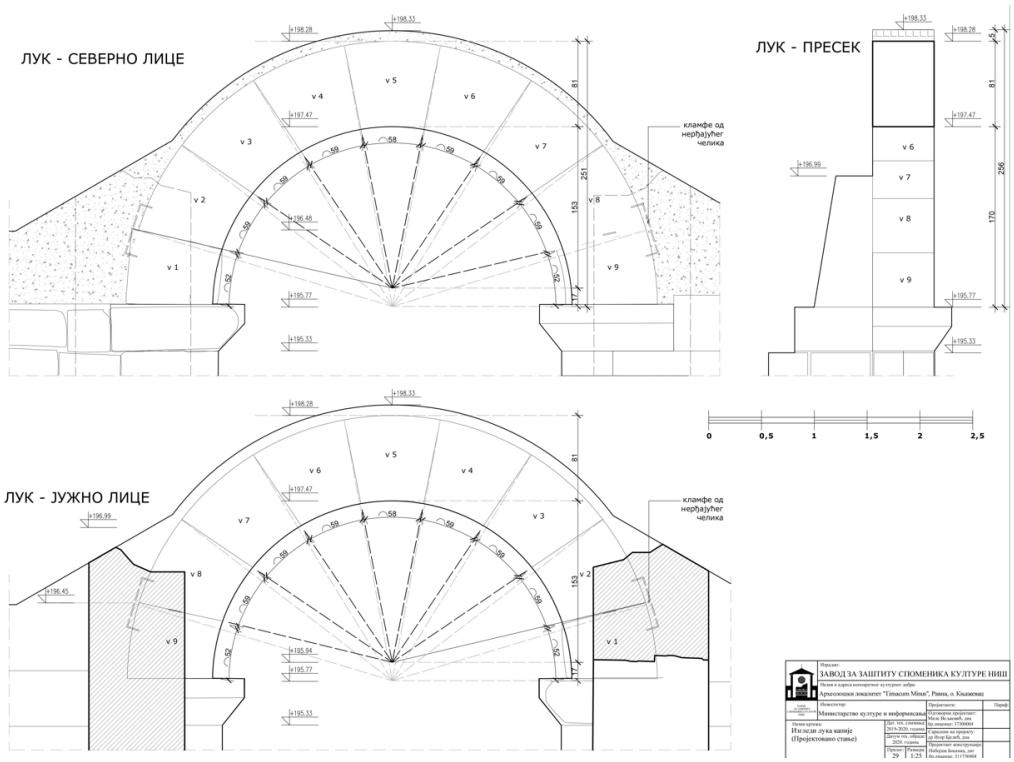


Figure 7. The detail of the arch of the gate according to the project of restoration (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

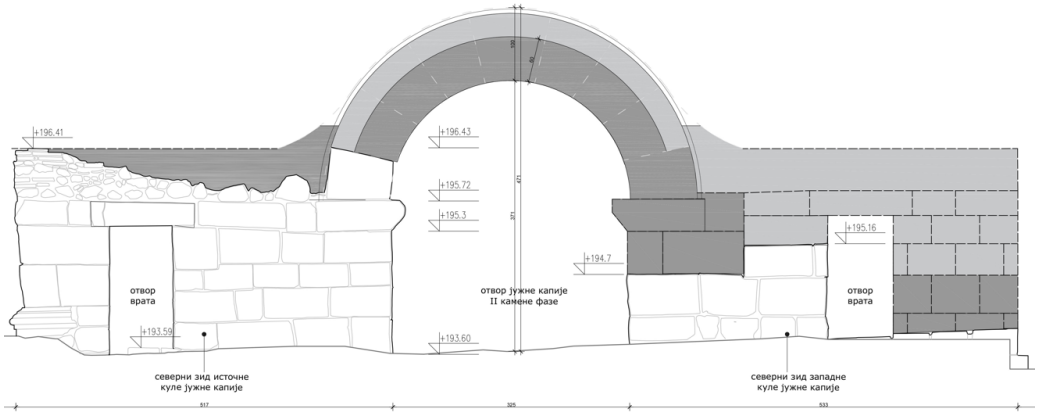


Figure 8. North façade of the restored South gate of Timacum Minus Minus according to the project of restoration (the documentation of the Institute for the Protection of Cultural Monuments in Niš)

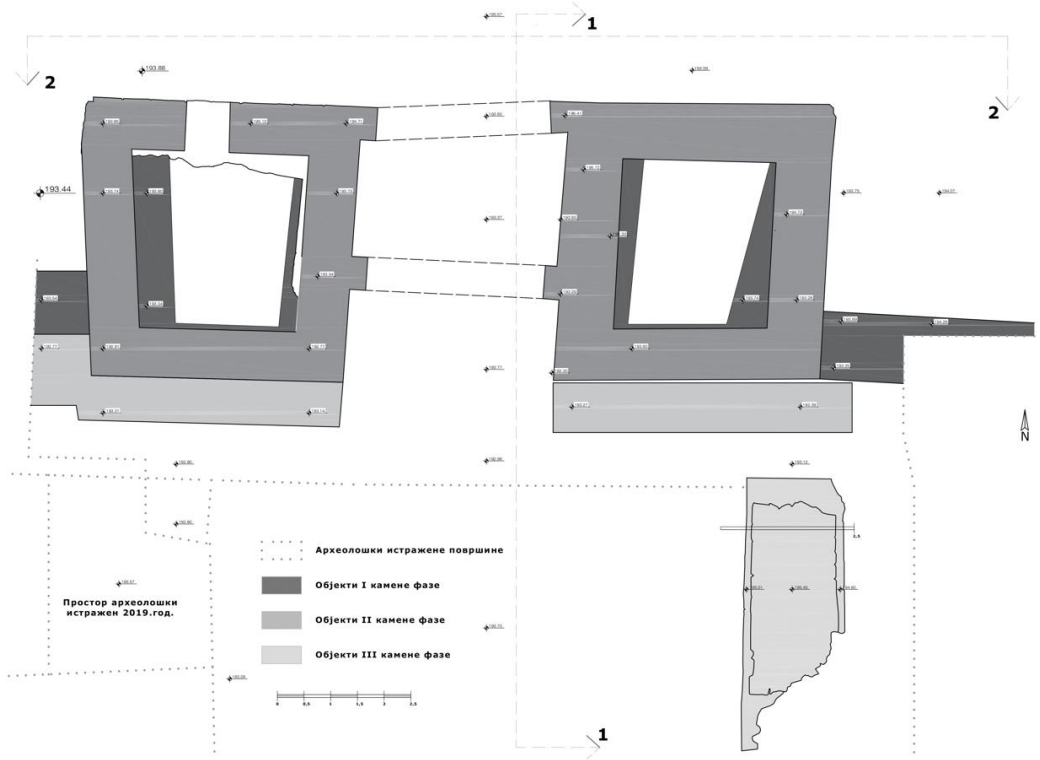


Figure 9. Plan of the South gate of Timacum Minus according to the project of restoration (the documentation of the Institute for the Protection of Cultural Monuments in Niš)



Figure 10. South Gate after the restoration (photo of I. Bjelić)

5. DISCUSSION

Two questions mentioned before were the subject of continuous debates among scholars, architects, and even masons. The first question was a proposition made by Nenad Šekularac about the method of intervention on the foundation part of the north wall of the east tower. That proposition was good in a way that it guaranteed the protection of the original structure and material of the wall above the ground level contra the proposition which involved the dismantling of the wall, no matter how expensive it would be. However, since our country's government gives financial resources for the culture, which are 0.68% of GDP, and only a small percentage of it can be used for the protection of immovable cultural monuments. Recently, because of the highly increased level of construction of buildings in towns, most endangered monuments are those in urban areas, so the archaeological sites are in most cases the last on the list for the approvals of financial resources. This reason was crucial for the experts from the regional Institutes for the protection of cultural monuments. Therefore proposition, which demanded high financial resources, is not appropriate for the archaeological site, which is not in an urban area, which is just the case of Timacum Minus. Also, in the masons ' opinion, the first proposition was too demanding for their skills and given opportunities on site.

The second big question was the level of restoration of the west tower. Namely, if we observe only the west tower, its north wall is not as high in a preserved state as that is the case with its counterpart on the east tower. The level where it would be shaped as a symmetrical replica of the north wall of the east tower meant that more than 50% of its structure would be restored. That approach is not a custom in the methodology of restitutions of cultural monuments, especially if those are so old (in our case from the late antiquity). However, this tower should be not observed uniquely, but as a part of the wider situation of Gate. The answer to this question was connected to the state of presentation of the Gate as a whole. Archaeological excavations provided data about the width of the entrance door to the west tower, as well as the level of the threshold, while the architectural analysis showed that the level of the architrave beam above that door should be at the same level as that one on the east towel – at the same horizontal as the impost cornice of the arch above the Gate. Therefore, the north wall of that tower was only one part of the north façade of the Gate, where we had more than enough data to restore the façade of ground-level structures. In other cases, if an east tower is presented in one way, and a west tower in another one, according to the state of the remains of each of them, then it would not be clear to visitors that those are symmetrical structures by which Gate has been controlled. This state of presentation would make succeeding problems with the level of presentation of separate phases too. Therefore, we concluded that there is firm evidence that the north wall of the west tower should be restored as a symmetrical replica of its counterpart on the east tower.

6. CONCLUSION

Project under the name "Preliminary design for restoration works on the southern gate with the tower towers at the archaeological site of Timacum Minus" has been conducted by the Regional Institute for the Protection of Cultural Monuments in Niš. However, the job of the restitution is a joint effort of three institutions. Besides the mentioned Institute from Niš, the participants of the project (direct or indirect) were also the Homeland Museum in

Knjaževac, as well as the Institute of Archaeology in Belgrade. A joint effort not only rescued the monument from the disintegration of a precious 1800-year-old Gate but created a new landmark in the area of archaeological site which was the main scope for the architects and archaeologists involved in this project.

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Review paper

FLOOD AND DROUGHT RISK MANAGEMENT SOLUTIONS IN SMART CITIES

Borislava Blagojević[1], Snežana Đorić-Veljković[2], Milan Gocić[3], Emina Hadžić[4]

Abstract

The frequency and intensity of floods and droughts are projected to rise under future climatic conditions. Urban areas, with their increasing populations and expanding built environments, are expected to face these challenges more acutely. In response, smart cities that leverage digital technologies for data collection and service delivery are well-positioned to address these risks more effectively than traditional cities. This study reviews, analyzes, and discusses how digital technologies are applied in managing urban flood and drought risks. Smart cities integrate information and communication technology alongside Internet of Things devices to optimize public services and foster citizen engagement. A literature review of smart city solutions across Europe highlights the application of risk assessment tools, decision support systems, and early warning mechanisms, in flood- and drought-related climate adaptation strategies, and overall city resilience. The findings underscore the urgent need for an integrated approach to managing these escalating risks, including shared technological solutions that address both hazards simultaneously.

Key words: *Urban Floods, Urban Droughts, Risk Management, Technological Solutions, Smart City*

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1. INTRODUCTION

Driven by rising global temperatures, altered precipitation patterns, and more extreme weather events, the frequency and intensity of both floods and droughts are projected to increase under future climate scenarios [1]. These hydrometeorological hazards significantly threaten human well-being, ecosystems, and economic stability. With climate change continuing to accelerate, the need for proactive and adaptive water risk management strategies becomes increasingly urgent [2].

Urban areas are particularly vulnerable to these growing risks due to their dense populations, high concentration of infrastructure, and often aging water management systems [3]. As cities expand, impervious surfaces multiply, disrupting the natural hydrological cycle, intensifying surface runoff during floods, and reducing groundwater recharge, leading to droughts. Additionally, the socio-economic diversity within urban populations often leads to unequal exposure and sensitivity to water-related hazards, complicating effective risk mitigation [4].

In this context, smart cities offer a promising approach to enhance resilience [5]. Smart cities are urban areas that embrace digital technologies and data-driven solutions. By integrating real-time monitoring, predictive analytics, and automated response systems, smart cities can more efficiently manage water resources, detect and respond to extreme events, and support informed decision-making [5]. Unlike traditional urban environments, smart cities are better equipped to anticipate hydrological hazards and implement targeted, adaptive measures that protect both infrastructure and vulnerable populations [6].

The number of smart cities has been steadily increasing since the 1960s, when Milton Keynes in the UK was established as one of the earliest examples of a smart city [7]. In 2025, the International Institute for Management Development (IMD) ranked 146 smart cities worldwide according to its Smart City Index [8]. This index evaluates residents' perceptions of the infrastructure and technological applications available in their cities. Of the ranked cities, 58 are located in Europe, 47 in Asia, 16 in North America, 10 in South America, 9 in Africa, and 6 in Australia. Similarly, the Smart Cities World platform [9] profiles 108 cities, with European cities making up the largest group, 37 in total.

This paper aims to analyze urban flood and urban drought-related solutions in selected European smart cities, with a focus on digital technologies, data, and system-based solutions. The structure of the paper is as follows: the methodology section outlines the criteria for city selection, as well as the review and analysis approach. The results section presents smart city solutions addressing the topics of interest. The discussion explores cross-cutting themes, and the conclusion highlights common technological approaches and shared solutions.

2. METHODOLOGY

The research was conducted through the following sequential steps: 1) Identification of a comprehensive list of smart cities; 2) Initial selection of candidate cities; 3) Literature review; 4) Organization of relevant references by city; 5) Final selection of smart cities based on literature availability and relevance; 6) In-depth study of selected literature for each city; 7) Thematic grouping of references based on the topics of interest; 8) Synthesis of findings by topic and identification of cross-topic linkages.

The Smart Cities World platform [9] was identified as the most appropriate source for generating the initial list of smart cities. From this platform, 37 European smart cities were identified for a preliminary review. The UK had the highest representation with 15 cities, followed by Spain, Germany, and Finland with three cities each. Sweden contributed two cities, while the Netherlands, Belgium, Ireland, Italy, Russia, France, Latvia, Poland, Estonia, Norway, and Austria each had one city.

The literature review was conducted using a targeted text mining approach, focusing on three main themes: 1) Connectivity and Data (C&D), 2) Urban Flood Risk Management (UFRM), and 3) Urban Drought Risk Management (UDRM).

Based on earlier work on water management solutions in smart cities [10], the C&D component of the review encompassed not only digital technologies for data collection and service delivery but also public engagement and education as key elements of effective implementation. Figure 1 illustrates the scope of this study, with blue boxes highlighting the primary research focus areas.

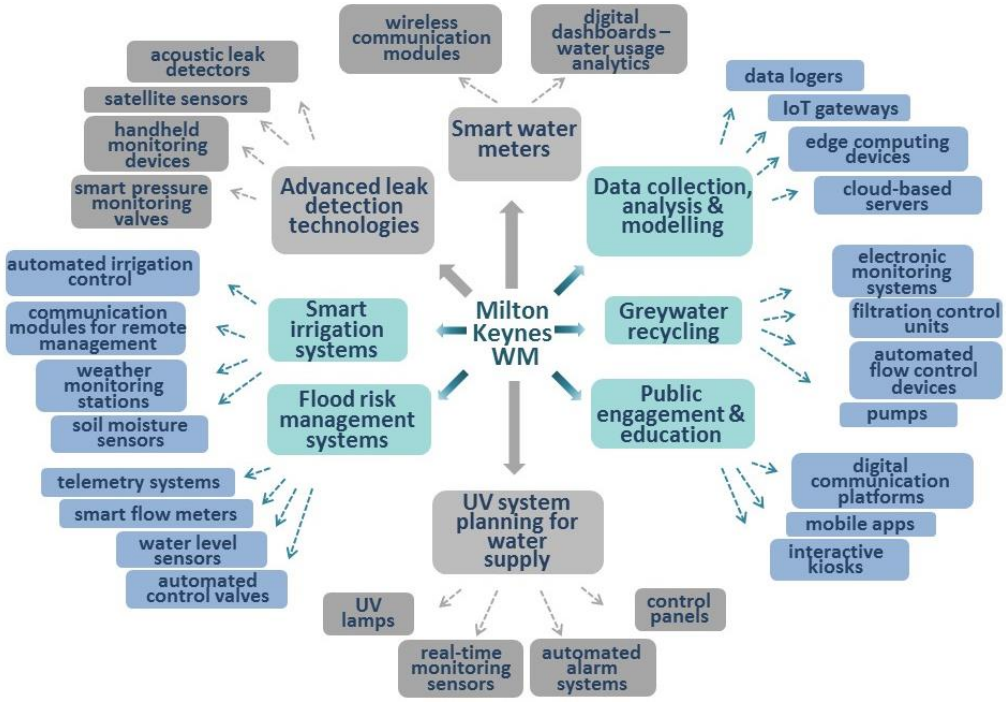


Figure 1. Blue boxes showing areas of research for this study within innovative solution elements and applied devices for water management (WM) in the smart city of Milton Keynes (Modified from: [10])

For UFRM, the literature search focused on identifying risk assessment tools, decision support systems, early warning mechanisms, and other flood-related climate adaptation strategies that contribute to overall city resilience. The primary interest was in pluvial floods, as these are typically managed at the municipal/city level, unlike fluvial, coastal, or flash floods, which generally fall under higher administrative jurisdictions.

The UDRM review followed a similar focus, targeting literature on tools, systems, and strategies used for drought risk assessment and response in urban environments. An alternative was placed on water scarcity and urban irrigation solutions, which are critical under changing climatic conditions.

3. RESULTS

The most abundant literature was found in the area of Connectivity and Data, followed by UFRM. The least represented theme in the literature was UDRM. Therefore, the final selection of cities included in this study was determined based on the availability and quality of sources related to UDRM, ensuring a balanced review of all three research themes.

The following cities are selected for this paper: Amsterdam (the Netherlands), Barcelona (Spain), Dortmund (Germany), Paris (France), and Vienna (Austria).

3.1. Amsterdam

The city of Amsterdam is the capital and largest city of the Netherlands, with a population of around 900,000. The Amsterdam Metropolitan Region is characterized by an integrated landscape of urban areas, water bodies, and green infrastructure. The prevailing land use in the Amsterdam region is agricultural land (56% primarily pasture and arable land) followed by about 25% urbanized space, of which over one third is impervious surface, and approximately 11% forest and nature areas [11].

Amsterdam is situated below sea level and has a historically developed water management system of canals, dikes, and pumping stations, making it particularly vulnerable to both pluvial and fluvial floods as well as sea-level rise. Green space per capita in central Amsterdam is limited, with spatial pressure from urbanization remaining a concern, although strong planning policies have preserved surrounding green belts and polder landscapes. The municipality has invested in expanding green-blue infrastructure, promoting climate-adaptive urban design, and implementing Nature-Based Solutions (NBS) to enhance both urban livability and flood resilience [12].

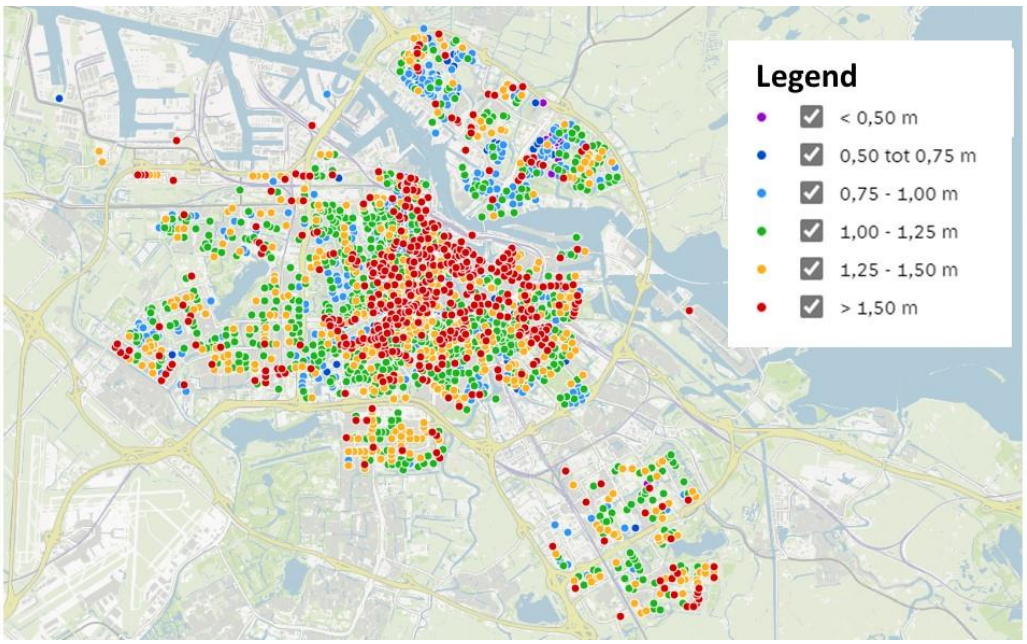


Figure 2. Groundwater table depth on the online map (Source: [13])

The “Rainproof Amsterdam” program launched in 2014, specifically addresses pluvial floods within the UFRM, and encourages decentralized rainwater management through green roofs, permeable pavements, and urban water buffers. The city also promotes multi-functional land use, where public spaces serve both recreational and water retention functions [12].

The UDRM is considered under the climate adaptation plan. Drought-prone locations are shown on the interactive online maps through groundwater table levels (Figure 2).

The Amsterdam University of Applied Sciences, together with 6 universities, 4 water boards and district water boards, 8 municipalities, and other partners, has just begun a five-year project (2025-2030) Thirsty Cities: Towards drought resilient cities. The project will explore how cities can cope with increasing drought [14].

Within the RESILIO project (2018-2021) [15], the 10,000m^2 area of new smart blue green roofs helps the city adapts to climate change by reducing impacts of heavy rain, urban heat island effect, and drought. These smart roofs have been created by repurposing the rooftops of climate-vulnerable neighbourhoods of Amsterdam. The roofs have been designed to capture and store rainwater, thereby mitigating flood risks and conserving water for use during droughts. They are equipped with smart valves and sensors that manage water levels by releasing stored water before storms, enhancing their capacity to absorb rainfall. Additionally, during dry periods, these systems retain water to support rooftop vegetation, contributing to urban cooling and biodiversity [15].

3.2. Barcelona

The Barcelona Metropolitan Area, home to over 5 million people, represents one of the most densely populated urban regions in Spain, with the city of Barcelona itself having a density of over 16,000 inhabitants/km^2. Land cover in the metropolitan area includes approximately 25% forest, 45% agricultural or semi-natural areas, and around 30% urbanized land, with a high share of impervious surfaces contributing to urban heat and flood risks [3]. Despite significant green infrastructure initiatives, green space per capita remains unevenly distributed, especially in older, densely built districts, prompting ongoing efforts to green streets, rooftops, and courtyards as climate adaptation measures.

Barcelona participated in the RESCCUE (Resilience to Climate Change in Urban Areas) project, which developed sectorial and integrated models to assess the resilience of critical urban services under current and future pluvial flood scenarios. These models analyze the behavior of urban services during heavy storm events (Figure 3), considering cascading effects due to infrastructure failures. The project aims to inform decision-making and enhance urban resilience strategies [16].

An alternative within NBS as measures in both UFRM and UDRM is studied in Barcelona for two floodable areas [17]. A more notable disaster is extreme drought, for which urgent water supply restrictions have been implemented. The findings for different scenarios and common parameters in calculations of water harvesting and rainwater infiltration could support the decisions to implement either green or blue NBS, depending on the hydrological balance in the study area [17].

Barcelona is recognized as a leader in smart water management, leveraging the Internet of Things (IoT) to optimize water usage. The city has deployed a network of sensors to monitor water consumption, detect leaks in real-time, and manage irrigation systems

efficiently. This approach has led to significant water savings and improved resource management [7].

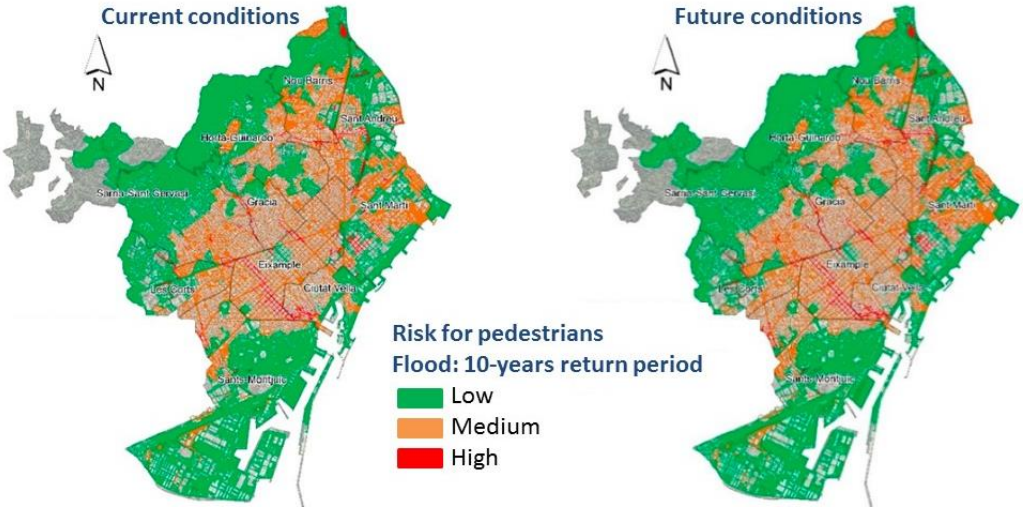


Figure 3. Flood risk maps for pedestrians for a 10-year return period design storms related to: Left- baseline and Right - business as usual (BAU) scenarios (Source: [16])

3.3. Dortmund

The city of Dortmund, located in the federal state of North Rhine-Westphalia, Germany, is the largest city in the historically industrial Ruhr area, with a population exceeding 600,000 residents. Despite its industrial legacy, nearly half of Dortmund's municipal territory comprises green spaces, including forests, agricultural land, parks, gardens, and natural reserves. The city has actively pursued the transformation of former industrial zones into green areas as part of its broader sustainability goals [18]. In line with climate change adaptation strategies, the City Council has developed a range of recommendations and measures aimed at mitigating the urban impacts of extreme heat, air pollution, heavy rainfall, and prolonged summer droughts [19].

Following a severe pluvial flooding event in July 2008, which resulted in significant damage despite the full functionality of the sewer system, the city initiated several key actions to improve its flood resilience [20]: 1) Formation of a flood protection working group; 2) Development of a civil protection emergency plan in collaboration with the Fire Department and the Federal Agency for Technical Relief; 3) Publication of a flood prevention information flyer; 4) Implementation of a hydrodynamic sewer network analysis to evaluate urban flood risks; 5) Appointment of a municipal flood prevention officer; 6) Formulation of a comprehensive flood prevention plan for both water and sewage systems; 7) Procurement of advanced technical equipment, including mobile high-capacity flood pumps.

Today, Dortmund employs a comprehensive, multifaceted approach to managing pluvial floods, combining infrastructure improvements, institutional planning, and advanced modeling techniques.

The city's local climate strategy, outlined in The Development Concept for Dortmund City Centre [19], advocates moving away from conventional stormwater drainage systems. Instead, it promotes the use of narrow surface channels, ditches, and vegetated areas to direct runoff, providing the dual benefit of urban cooling and stormwater management. Stored

water in cisterns, pools, and green spaces is also integrated into this system to manage overflow and mitigate extreme rainfall effects. Green roofs on underutilized buildings in the city center are also being promoted as part of this strategy. With plans to establish a green roof registry and develop regulations for both flat and slightly inclined roofs, the city is clearly prioritizing NBS for improved environmental sustainability, contributing simultaneously to UFRM and UDRM.

Innovative technologies have also been piloted in Dortmund. Stavroulakis et al. [21] propose a novel system architecture for augmented reality (AR) flood visualization, currently being tested in the city. This AR system enables rescuers equipped with wearable devices to access real-time visualizations of floodwater levels and optimal evacuation routes, based on large-scale data analytics from open data sources on weather and critical infrastructure (Figure 4).

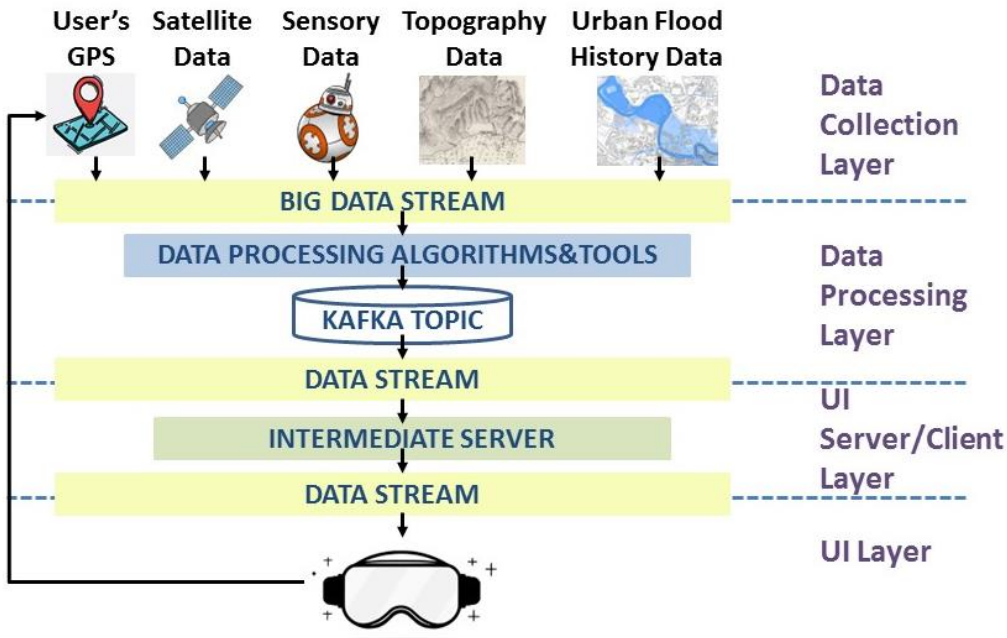


Figure 4. Augmented Reality flood visualisation system architecture and layers (Source: [21])

Furthermore, the city is supporting the deployment of a cutting-edge biometeorological sensor network, alongside a nowcasting service, to monitor outdoor thermal comfort [22]. While primarily intended to support Dortmund's forthcoming Heat Action Plan, this smart-city initiative uses in-situ and remotely sensed data to generate near real-time assessments of urban thermal conditions. The potential application of this system for UDRM highlights Dortmund's commitment to integrating digital innovation into climate adaptation and resilience planning.

3.4. Paris

The Paris Region, home to approximately 12 million inhabitants, nearly one-fifth of France's population, includes the city of Paris, the most densely populated capital in Europe. Land cover in the region comprises 23% forest, 47% cultivated land (primarily intensive open-

field crops), and 21% urbanized area, of which 16% is fully impervious [23]. Green space per capita is especially limited within the inner ring of the Paris Region, which continues to experience significant land take, with over 900 hectares of rural land lost to urbanization each year. This situation presents a considerable challenge for managing pluvial floods. However, the City of Paris is actively pursuing greening strategies, including the creation of 100 hectares of green roofs and public squares, along with an additional 30 hectares allocated for urban agriculture. These efforts, aligned with the Paris Climate Action Plan and the "Soil & Rainwater Plan," aim to enhance the city's capacity to manage stormwater and adapt to future climate conditions [23, 24].

The city has also sought to institutionalize green infrastructure by making it a legal requirement in new developments, thereby promoting NBS and integrating biodiversity considerations, primarily to mitigate urban heat island effects and restore local biodiversity [25]. A key concern among stakeholders implementing these urban flood solutions is the quality of stormwater runoff. Through its Rain Management Plan, Paris is in the process of deploying NBS capable of managing rainfall events that exceed rain depth of 16 mm, the threshold of the sewer system's capacity [25].

While the expansion of green spaces offers benefits for mitigating urban heat and managing stormwater, it may also increase water demand, raising concerns from an UDRM perspective. A severe drought could significantly disrupt economic activity in the Paris Region, which generates one-third of France's GDP. Although agriculture and manufacturing are the most vulnerable sectors, urban expansion could also intensify drought risks, particularly through structural damage caused by clay shrinkage [26]. To prepare for a water-scarce future, three climate adaptation scenarios have been developed for the Paris Metropolitan Area, with water reuse (recycling) identified as a key strategy [26] (Table 1).

Table 1. Examples of annual water volumes saved under different adaptation measures in the Paris region (Source: [26])

Objective	Reduction potential (millions of m^3)	Contribution to the target of a 10% reduction in abstraction	Contribution to per-user target
Reuse of 1% of treated wastewater	57.5	44.2%	100%
Reduction in leakage	20	15.3%	26%
Reuse of rainwater in 20% of buildings	28.6	22%	37.1%
Reuse of rainwater for irrigation	4.1	3.1%	16%
Reuse of greywater in 20% of buildings	52-139	40%	67.4-100%

Paris employs a comprehensive, data-driven approach to both flood and drought risk management that integrates advanced modeling, smart infrastructure, and sustainable planning. However, these systems are primarily designed for managing fluvial flood risks and water resources. A noted challenge remains the fragmented nature of governance: different public and private sector stakeholders often work in silos, hindering the implementation of integrated strategies necessary to build systemic urban resilience [27].

3.5. Vienna

The City of Vienna, Austria's capital and largest city, is home to nearly 2 million inhabitants and is one of the fastest-growing urban areas in Central Europe. Land cover within Vienna's municipal boundaries includes approximately 20% forest, 15% agricultural land, and nearly 40% built-up areas, with about 27% of the city covered by green spaces such as parks, gardens, and recreational areas [3]. With its long-standing focus on sustainable urban development, Vienna implements extensive green infrastructure policies including the Urban Heat Island Strategy Plan and Smart City Wien Framework Strategy to increase resilience to climate-related risks such as pluvial flooding and heatwaves, while maintaining a high quality of life for its residents [28]. Vienna's UFRM strategies aimed at pluvial flooding rely upon the Dual Infiltration System (a dual infiltration model that differentiates between contaminated and clean rainwater), and the Green Infrastructure and Sponge City Concept. The latter implies the measures aiming to make urban areas more resilient to flooding by absorbing and retaining rainwater. The most notable example of strategy implementation is a completely new suburb area "Seestadt Aspern" [29].

Vienna is implementing wireless ad-hoc sensor networks to monitor drought stress in specific crops and urban greenery. These networks allow for long-term observation of environmental parameters, providing valuable data to inform water resource management and drought mitigation strategies [30].

4. DISCUSSION

The analysed cities are ranked according to its Smart City Index [8] among 146 cities, while Dortmund is not measured. Besides, each city is assigned to one of four groups, based upon its Human Development Index (HDI) values. The cities are distributed into four groups based on the Global Data Lab's Subnational Human Development Index (SHDI) score of the city they are part of. Within each SHDI group, cities are assigned a 'rating scale' (AAA to D) based on the perceptions-score of a given city compared to the scores of all other cities within the same group (Table 2). In the case of studied cities, groups 1 and 2 are important. For group 1 (highest HDI quartile), scale is AAA–AA–A–BBB– BB, and for group 2 (second HDI quartile), scale is A–BBB– BB–B– CCC [8]. There are two pillars for which perceptions from residents are solicited: The Structures pillar referring to the existing infrastructure of the cities, and the Technology pillar describing the technological provisions and services available to the inhabitants.

Table 2. Studied smart cities ranking and rating for 2024 (Source: [8])

Smart city	Ranking (out of 146)	Rating	Factor rating		Group
			Structures	Technologies	
Amsterdam	17	A	AA	AA	1
Barcelona	92	CCC	B	BB	2
Paris	71	BB	BB	A	1
Vienna	26	A	A	A	1

Although the topics of UFRM and UDRM are not included in the survey, the general impression about individual studied smart cities is in an agreement with our results.

Amsterdam combines decentralized green infrastructure and smart technologies, such as blue-green roofs and smart valves, to manage both flood and drought risks. The city's

ongoing “Thirsty Cities” project and Rainproof initiative demonstrate a proactive, cross-sectoral approach to climate resilience.

Barcelona applies advanced modeling and IoT systems to address urban flood and drought risks, integrating NBS strategies tailored to hydrological conditions. Its smart water management and participation in RESCCUE position it as a leader in adaptive urban planning.

Dortmund has implemented a comprehensive flood resilience strategy combining traditional infrastructure, NBS, and cutting-edge technologies like AR flood visualization and thermal monitoring. The city’s regulatory and planning frameworks strongly support long-term integration of green infrastructure.

Paris promotes extensive greening through legal mandates and data-driven stormwater strategies, aiming to enhance flood resilience and urban biodiversity. However, increasing drought risk and fragmented governance present challenges to fully integrated water management.

Vienna applies sponge city concepts and smart monitoring systems to manage both urban flooding and drought stress. The city’s systemic approach combines policy, infrastructure, and digital tools for high-quality, climate-resilient urban development.

5. CONCLUSION

Smart cities are committed to enhancing urban livability through the integration of modern technologies. Based on the review and analysis of five European smart cities—Amsterdam, Barcelona, Dortmund, Paris, and Vienna—in the context of urban flood risk management (UFRM) and urban drought risk management (UDRM), the following conclusions can be drawn:

1. Climate adaptation measures targeting heatwaves and urban heat islands have indirectly supported urban drought risk management, primarily through greening initiatives. However, concerns have been raised regarding the availability of water for maintaining such green infrastructure during periods of water scarcity.
2. All five cities are actively advancing the implementation of nature-based solutions (NBS) to address both flood and drought risks, highlighting a shared strategic approach toward sustainable and resilient urban development.
3. Technological innovation in support of climate resilience is highly developed, with some cities piloting advanced tools—such as virtual reality (VR) and augmented reality (AR)—for infrastructure monitoring, risk visualization, and public engagement, although these technologies are currently in experimental stages.

Future research should focus on developing integrated frameworks that combine NBS with digital twin technologies, allowing cities to model, predict, and respond to both floods and droughts in a unified system. Comparative studies across cities should investigate the long-term performance and co-benefits of different NBS types under varied climatic, hydrological, and socio-political conditions. Further, governance research is needed to understand how institutional structures either enable or inhibit systemic adaptation across sectors. Co-creation processes that include vulnerable communities, interdisciplinary experts, and utility providers should be strengthened to ensure that innovation is inclusive, scalable, and context-sensitive. The next phase of urban water resilience lies in the fusion of nature, data, and design into dynamic, adaptive systems.

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Research paper

IMPLEMENTING AN ESG STRATEGY IN A CONSTRUCTION COMPANY

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Abstract

Implementing an ESG strategy in business is one of the important steps on the path to sustainable development. In the construction sector, which is one of the largest consumers of natural resources and producers of emissions, the implementation of ESG principles is becoming a necessity.

The aim of the article is to describe the issue of implementing a sustainability strategy and setting specific ESG (environmental, social, governance) goals in the construction industry and a case study, including a description of the implementation of an ESG system in a selected construction company and the design of possible adjustments leading to improved functionality of this system.

ESG is a systematic framework that evaluates the non-financial performance of companies in three main ESG areas: E – environmental, S - social, G - governance.

This article focuses primarily on the environmental component of the ESG model, which in the context of the construction industry includes efficient resource management, waste minimization, recycling of building materials and emission reduction. The case study analyzes a specific contract that consists of the demolition of old industrial buildings. This project is unique in that it uses crushed concrete recyclate to create the fill body under the floors. The work focuses on a detailed analysis of the process, from initial plans and preparation, through the implementation of the work, to the evaluation of the results and the identification of recommendations for future projects. The work seeks to highlight the possibilities of improving environmental efficiency through a responsible approach to waste and recycling. At the same time, it emphasizes the need to introduce innovative technologies and strategies that contribute to the sustainable development of the construction industry.

Key words: ESG strategy, construction industry, recycling, circular economy

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1. INTRODUCTION

Global challenges such as climate change, increasing waste production and depletion of natural resources are creating increasing pressure for the implementation of sustainable solutions in construction companies. The ESG strategy provides a framework for achieving this goal while taking into account the impact of all its activities on the environment. Special emphasis is placed on the issue of waste management, which is one of the most pressing areas of environmental sustainability in the construction industry. Recycling and reuse of materials represent promising solutions that reduce the burden on landfills, save natural resources and support the circular economy [1,2].

Implementing an ESG strategy in business is one of the important steps on the path to sustainable development. In the construction sector, which is one of the largest consumers of natural resources and producers of emissions, the implementation of ESG principles is becoming a necessity. The aim of this strategy is to support sustainable development and improve the environmental, social and governance aspects of business processes [3,4].

The ESG framework provides a comprehensive view of the sustainability of organizations, combining environmental, social and governance aspects. Its multidimensional structure allows for the identification and management of various changes and opportunities, from climate change to social inequalities. ESG analysis thus offers a valuable tool for strategic decision-making, enabling not only financial decisions but also an understanding of broader societal contexts [5].

In the context of European policy, the position of the ESG framework has been significantly strengthened in recent years. This framework is closely linked to EU goals, such as the 2019 European Green Deal, which commits all Member States to achieve climate neutrality by 2050, or the 2030 Agenda, of which 17 Sustainable Development Goals are a key part. In response to the growing importance of ESG, the introduction of binding documents that Member States must incorporate into their national legislation. The key document in this area is the Directive of the European Parliament and of the Council (EU) 2022/2464, entitled Corporate Sustainability Reporting Directive (CSRD), which introduces requirements for reporting non-financial sustainability information, thereby increasing transparency, reliability and comparability of data that will facilitate decision-making for all stakeholders [6,7].

From the beginning of 2024, companies to which this obligation applies must regularly publish sustainability reports. Obligatory entities are organizations that meet at least two of the following three conditions, namely that the company has more than 250 employees, has a net turnover of at least 1 billion CZK (40 million EUR), and balance sheet assets are higher than 500 million CZK (20 million EUR). [8] It is clear from these conditions that these are mainly large companies.

Since the article focuses only on the Environmental part of the ESG strategy, namely on waste management, this issue will be discussed only briefly. Waste management is a key area of environmental policy, focused on effective waste management in accordance with the principles of sustainable development. Modern waste management plays an important role in protecting the environment and public health. At the same time, it contributes to the circular economy, thereby supporting the reduction of the consumption of primary raw materials. An important tool in this area is legislation, which sets out rules and obligations for individuals, businesses and public administration [9].

In the field of waste management, the Czech Republic is governed not only by national legislation, but also by European directives. The European Union has adopted several framework directives aimed at regulating waste flows and reducing negative impacts on the environment. Directive (EU) 2018/851 of the European Parliament and of the Council constitutes the legal basis for modern recycling and waste management. It clearly defines what can be considered waste and sets criteria according to which materials can be classified as either by-products, products that are created as a by-product of the production process, or lose their waste status when certain conditions are met. An important aspect of this directive is the definition of the use and recognition of the potential benefit of waste [10].

In Czech legislation, waste management is primarily regulated by the aforementioned Act on Waste No. 541/2020 Coll., which divides waste into only two basic categories – other and hazardous. Together with Act No. 545/2020 Coll., on packaging and other related legal regulations regulate all aspects of waste management, from its generation to final disposal. They set strict requirements for waste sorting, collection, recycling and disposal, thus their aim is to minimize the negative impacts of waste on the environment, promote recycling and reuse, and at the same time set clear rules for waste management [11,12]. According to the Waste Act, waste generators and persons authorized to conduct waste business are obliged to send reports on annual waste production and management to the relevant municipal office of the municipality with extended obligations. This data is entered into the national ISOH2 database and is subsequently sent to the European Commission [12].

Waste classification is necessary for the purposes of their correct recovery and management. Waste is divided according to several criteria, such as origin, composition and hazard. An important document for waste classification is the Decree on the Catalogue of Waste and Assessment of Waste Properties No. 8/2021 Coll., which contains a detailed list of all types of waste and their classification into individual categories [13].

Many authors from different countries of the world deal with the management of the circular economy, or rather the circular economy. For example, Tomič and Shneider published an article in 2020 in terms of the socio-economic impacts of changing the system structure of the circular economy [14]. Waste management in the sense of energy recovery was addressed by the authors Brunner and Rechberger, who identified this as key for sustainable waste management [15]. E-waste in an international context, where they presented primarily an overview of trade flows, regulations, hazards, waste management strategies and technologies for value recovery, was addressed by the authors Ilankoon, Ghorbani, Chong, Herath, Moyo and Petersen [16]. An overview of waste management decision-making methods in the construction industry was described in an article by Palafox-Alcantar, Hunt, and Rogers [17]. The possibility of using fresh concrete waste in concrete for non-structural engineering works as a waste management strategy was already discussed in 2017 by Rughooputh, Rana, and Joorawon [18]. The application of smart waste management was discussed in 2021 by Petriwi, Kristinayanti, Andayani, Aryawan, Indrayanti, and Sudiarta at the Department of Civil Engineering, Bali State Polytechnic [19]. The redefining of construction and demolition waste management systems and best practices for construction works was discussed by Sáez, Báez, and Navarro in 2020 [20]. A case study on the dynamic analysis of the construction and demolition waste management system in Tehran, Iran was compiled by Ghanbari in 2022 [21]. Last but not least, the authors Drochytka, Dufek, Michalčíková and Hodul studied the possibility of using special types of construction and demolition waste in the construction industry in their article in 2020 [22].

2. METHODOLOGY

The case study deals with the identification, sorting, and analysis of individual types of waste. In order to carry out these, the individual types of waste were identified in two phases of the construction contract, namely:

- design phase,
- implementation phase.

In the design phase, waste was identified from the project documentation, where the expected types of waste to be produced were considered.

In the implementation phase, waste was identified from the implemented construction budget and from the construction company's accounting, where invoices for waste disposal were identified from specialized companies dealing with this issue.

The following phases were used within the methodology:

- identification,
- description,
- analysis,
- comparison,
- evaluation.

3. CASE STUDY

The case study is based on a construction contract that includes the demolition of 9 buildings intended for various types of activities. The construction company that implemented this large contract is medium-sized. This means that it is not currently subject to the ESG framework obligation, but within the framework of waste management (i.e. the Environmental area), this company must report the amount of construction and demolition waste produced. The case study focuses on identifying construction and demolition waste in some phases of the construction contract.

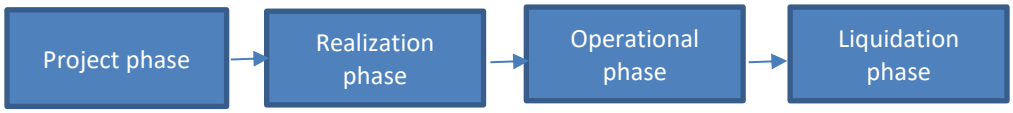


Figure 1. View construction contract phases [source own]

The aim of the study is to identify the differences between planned and actual waste volumes and to analyse the factors that influenced these differences. Attention is paid to technological processes, planning quality, work efficiency and possibilities of separation and recycling on the construction site. An important part of the analysis is the examination of the use of the waste generated, assessing whether the principles of the circular economy have been observed and the amount of waste disposed of in landfills has been minimised.

The results of this analysis can provide valuable insights into the possibilities of streamlining waste management in the construction industry and linking the individual phases of the construction contract from the perspective of the generated construction and demolition waste.

3.1. Description of construction order

The construction contract concerns the demolition of a site that was previously a manufacturing plant. This site consists of several buildings that form a single functional unit. These are buildings built around the third quarter of the 20th century, which are technologically outdated, energy inefficient and no longer meet current requirements for industrial production. They are built from materials that corresponded to the time of their construction and do not show any major static defects that threaten stability. However, there are signs of degradation and wear, especially in materials with a shorter lifespan, such as wooden structures, hole fillings, metalwork and plumbing elements or external surface finishes. The perimeter structures do not meet current thermal and energy standards. There are a total of 9 different buildings - these are mainly former production halls and storage areas, and the site also includes a former administration building, a bicycle shed, a stonemason's workshop and a sauna.

The demolition was preceded by emptying the buildings, dismantling the technologies and thoroughly cleaning all areas. The scope of the demolition included the removal of above-ground and underground parts of the buildings, including infrastructure and paved areas with a total area of approximately 7,000 m2. The infrastructure of the area includes gas, electricity and water distribution, but their exact condition and routes were not known. According to available information, there was no sewage network in the area. During the removal of the buildings, a significant amount of demolition materials of various types were created, which are related to the scope and nature of the structures and materials used. The demolition work was carried out using procedures that maximize the reuse or recycling of the resulting materials. suitable for recycling in the construction industry. The waste generated by the buildings was divided into several basic groups according to their nature based on the Waste Catalogue. The estimate of their quantity is only indicative and is based on the scope of the planned work. The approximate amount of waste produced during the implementation of the construction contract is created in the project part, when the construction contract budget is created based on the project documentation. The amount of waste is shown in Table 1.

The demolition of the buildings was carried out with an emphasis on sorting and recycling the resulting construction waste. Extensive landscaping was also carried out simultaneously with the demolition. An embankment was constructed on the compacted plain using demolition recyclate. The biggest problem during the demolition was the large differences in the obtained recyclate. This was due to the non-existent project documentation of the original buildings. Although the quality of the materials seemed to be in line with the assumptions, the higher volume required additional modifications and increased demands on logistics and separation, which resulted in increased financial costs.

3.2. Utilization of individual waste generated for recycling

Before the demolition work began, it was assumed that part of the concrete raw material would be used in the construction and the remaining amount would be left on the investor's land. Despite the higher amount of **concrete waste material** produced, it was found that this volume was not sufficient to cover all the material requirements of the new project. All available concrete raw material was subsequently used in the construction work as a fill body under the floor of the new industrial building, and due to the increased demands on the project, it was also necessary to purchase additional aggregate.

In the case of **waste from brick structures**, the amount of waste increased compared to the original assumptions. The investor did not consider using this type of waste in the implementation of the new building (after the demolition of the existing building, and therefore it was taken to a landfill, where it was subsequently materially evaluated. This procedure takes into account the principles of the circular economy and contributes to increasing recycling and reuse of construction and demolition materials.

Before the demolition itself, **all glass elements** (windows, doors) were carefully dismantled, which were then stored in a designated place in marked containers. This glass waste was then transported to facilities specializing in its recycling.

The separated **plastic was** stored in marked containers, from where it was transported to recycling facilities. Recycling of glass and plastic waste not only reduces the amount of waste deposited in landfills, but also supports the principles of the circular economy and the fulfillment of legislative goals of reducing the environmental burden.

Asphalt mixtures, tar and products from it were mechanically removed and collected in designated places to prevent contamination with other waste. They were then transported to a recycling facility where they were crushed, cleaned and processed. This process supports the reuse of asphalt waste, minimizing the need for new raw materials and maximizing the use of existing construction materials.

All types of **metal waste** were materially recovered, which is an effective and environmentally responsible solution. Metal elements were dismantled manually or mechanically, taking care to minimize their damage and contamination with other materials. Separated waste was stored in designated areas and transported to a waste processing facility.

Soil formed a significant part of the waste generated. Clean and uncontaminated soil was used for backfilling and landscaping. Before being used, the soil had to be screened, which means sieving it to remove unwanted particles such as construction material residues, stones, roots or other impurities. The screened soil has a homogeneous composition and better properties (compactionability, grain size) for further use.

The original estimates regarding the amount of **insulation waste material** turned out to be inaccurate, the actual amount was higher than expected. Due to the contamination of the material, it had to be deposited in a specialized construction waste landfill. This type of waste must be handled in accordance with strict environmental regulations.

Other mixed construction and demolition waste was deposited in a specialized construction waste landfill. Recycling is considered an unsuitable waste treatment option in this case, due to the demanding implementation directly on the site of the demolition work.

For **other municipal waste** – paper, plastic packaging, textiles, it was necessary to ensure proper separation. This waste was first sorted at the place of origin, where the individual materials were separated into different containers or bins. Waste that is suitable for recycling was transported to a facility for further processing. If the waste could not be separated, it was taken to a landfill, where it was subsequently deposited. This approach takes into account the need to minimize the environmental impact by choosing landfilling only as a last resort.

3.3 Result of Case Study

Table 1 shows a comparison of the expected and actual amounts of waste generated during demolition, including variations in volume and costs associated with disposal. As

stated in the previous chapter, the expected amounts of waste were determined based on available data from the design phase, i.e. from the project documentation. The actual amount of waste in the implementation phase was determined from the construction contract implementation budget and based on the accounting output, where invoices for the removal and disposal of individual types of waste in specialized centers were identified. The actual amount of waste confirmed significant variations in the volume of individual types of waste, which was mainly caused by incomplete project documentation and failure to take into account the specifics of the demolished area, which was previously used as a facility for the production of small concrete elements. The exact amount of waste could not be determined, with the exception of categories 17 06 – Insulation material and 17 09 – Other construction and demolition waste, where data is available from cash receipts issued by the facility after receiving the waste at the landfill, i.e. from the construction company's accounting.

Table 1 therefore shows the individual types of waste that were generated within the construction contract, and the amounts were identified in two phases of the construction contract, namely:

- project phase – the amount is determined from the project documentation,
- implementation phase – the amount is determined from the implemented construction budget and from the construction company's accounting.

Table 1. Overview of types of demolition waste with expected and actual quantities and costs, [source own]

Catalog number	Waste name	Estimated quantity [t]]	Actual quantity [t]	Deviation [t]	Estimated costs [CZK]	Actual costs [CZK]]
17 01	**Concrete, bricks, tiles and ceramics**	**7 584.66**	**13 909.00**	**6 324.34**	**-**	**-**
17 01 01	Concrete	5 976.98	11 452.00	5 475.02	-	-
17 01 02	Bricks	1 523.02	2 457.00	933.98	-	for transportation
17 01 07	Mixtures or separate fractions of concrete, bricks, tiles and ceramic products not specified under heading 17 01 06	84.66	-	-	-	-
17 02	**Wood, glass and plastics**	**27.23**	**-**	**-**	**-**	**-**
17 02 01	Wood	12.41	-	-	-	-
17 02 02	Glass	12.29	-	-	-	-
17 02 03	Plastics	2.53	-	-	-	-
17 03	**Asphalt mixtures, tar and tar products**	**3.95**	**-**	**-**	**-**	**-**
17 03 02	Bituminous mixtures other than those mentioned in 17 03 01	3.95	-	-	-	-
17 04	**Metals**	**44.16**	**-**	**-**	**-**	**-**
17 04 01	Copper	0.42	-	-	-	-
17 04 02	Bronze	0.63	-	-	-	-
17 04 05	Brass	39.86	-	-	-	-
17 04 07	Aluminum	1	-	-	-	-
17 04 11	Iron and steel	2.25				

Catalog number	Waste name	Estimated quantity [t]]	Actual quantity [t]	Deviation [t]	Estimated costs [CZK]	Actual costs [CZK]]
	Mixed metals	-	-	-	-	-
17 05	**Soil (including excavated soil from contaminated sites), aggregates, excavated waste rock and tailings**	**1 502.82**	**-**	**-**	**-**	**-**
17 05 04	Soil and aggregates other than those mentioned in 17 05 03	1 502.82	-	-	-	-
17 06	**Insulation material and building materials containing asbestos**	**1.25**	**54.02**	**52.77**	**-**	**40 888.00**
17 06 04	Insulation materials other than those mentioned in 17 06 01 and 17 06 03	1.25	54.02	52.77	-	40 888.00
17 09	**Other construction and demolition waste**	**2.65**	**19.64**	**16.99**	**-**	**20 610.00**
17 09 04	Mixed construction and demolition wastes other than those mentioned in 17 09 01 and 17 09 03	2.65	19.64	16.99	-	20 610.00
20 03	**Other municipal waste**	**6.44**	**-**	**-**	**-**	**-**
20 03 01	Mixed municipal waste	4.44	-	-	-	-
20 03 99	Municipal waste not otherwise specified	2	-	-	-	-
Total		**9 173.16**	**-**	**-**	**4 000 000**	**5 231 453**

Note: 1 Euro = 25.50 CZK

To understand the data in Table 1, it is necessary to add several conditions:

- the estimated quantity was determined in the design phase, i.e. from the design documentation,
- the actual quantity was determined based on the implemented construction budget of the construction contract, or from accounting, i.e. from invoices from specialized companies that deal with waste management,
- if the values of the estimated quantity and the actual quantity differ, or are not determined in one, then they were not identified at this stage,
- the total price of the estimated quantity was determined in the design phase, i.e. as estimated and was determined as a whole,
- the total price of the actual quantity was determined based on the implemented construction budget or directly from the accounting of the construction company.

4. DISCUSSION

From the case study, which included a construction contract focused on the demolition of 9 buildings made of various types of material, it is clear that waste management, especially construction and demolition waste, needs to be further streamlined. From the description of the case study, it is clear that there is currently pressure not only on construction companies

to approach the management of construction contracts in an ecological, i.e. environmentally friendly way. However, it is clear here, especially from Table 1, that not all tools for the management of effective waste management exist yet. Especially in the design phase, where in this part of the construction project, with inaccurate or completely missing input data, it is not possible to specify in detail the expected individual types of waste. For example, this fact can be caused, as in this case study, by the lack of original project documentation.

From Table 1, it is clear that large deviations in quantity were found for almost all individual types of waste, which is due to ignorance of the original project documentation and ignorance of the structures of the original 9 buildings. The total estimated price was also inaccurately estimated, with the difference between the actual and estimated price being a 30% increase over the estimated value. This increase is again due to unfamiliarity with the terrain, the construction of demolished buildings that are not visible (e.g. foundations that are underground) and the lack of original project documentation that would map the current state of the buildings.

5. CONCLUSION

The implementation of an ESG strategy in the construction industry is necessary not only as a response to growing environmental, social and legislative requirements, but also as a key step towards the sustainable development of the entire sector. This diploma thesis, focusing on the environmental component of ESG, analyzes the issues of waste management, recycling of construction materials and specific possibilities for the use of crushed concrete recyclate in the construction of a new industrial complex. The results point to the fact that responsible management of construction waste, its recycling and reuse represent effective solutions for reducing the ecological footprint of construction companies, while supporting the circular economy.

Although the environmental (E) component of ESG plays a key role in the analyzed construction company, its implementation should be only the first step. It is recommended to gradually expand the strategy to include social (S) and governance (G) aspects. Adopting these pillars can bring several significant benefits to the company. Emphasis on the social dimension can improve the working environment, increase employee satisfaction and loyalty, and at the same time strengthen the company's reputation in the market. The management pillar emphasizes transparency, ethical business and effective risk management, which leads to long-term stability of the company.

The example of a specifically addressed project demonstrates the effectiveness of the use of recycled materials, while also showing the challenges associated with their wider implementation. These challenges include insufficient legislative support, the simplicity of landfilling compared to other methods and the need for technological innovations. Changing this situation requires the introduction of higher landfill fees, support for recycling centers and the dissemination of awareness in the field of recycling.

In conclusion, it can be stated that the implementation of ESG principles in the construction sector is not only a challenge, but also a huge opportunity. This work points to the practical possibilities and benefits of a responsible approach to construction and demolition waste and provides opportunities for its further use. Sustainability in the construction industry should not be perceived only as an obligation, but as a strategic

investment in the future, which brings innovation, increases efficiency and supports the long-term competitiveness of the entire sector.

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Research paper

FLEXURAL STRENGTH CAPACITY OF THE CONCRETE BEAMS PRODUCED USING DIFFERENT CONCRETE VARIABLES

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Abstract

Flexural strength capacity of the concrete beams depends on different variables such as compressive strength of the concrete, type of the reinforcement used, amount of the reinforcement and cross section of the beam. The flexural strength is expressed as Modulus of Rupture, and it is determined according to ASTM C 293 (center-point-loading). This research is dedicated to investigation of the flexural strength capacity of the concrete beams fabricated using different type of concrete mixtures and different type of reinforcement. The tests presented here were conducted on concrete beams having square cross sections 6 x 6in with 5 ft in length (15cm x 15cm x 1.52m) at Kennesaw State University. Two different types of reinforcement were investigated: type #4 (13mm) rebar and Greenbar 2x1/2in Fiberglass #4 (13mm) rebar along with two different concrete mixture types. Type III cement was used in order to achieve high early strength, and beams were tested to failure when concrete reached prescribed value of 4000 psi (27.6 MPa). In this experimental program load-deflection relationship, load capacity and ductility were the main parameters which were investigated.

Key words: *Flexural Strength Capacity, Ductility, Load-Deflection relationship*

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1. INTRODUCTION

Flexural strength is a fundamental parameter in evaluating the performance of reinforced concrete members subjected to bending. It is influenced by multiple factors, including the compressive strength of the concrete, the type and amount of reinforcement, and the geometry of the cross section. The flexural strength of concrete beams is commonly expressed as the Modulus of Rupture and is typically determined through standardized testing procedures such as ASTM C293, which utilizes a center-point loading method.

In recent years, there has been growing interest in exploring alternative reinforcement materials and concrete mixtures to enhance structural performance and durability. Among these alternatives fiberglass reinforcement—have emerged as a promising substitute for conventional steel reinforcement, particularly in aggressive environments where corrosion resistance is critical. According to Ahmed Lamine investigation [1] the gain in terms of concrete strength by reinforcement with fiberglass was significant and around 37% and decrease in the radial deformation was observed. Xiangije Ruan and Chunhua Lu [2] found that ultimate flexural capacity of GFRP concrete beams was nearly 91-97% of that of steel reinforced concrete beams. Hadi et al. concluded that the ultimate load of the concrete beams fabricated with pultruded GFRP grating mesh ranged between 19-38% higher than the ultimate load of the beams produced with steel rebars [3].

At Kennesaw State University, complex experimental and analytical studies of stress-deflection state, the formation and development of normal cracks on concrete beams produced with two different concrete mixtures and two different types of reinforcement have been carried out. This study investigates the flexural behavior of concrete beams reinforced with two different types of reinforcement—traditional #4 (13 mm) steel rebar and #4 (13 mm) Greenbar fiberglass rebar—combined with two distinct concrete mixtures. All beams were fabricated using Type I cement and were tested to failure upon reaching a prescribed value of compressive strength of 4000 psi (27.6 MPa). The experimental program was focused on evaluating key performance metrics, including load-deflection behavior, ultimate load capacity, and ductility. The results provide comparative insight into the structural effectiveness of steel and fiberglass reinforcement under standardized loading conditions, contributing to ongoing discussions on the viability of non-metallic reinforcements in structural applications.

2. MATERIAL

Two types of reinforcement were used in this research Greenbar2X Fiberglass Rebar #4 and Steel Rebar #4. Fiberglass Rebar has higher tensile strength and durability with lighter weight in comparison to steel rebar. Two different types of concrete mixtures were investigated with the granite as aggregate [4] as shown in Tables 1 and 2. The second concrete mixture had Fly Ash as a replacement of 30% of cement.

Water to cement ratios for all concrete beams was 0.32 with compressive strength of concrete of 4000psi (27.6 MPa). Type I cement was used in this research. Compressive strength was reached after 9 hours. Granite was used as aggregate with 100% passing the 3/8 in sieve. Prior to the casting operation, all the material was dried in an oven to gain consistency in mixture proportions. The aggregates were dried in an oven at 200 deg Fahrenheit for approximately 24 hours to ensure the moisture content was zero. After drying, the aggregates were then stored in a dry storage container until they were used for batching.

Two hours before the mixing operation, the materials were weighed and stored in buckets located in a temperature-controlled room until the concrete was batched. This procedure ensured consistency in batch temperature and almost the same slump for all mixes [4, 5, 6].

To mitigate plastic shrinkage, MasterFiber M100 was added to both concrete mixtures. The slump test was conducted immediately before casting, yielding a value of 7 inches (17.8 cm).

Table 1. Concrete Mix Design #1

Material	Weight lbs/yd^3 (kg/m^3)
Cement	813.8 (482.8)
Water	260.4 (154.5)
Crushed Granite	1447 (858.5)
Sand	1447 (858.5)
HRWR	81 fl.oz/yd^3 38.8ml/m^3
MasterFiber M100	0.50 (0.3)

Table 2. Concrete Mix Design #2

Material	Weight lbs/yd^3
Cement	572.5 (339.3)
Fly Ash	241.3 (143.2)
Water	260.4 (154.5)
Crushed Granite	1447 (858.5)
Sand	1447 (858.5)
HRWR	81 fl.oz/yd^3 38.8 ml/m^3
MasterFiber M100	0.50 (0.30)

3. METHODOLOGY

This experimental study was designed to investigate the flexural behavior of concrete beams reinforced with two different types of longitudinal reinforcement: traditional steel and fiberglass rebar. A total of two beam specimens were fabricated using identical dimensions and concrete mix design, with the only variable being the type of reinforcement as shown in Figure 1.

Each beam had a square cross section measuring 6 in × 6 in (15 cm × 15 cm) and a total length of 5 ft (1.52 m). One beam was reinforced with a conventional #4 (13 mm diameter) steel rebar, while the other incorporated a #4 (13 mm) Greenbar fiberglass rebar, a composite material commonly used in corrosion-resistant applications. After casting, the beams were moist-cured under controlled laboratory conditions until the concrete reached a target compressive strength of 4000 psi (27.6 MPa), at which point they were tested to failure.



Figure 1. Beam Cross Section a) Fiberglass #4 as reinforcement b) Steel Rebar #4 [7]

Flexural testing was conducted in accordance with ASTM C293, employing a center-point loading setup to measure the Modulus of Rupture. During testing, key parameters including load-deflection response and maximum load capacity were recorded. Comparative analysis was performed to assess the influence of reinforcement type on the structural performance of the beams under flexural loading.



Figure 2. Concrete Beam Setup

4. RESULTS

This research was focused on investigation of the beams produced with different type of reinforcement and concrete mixtures. Fiberglass #4 and Steel Rebar #4 were used in testing, and concrete mixture having angular aggregate and Microfiber and concrete mixture with fly ash as a replacement of cement. Three-point flexural tests were done in order to understand the effect of different type of reinforcement and concrete mixtures on Modulus of Rupture. The experimental results reveal varied mechanical responses across specimens, highlighting differences in stiffness, ductility, and load capacity.

All specimens exhibited an initial elastic response marked by proportional increases in displacement with load. Mix#1 with Fiberglass and Mix#2 with Steel Rebar showed higher

maximum load capacities of 4400 lbs (19.57 kN) and 4800 lbs (21.35 kN), respectively, while Mix #1 with Steel Rebar and Mix #2 with Fiberglass reached lower peak loads of 3000 lbs (13.34 kN) and 1000 lbs (4.45 kN).

Table 3. P-δ values Mix #1 with Fiberglass

P (lbs) (kN)	δ (in) (cm)
460 (2.05)	0.041(0.10)
960 (4.27)	0.183 (0.46)
1200 (5.34)	0.240 (0.61)
1500 (6.67)	0.299 (0.76)
2000 (8.89)	0.451 (1.14)
2500 (11.12)	0.552 (1.40)
3000 (13.34)	0.562 (1.43)
3500 (15.57)	0.569 (1.44)
4000 (17.79)	0.565 (1.44)
4400 (19.57)	0.548 (1.39)

Table 4. P-δ values Mix #1 with Steel rebar

P (lbs) (kN)	δ (in) (cm)
350 (1.56)	0.045 (0.11)
730 (3.25)	0.177 (0.45)
1000 (4.45)	0.216 (0.55)
1500 (6.67)	0.284 (0.72)
2000 (8.90)	0.389 (0.99)
2500 (11.12)	0.497 (1.26)
3000 (13.34)	0.606 (1.54)

Table 5. P-δ values Mix #2 with Steel rebar

P (lbs) (kN)	δ (in) (cm)
350 (1.56)	0.014
530 (2.36)	0.069
850 (3.78)	0.092
1050 (4.67)	0.122
1500 (6.67)	0.149
2000 (8.90)	0.190
2500 (11.12)	0.224
3000 (13.34)	0.228
3500 (15.57)	0.243
4000 (17.79)	0.289
4800 (21.35)	0.473

Table 6. P-δ values Mix #2 with Fiberglass

P (lbs) (kN)	δ (in) (cm)
500 (2.22)	0.074 (0.20)
1000 (4.45)	0.162 (0.41)

Mix #1 with Steel rebar showed a more gradual and ductile response with steady displacement increase up to 3000 lbs (13.34 kN), without clear softening.

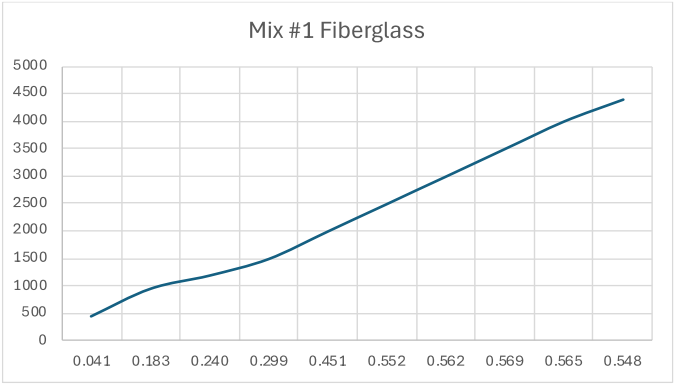


Figure 3. P-δ diagram for Mix #1 produced with Fiberglass

Mix #1 with Fiberglass demonstrated early stiffness followed by a plateau in displacement beyond 2500 lbs (11.12 kN), suggesting onset of softening.

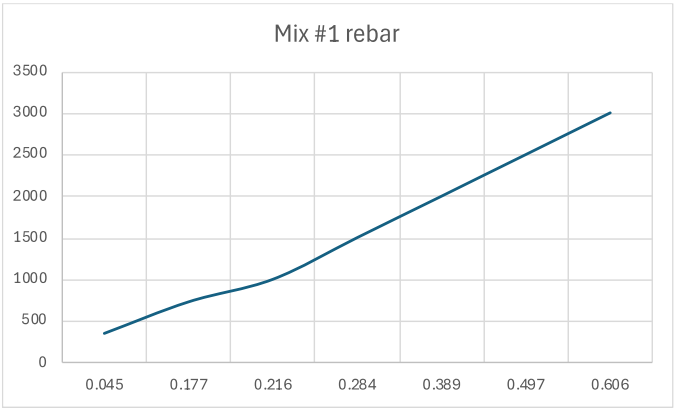


Figure 4. P-δ diagram for Mix #1 produced with Steel Rebar

Mix #2 with Steel rebar sustained the highest load, with displacement increasing gradually and reaching 0.473 in (1.20 cm) at 4800 lbs (21.35 kN), showing strong stiffness retention.

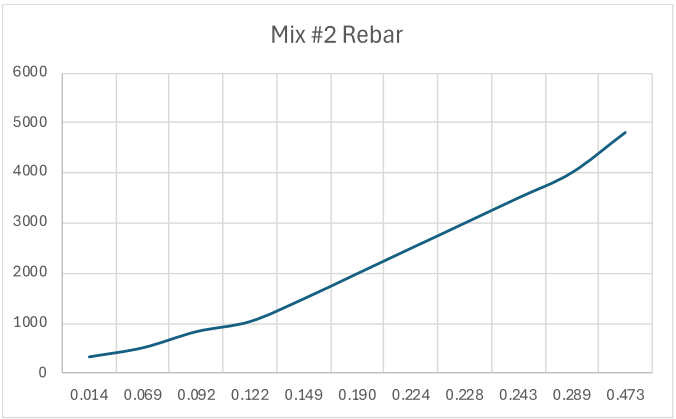


Figure 5. P-δ diagram for Mix #2 produced with Steel Rebar

Mix #2 with Fiberglass was tested only up to 1000 lbs (4.45 kN), aligned with early-stage elastic behavior observed in other specimens, confirming consistency in initial stiffness.

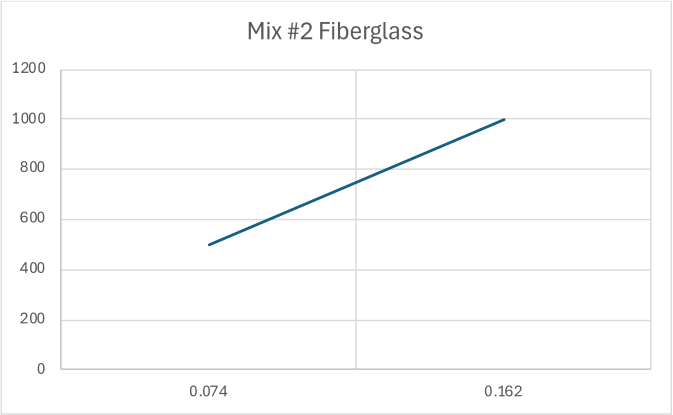


Figure 6. P-δ diagram for Mix #2 produced with Steel Rebar

The Modulus of Rupture values were as follows: Mix #1 reinforced with fiberglass achieved 1833 psi (12.64 MPa), Mix #1 with steel rebar reached 1250 psi (8.61 MPa), Mix #2 with steel rebar recorded 2000 psi (13.79 MPa), and Mix #2 reinforced with fiberglass measured 416 psi (2.87 MPa).

5. CONCLUSIONS

This study evaluated the load–displacement behavior of four structural specimens under monotonic loading. The experimental results revealed notable differences in mechanical responses, which can be summarized as follows:

- Mix #1 with Fiberglass and Mix #2 with Steel Rebar demonstrated the highest load capacities, reaching 4400 lbs (19.57 kN) and 4800 lbs (21.35 kN), respectively. Mix #1 with Fiberglass exhibited early stiffness with a subsequent plateau, indicating potential damage or softening, whereas Mix #2 with Steel Rebar maintained stiffness with a gradual displacement increase, suggesting enhanced structural resilience.
- Mix #1 with Steel rebar showed a stable and ductile response with moderate peak load (3000 lbs or 13.34 kN), indicating consistent deformation without early loss of strength.
- Mix #2 with Fiberglass, limited to lower load levels, confirmed the initial elastic stiffness trend common across all specimens, serving as a baseline for early-stage structural behavior.

The observed variability among specimens emphasizes the influence of material properties, geometric factors, or boundary conditions on structural performance. These findings underscore the importance of testing multiple specimens to comprehensively characterize load-bearing capacity and deformation behavior.

Overall, the results provide valuable insight into the load bearing and deformation characteristics of the tested materials, informing design considerations and further investigations aimed at improving structural reliability and safety.

The differences in behavior also highlight the potential of hybrid reinforcement systems in tailoring structural performance for specific applications. Future research may explore cyclic loading conditions, long-term durability, and the effects of scale to better simulate real-world performance. Additionally, finite element modeling could be used to complement experimental findings and refine predictive models.

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Research paper

CONTEMPORARY HOUSING TRENDS IN NIŠ, SERBIA: AN ANALYSIS OF MARKET CONDITIONS AND REGULATORY COMPLIANCE

Slavisa Kondic[1], Katarina Medar[2] , Milica Zivkovic[3], Vojislav Nikolic[4], Mirko Stanimirovic[5]

Abstract

This study investigates contemporary housing trends in Niš, Serbia, focusing on urban planning, architectural practices, and socio-economic conditions influencing the local housing market. The primary objectives are to identify prevailing housing trends, assess their conformity with current regulatory frameworks, and propose improvements to planning policies. Employing a mixed-method approach, the research combines qualitative analysis of architectural developments, and regulatory compliance, supported by case studies of recent residential projects. The study highlights key market conditions affecting housing development, including limited purchasing power among potential tenants and increasing demand for affordable apartments. A noticeable preference for multi-family residential buildings has emerged, driven primarily by economic factors. Findings indicate partial alignment of these market-driven trends with existing regulatory constraints, pointing to specific limitations in current planning and regulatory practices. The research emphasizes the importance of revising regulatory frameworks to better address affordability issues, thus facilitating sustainable development and effectively responding to the housing needs of the population in Niš.

Key words: *Housing, Market Conditions, Affordability, Regulatory Compliance*

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1. INTRODUCTION

In the post-socialist context of Southeast Europe, housing systems have been reshaped by market liberalization and limited public investment [1]. Serbia, like many countries in the region, has undergone a profound transformation in its housing sector. The retreat of the state from housing construction, coupled with constrained regulatory enforcement capacity, has contributed to the emergence of an investor-driven housing market [1, 2]. These developments raise concerns about both the spatial adequacy and affordability of newly produced housing units. "The economic and political situation in the last twenty years has caused a fall in overall standards, affecting the quality of newly built dwellings... The average floor area of post-2001 apartments (53.0 m²) reflects a decline to 18.1 m² per person" [2].

The city of Niš, Serbia's third-largest urban center, offers an instructive case for examining the relations between housing production, affordability, and regulatory compliance. In recent years, Niš has experienced accelerated residential construction driven by rising demand. Simultaneously, there has been a growing prevalence of compact apartments targeted at buyers with limited purchasing power, mirroring broader post-socialist regional trends in residential construction and affordability challenges [1, 3]. These trends bring renewed attention to whether newly constructed housing units adhere to the national minimum spatial standards established by the regulatory framework – namely, the Rulebook on Conditions and Norms for the Design of Residential Buildings and Apartments [4].

Affordability challenges are central to this analysis. Although Niš remains more affordable than Belgrade, rapid increases in housing prices have significantly outpaced income growth. In 2024, the average price of newly built apartments in central Niš reached €1,774 per m², with average unit sizes around 57 m² [5]. By early 2025, real estate market data indicate that new apartments in prime areas of Niš exceeded €2,200/m². In contrast, the average net annual salary in Serbia for 2023 was around RSD 1,141,116 (≈€9,760) [6]. At this rate, a 55 m² apartment (costing roughly ≈€97,500) equates to about ten years of the average household income. This data had shown severity of the affordability gap. This financial strain often compels developers to design smaller units that may approach or fall below the minimum legal thresholds for floor area, potentially compromising the functional and qualitative aspects of living space.

This paper investigates the extent to which newly designed multi-family housing projects in Niš comply with the national minimum apartment size standards, and explores the economic and spatial rationales for any observed non-compliance. The analysis is based on a systematic review of 31 residential projects, comprising 1,155 individual apartment units, submitted as part of architectural documentation for urbanistic projects in recent year. Through comparative and compliance-based analysis, the study identifies deviations from prescribed norms, and contextualizes these findings within broader patterns of urban development and housing demand.

The objectives of this research are twofold. First, to quantify the level of alignment between current housing development practices in Niš and the Serbian regulatory framework for minimum dwelling areas. Second, to interpret these empirical findings in light of socio-economic pressures, market dynamics, and institutional constraints. In doing so, the paper contributes to ongoing debates on housing standards, affordability, and spatial justice in transitional urban contexts, with Niš serving as a central case study.

2. REGULATORY FRAMEWORK

Apartment design in Serbia is governed by a detailed regulatory framework that specifies minimum net floor areas based on apartment typology. The key legal instrument is the Rulebook on Conditions and Norms for the Design of Residential Buildings and Apartments (Official Gazette RS, Nos. 58/2012, 74/2015, and 82/2015). This Rulebook defines binding minimum sizes for apartments according to their functional structure. The prescribed minimum net floor areas are as follows:

- Studio apartment (garsonjera): ≥ 26.00 m²
- One-room apartment: ≥ 30.00 m²
- One-and-a-half-room apartment: ≥ 40.00 m²
- Two-room apartment: ≥ 48.00 m²
- Two-and-a-half-room apartment: ≥ 56.00 m²
- Three-room apartment: ≥ 64.00 m²
- Three-and-a-half-room apartment: ≥ 77.00 m²
- Four-room apartment: ≥ 86.00 m²
- Four-and-a-half-room apartment: ≥ 97.00 m²

In addition to these dwelling-level standards, the regulation also prescribes minimum floor areas for individual rooms (e.g., 16.00 m² for a living room, 11.00 m² for a double bedroom, 7.00 m² for a single bedroom (“half-room”). These quantitative norms aim to ensure basic spatial functionality, hygiene, and habitability.

2.1. Comparative Regional Approaches

Regulatory approaches to minimum dwelling sizes vary across Southeast and Central Europe. For example, Croatia employs implicit size standards in its state-subsidized housing programs (assigning roughly 40 m² for a one-person household and 60–65 m² for a four-person household). Slovenia favors performance- based criteria rather than fixed apartment sizes, ensuring spatial quality through room proportions and functional criteria (e.g., minimum bedroom widths). Hungary sets minimum areas per room (e.g., 8 m² for a single-occupancy room, 12 m² for a double room) but does not prescribe overall apartment sizes. Romania incorporates mandatory minimums in its urban planning codes (a two-room apartment must be at least 52 m², including an 18 m² living room and 12 m² bedroom; a one-room apartment must not be smaller than 37 m²). These examples reflect differing balances between prescriptive regulation and design flexibility.

Serbia’s model remains highly formalized, with explicitly quantified norms at both the apartment and room levels. Serbia’s regulatory framework, including the Rulebook on Conditions and Norms, establishes clear minimum spatial standards for housing. However, enforcement remains inconsistent due to institutional inertia, political leniency toward developers, and market pressures favoring affordability.

2.2. Challenges in Enforcement

Despite the clarity of Serbia’s normative framework, effective implementation faces challenges. Local permitting authorities often have incentives to interpret size norms flexibly, especially in the context of development pressures. Post-construction legalization processes

(whereby apartments are registered and legalized after the fact) may overlook minor non-conformities. Economic pressures create additional incentives for minimizing unit sizes; in a market with strong demand for low-cost housing, developers may be tempted to design apartments just below regulatory thresholds. In Niš and similar cities, these factors combine to create a regulatory environment where formal requirements exist on paper, but effective control over their consistent application may be limited.

3. HOUSING MARKET CONTEXT IN NIŠ

Niš, with a population of approximately 250,000, serves as the principal administrative, economic, and educational center of southern Serbia. Historically an industrial hub from socialist period, Niš has diversified its economy in recent years through foreign direct investment in manufacturing and information technology. The University of Niš reinforces the city's role as a regional knowledge center. Despite these advances, Niš continues to lag behind Serbia's northern urban centers in income and labor market indicators. Lower average wages and a persistent affordability gap make Niš's housing market particularly sensitive to price fluctuations. The city's modest income profile amplifies the impact of rising housing costs, influencing both demand and supply dynamics in the residential sector.

Statistical data from 2024 highlight Niš's income disparities. In April 2024, the average net monthly salary in Niš was around RSD 92,987, compared to the national average of RSD 96,614 (a gap of roughly 3.7%). In the capital Belgrade, the average net salary exceeded RSD 121,800 during the same period. On an annualized basis, net income in Niš is on the order of €9,500–10,000 (depending on exchange rate and inflation assumptions). Median wages are even lower, indicating that a substantial portion of the population earns significantly less than the average. These figures imply that many households in Niš have limited purchasing power for housing, reinforcing the demand for smaller, more affordable apartment units.

Niš's housing market has seen notable price increases in recent years. According to the Republic Geodetic Authority, the average price per square meter for new-build apartments in the last half of 2024 was €1,774 in Niš. In central municipalities like Medijana, prices reached above €2,000/m². This represents a significant rise from previous years and reflects sustained demand amid constrained supply. By comparison, Belgrade's new apartment prices exceed €2,400/m², making Niš more affordable in absolute terms. However, when measured against local incomes, housing remains expensive: the gap between prices and earning capacity continues to strain affordability in Niš.

When housing costs are measured against average incomes in Niš, the affordability gap becomes evident. For example, a newly constructed 55 m² apartment at €1,774/m² would cost about €97,500. With an average net annual income of roughly €9,800, this implies over ten years of gross income (assuming an extreme case of saving the entire salary, which is unrealistic given living expenses). Surveys suggest that more than half of young adults and families in Niš cannot afford homeownership without family assistance or subsidized mortgage programs. Renting is similarly burdensome: average monthly rents for one-bedroom apartments in 2024 were around €210–230, consuming a significant portion of household income.

These economic conditions have important implications for housing design. The demand structure in Niš is dominated by young professionals, students, and first-time buyers – groups that typically require affordable, small-scale units. Developers have responded by prioritizing compact apartments, particularly studios and one-bedroom units in the 30–45 m² range. While such a strategy increases marketability and allows lower absolute sale prices, it often results in units that approach the minimum regulatory thresholds for habitability. There is also evidence of "micro-apartments" entering the market, with areas as low as 21– 25 m². The increasing prevalence of undersized apartments in Niš reflects a structural tension between market responsiveness and regulatory compliance. In summary, although Serbian planning regulations prescribe minimum spatial standards, enforcement mechanisms are weak and demand-side pressures frequently incentivize borderline solutions. In Niš, the rise of undersized units is a clear manifestation of developers' attempts to balance construction costs, saleability, and the city's limited purchasing power – often at the expense of spatial adequacy and long-term housing quality.

4. METHODOLOGY

This study employs a quantitative, document-based approach to evaluate compliance with spatial regulations. The analysis is based on technical specifications extracted from architectural project documentation for 31 multi-family residential projects in Niš, completed or designed between January 2024 and April 2025. Projects were selected to represent a broad range of developers, urban locations, and apartment typologies, subject to the availability of complete apartment specification tables.

The dataset comprises 1,155 apartments across these projects, representing a substantial and diverse sample of Niš's recent housing production. Each apartment's declared typology (e.g., studio, one-room, two- room, etc.) and its net usable floor area were recorded.

Each apartment's net floor area was systematically compared against the minimum thresholds defined by the Rulebook. The key size standards used in the analysis include 26.00 m² for a studio, 30.00 m² for a one-room unit, 40.00 m² for a one-and-a-half-room unit, and so on up to 97.00m2 for a four-and-a-half-room unit. A unit was classified as compliant if its area met or exceeded the relevant threshold, and non-compliant otherwise.

The resulting data were tabulated and subjected to descriptive statistical analysis. This included calculating overall compliance rates, compliance by apartment typology, and compliance by project. The analysis also examined frequency distributions of apartment sizes relative to standards and identified patterns of deviation.

The study is limited to formal design documentation. It does not account for any informal modifications that may occur during construction or for post-occupancy changes. Additionally, the analysis relies on the declared typology of each apartment as reported by project architects; discrepancies between declared use and actual functional layouts could introduce classification errors. Despite these limitations, the dataset provides a robust basis for identifying systemic trends and regulatory tensions in contemporary residential development in Niš.

5. RESULTS AND ANALYSIS

Out of the 1,155 apartments analyzed, a total of 890 units meet the legal minimum area standards, while 265 units fall below the required thresholds. In percentage terms, 77.1% of apartments are compliant, and 22.9% are non-compliant with the Rulebook's minimum size norms. This indicates a substantial level of regulatory non-compliance in newly designed housing projects. It is notable that most of the analyzed projects were completed or planned in 2024–2025, meaning they should have been subject to the latest regulatory standards.

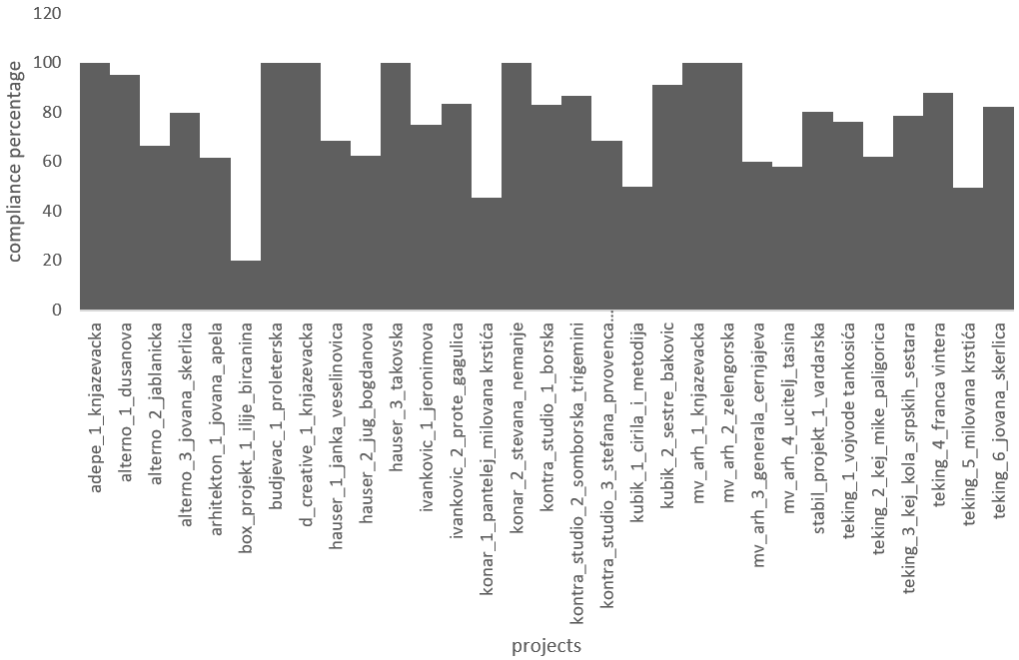


Figure 1. Compliance Rate by Projects

Compliance rates vary widely across the sample. Some developments exhibited full conformity (100% of units compliant), whereas others had non-compliance rates exceeding 50%. In general, projects targeting entry-level buyers or rental investors with smaller unit types tended to show higher rates of undersized apartments. In fact, among the 31 projects, seven achieved 100% compliance (i.e., all units met minimum sizes), while three projects had overall compliance below 50%. The lowest compliance was observed in a budget-oriented project with only 20% of its 5 units meeting standards, and two other projects with compliance around 45–49% (Figure 1).

When the data are disaggregated by apartment typology, clear patterns emerge. Smaller and more economical apartment types have significantly higher rates of non-compliance. Specifically, the typology- specific compliance rates are as follows:

- Studio apartments (garsonjera, min. 26.00 m²): 45 total units; 30 compliant (66.7%), 15 non- compliant (33.3%).
- One-room (one-bedroom) apartments (min. 30.00 m²): 40 units; 29 compliant (72.5%), 11 non- compliant (27.5%).
- One-and-a-half-room apartments (min. 40.00 m²): 141 units; 118 compliant (83.7%), 23 non- compliant (16.3%).

- Two-room (two-bedroom) apartments (min. 48.00 m²): 403 units; 233 compliant (57.8%), 170 non- compliant (42.2%).
- Two-and-a-half-room apartments (min. 56.00 m²): 223 units; 198 compliant (88.8%), 25 non- compliant (11.2%).
- Three-room apartments (min. 64.00 m²): 186 units; 174 compliant (93.5%), 12 non-compliant (6.5%).
- Three-and-a-half-room apartments (min. 77.00 m²): 48 units; 39 compliant (81.2%), 9 non- compliant (18.8%).
- Four-room apartments (min. 86.00 m²): 62 units; 62 compliant (100%), 0 non-compliant (0%).
- Four-and-a-half-room apartments (min. 97.00 m²): 7 units; 7 compliant (100%), 0 non-compliant (0%).

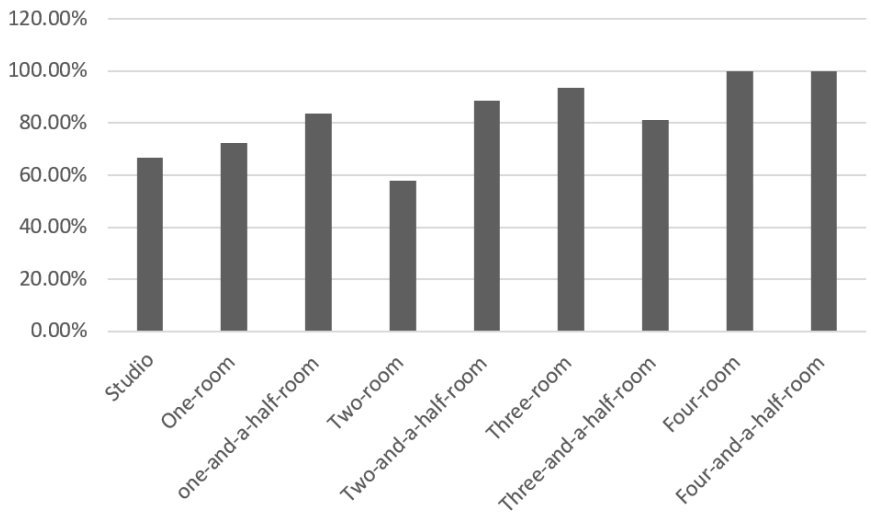


Figure 1. Compliance Rate by Apartment Type

The highest rates of non-compliance were observed in the smallest unit types (Figure 2). In particular:

- Two-room (two-bedroom) apartments had the lowest compliance: only 57.8% of such units met the minimum size, meaning 42.2% fell short of the 48 m² threshold;
- Studio apartments had 66.7% compliance (33.3% non-compliance) against the 26 m² minimum;
- One-room (one-bedroom) apartments had 72.5% compliance (27.5% non-compliance) relative to the 30 m² minimum.

Apartments of three rooms or larger showed much higher compliance. All four-room and four-and-a-half- room units fully complied with standards. Three-room apartments were 93.5% compliant. The remaining smaller categories – one-and-a-half-room and two-and-a-half-room – had compliance rates of 83.7% and 88.8%, respectively. The relatively higher non-compliance in two-room and studio typologies indicates that spatial deviations are concentrated in the most cost-sensitive market segments, supporting the view that deviations from norms are structurally linked to affordability constraints and developer strategies.

At the level of individual projects, compliance rates range from 100% down to as low as 20%. Budget- oriented projects or those with a high proportion of small units often saw the largest shortfalls. In several projects, specific categories of apartments were uniformly undersized: for instance, in one project all declared one-and-a-half-room units fell below the 40 m² minimum.

These project-level disparities reveal a systematic pattern in the design and classification of residential units. Developers operating in affordability-constrained markets often prioritize maximizing the number of units by reducing individual unit sizes to just below the legally prescribed thresholds. Despite these reductions, typological labels are frequently retained—for instance, a 36 m² unit may be designated as a “one-and-a-half-room” apartment, although the regulatory minimum for that category is 40 m². This practice of typological mislabeling enables a circumvention of regulatory standards and undermines the intended function of minimum housing norms. Furthermore, it introduces a hidden dimension of spatial inadequacy: the actual occupancy of such units often exceeds their nominal design capacity. For example, two-room apartments—typically intended for two-person households—are commonly inhabited by families of three or four. This divergence between design standards and real-life usage implies that the effective performance of the housing stock is even lower than formal indicators suggest, exacerbating concerns about overcrowding, residential discomfort, and long-term housing quality.

The extreme cases at the project level highlight weaknesses in both the permitting process and enforcement. That some buildings achieved 100% compliance (often high-end projects with larger unit mixes) while others had compliance rates below 50% underscores inconsistent oversight. It suggests that formal regulatory norms are sometimes applied flexibly or not enforced rigorously, allowing significant deviations in lower-end developments.

Overall, the empirical analysis yields the following key findings:

- Overall compliance was 77.1% (890 of 1155 units), leaving 22.9% non-compliant.
- Non-compliance is strongly associated with small-unit typologies. Two-room, studio, and one- room apartments exhibit the highest violation rates. In contrast, all large units (four-room and above) are compliant.
- Systematic under-sizing is evident. Many non-compliant units were only marginally below the thresholds, indicating a deliberate strategy of “just enough reduction” to squeeze out additional units.
- Developer strategies reflect market demand. The data suggest that developers reduce unit sizes in order to meet price points for cost-sensitive buyers, prioritizing marketability over strict adherence to minimum area standards.
- Institutional enforcement appears limited. The prevalence of undersized units, especially in certain projects, implies that regulatory oversight is insufficient or unevenly applied.

These findings will inform the subsequent discussion on the policy and planning implications of the observed compliance gap.

6. DISCUSSION

The concentration of non-compliant units among smaller typologies underscores the vulnerability of spatial standards to affordability pressures. In Niš's market context – with relatively low average incomes – developers face strong incentives to cater to buyers who demand lower purchase prices. Small apartments, by virtue of their smaller floor areas, allow total sale prices to remain within reach of such buyers. As a result, design decisions are increasingly shaped by price ceilings rather than by considerations of habitability and spatial quality. Economic pressures were critical drivers for downsizing [7].

The proliferation of borderline-compliant studios and one-bedroom apartments reveals that formal minimum standards are frequently treated as aspirational rather than obligatory. Even though the legal norms aim to ensure adequate living space, the reality is that many of the most affordable units fall short of these norms. This aligns with wider regional trends in post-socialist cities, where housing standards are often compromised in practice. Studies from Croatia, Romania, and Hungary have similarly found that in rapidly growing markets, compact units dominate new construction to meet the needs of cost-constrained buyers (e.g., young professionals, students, first-time households). Serbia's case is notable because the legal norms are clearly defined on paper, yet enforcement appears weak. Thus, while the rulebook provides a strong formal baseline, the market and institutional context lead to a significant gap between official standards and realized housing stock.

Evidence from the data suggests a degree of regulatory ambiguity and gaps in the institutional framework. The practice of nominally classifying undersized units as larger typologies (e.g., labeling a unit just under the minimum as a higher-category apartment) indicates that the current typology classification system can be manipulated. This "typological flexibility" allows developers to effectively sidestep the rigid area thresholds. Such tactics point to weaknesses in how building permits are checked and in how building usage is later verified.

Moreover, the findings highlight that formal compliance is uneven across development types. High-end projects and those catering to wealthier segments have strong incentives to meet and even exceed standards, as these consumers may demand larger, higher-quality units. In contrast, projects aimed at the lower end of the market have little regulatory pressure (and higher market pressure) to comply strictly. The result is a de facto dual housing market, where regulatory oversight functions primarily in one segment but not in another.

The persistent shortfall in regulatory compliance among smaller housing units raises critical concerns regarding social equity and spatial justice. Minimum area standards are established to protect residents from substandard living conditions. However, when nearly one in four newly constructed apartments fails to meet these legal thresholds, the protective function of regulation is significantly undermined. Smaller and ostensibly more affordable units, which are typically targeted toward economically vulnerable populations, are most frequently undersized. As a result, the households with the fewest resources often inhabit the least adequate living spaces. Moreover, partial enforcement disproportionately affects higher-end developments, while low-income households are permitted to occupy substandard units—effectively reinforcing disparities in housing quality.

These findings suggest that the current approach to regulation may be misaligned with socioeconomic realities. While rigid enforcement may uphold formal compliance, it risks

pushing vulnerable populations out of the formal housing market altogether—particularly in the absence of alternative housing solutions. Conversely, tolerating widespread noncompliance erodes the normative legitimacy of planning frameworks. Policymakers are thus confronted with a deeper structural dilemma: rather than merely choosing between enforcement and flexibility, they may need to reconsider whether current standards remain appropriate. Given the widespread manipulation of typologies and systematic undersizing of units, it may be necessary to revise regulatory benchmarks to reflect actual patterns of demand and affordability—thereby ensuring that planning standards both protect minimum living conditions and remain realistically enforceable in evolving market contexts. In this regard ”State subsidies should be targeted to meet two objectives: first, to ensure that housing is provided for low-income households and, second, to intervene to ensure that housing is both accessible and affordable” [1].

7. CONCLUSIONS AND RECOMMENDATIONS

This study examined the degree to which newly designed residential units in Niš, Serbia, comply with the country’s regulatory minimum size standards. An analysis of 31 multi-family housing projects (comprising 1,155 apartments) revealed that compliance with these standards is incomplete. Overall, 77.1% of the apartments met the minimum net floor area requirements, whereas 22.9% fell short. Non-compliance was most pronounced among smaller unit types: studio, one-bedroom, and two-bedroom apartments exhibited the highest rates of undersizing. These trends likely reflect affordability constraints and developer strategies in a market characterized by limited purchasing power among buyers. In contrast, larger units with three or more rooms generally met the standards. Taken together, these findings highlight a misalignment between the formal regulatory intent and actual housing design practices. Serbia’s national building regulations provide clear minimum area thresholds, yet nearly one-quarter of new apartments in Niš fall below these prescribed minima. This discrepancy is not marginal but systemic; it indicates that, as currently enforced, these spatial regulations do not guarantee adequate habitability across all market segments. Enforcement appears selective, with some developers resorting to typological labeling and minimal unit sizing to capture demand at the low end of the market. Indeed, Petković-Grozdanović et al. (2017) argue that it is important to “protect the lower limit of the quality” by specifying a “minimum limit which should not be crossed.” They further warn that the minimum standard of housing “should not be taken as the literal minimum,” but should instead serve as a safeguard against social problems affecting low-income tenants [2].

Based on the analysis, several recommendations emerge for policy and planning:

1. Strengthen Regulatory Oversight: Local authorities should enhance their capacity to verify compliance with minimum area standards during the permitting process. This could involve more rigorous review of floor plans and checks against the Rulebook thresholds. Special attention may be needed for the small-unit typologies most prone to non-compliance. Institutional inertia and lack of sufficient staffing and resources in local permitting authorities present significant challenges.

2. Introduce Typology-Based Monitoring: Regulators should develop clear, functional criteria accompanying formal typology classifications. For instance, requiring documentation of room functions and dimensions (not just the number of rooms) could reduce ambiguity. Such measures would limit misuse of labels like “one-and-a-half-room” for units that do not meet the functional intent of that category. Resistance from developers and additional administrative burdens on regulatory bodies are key challenges to this approach.
3. Promote Affordable and Compliant Housing: The government could establish incentives for developers who provide affordable housing that also meets spatial standards. Examples include expedited permitting, tax relief, or grants for projects that include a mix of unit sizes and incomes. This would help align market incentives with compliance goals. Securing sufficient funding and political commitment to effectively implement these incentives is a significant challenge.
4. Integrate Affordability into Planning: Urban planning should proactively address affordability. This might involve allocating land for public or cooperative housing projects that prioritize habitability and quality over minimal feasibility. By ensuring there is supply of legitimately affordable units, the pressure on private developers to undersize apartments could be alleviated. Land scarcity in desirable urban areas and potential resistance from private sector stakeholders pose substantial challenges.
5. Enhance Transparency and Data Accessibility: Creating publicly accessible databases of approved residential projects (including data on unit sizes and compliance status) would improve market transparency. Such a registry would allow citizens, researchers, and policymakers to monitor trends and hold developers and authorities accountable for adherence to standards. Technical capacity limitations for data collection, maintenance, and ensuring ongoing accuracy and public accessibility are notable implementation hurdles.

These recommendations underscore a dual-track approach: reinforcing compliance where possible, while addressing the economic drivers of undersizing. The goal is to ensure that Serbia’s housing sector can meet both functionality and equity objectives. By realigning regulatory enforcement with housing affordability policies, Serbia could begin to narrow the gap between aspirational design standards and the reality of housing production. Serbia’s regulatory framework must evolve to balance affordability with enforceable spatial norms—a necessity underscored by Niš’s compliance gaps [8].

The case of Niš illustrates that formal minimum area standards, no matter how well-defined, require active enforcement and supportive policies to be effective. As long as the market rewards smaller units and enforcement remains inconsistent, a significant portion of new apartments will continue to fall below the prescribed spatial norms. Policymakers must therefore tackle both sides of the equation – tightening oversight and expanding access to genuinely affordable housing – to ensure that minimum standards serve their intended protective role in practice.

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Research paper

ASSESSING ATTITUDES TOWARDS COLIVING IN NIŠ: A SURVEY-BASED ANALYSIS OF HOUSING PREFERENCES AND SOCIAL PERCEPTIONS

Katarina Medar[1], Slavisa Kondic[2], Nemanja Randjelović[3], Sofija Ickovski[4]

Abstract

This study explores the feasibility and social acceptance of coliving as an alternative housing model in Niš, Serbia. The primary objective of the research is to assess awareness, preferences, and concerns regarding coliving compared to traditional renting among potential users, including students, young professionals, digital nomads, and remote workers. The research employs a quantitative survey methodology, collecting data through an online questionnaire distributed among targeted demographics in Niš. The survey includes multiple-choice questions covering demographic factors, housing preferences, pricing expectations, and cultural attitudes toward shared living arrangements.

By analyzing the collected data, this study aims to identify key factors influencing housing choices and perceptions of coliving in Niš. The findings will provide insights into the potential demand for coliving spaces, the main incentives and deterrents for prospective residents, and the economic and social factors that could impact the successful implementation of coliving projects. This study contributes to a broader understanding of how coliving can be adapted to local contexts, offering a potential model for sustainable urban housing development in mid-sized cities. The results of this research will be valuable for architects, urban planners, and investors exploring coliving as a viable housing solution in Niš. Further research will be needed to assess the long-term economic viability and cultural acceptance of coliving in the region.

Key words: *Coliving, Housing preferences, Social acceptance, Economic viability, Sustainable housing*

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1. INTRODUCTION

Urbanization, technological advancements, and migration—defining features of modern society significantly shape housing dynamics. In response to the growing housing crisis [1], innovative housing typologies are emerging. Coliving, as an alternative and modern housing typology, has been evolving globally for many years, particularly in more developed countries [2].

Coliving has emerged as a transformative housing model, blending private living spaces with shared communal areas to address urban challenges such as rising rental costs, social isolation, and housing shortages [3]. Rooted in the sharing economy [4], coliving emphasizes affordability, flexibility, and community-building, attracting digital nomads, students, and young professionals in cities like Berlin, Lisbon, and Singapore [5].

While academic discourse is largely centered on Western contexts, post-socialist cities in Southeast Europe, with their unstable housing markets and shifting economic conditions [6], present both unique challenges and untapped potential for coliving. The prevailing housing typologies in Serbia are mostly traditional, including single-family and multi-family housing, while living outside the nuclear family primarily involves renting market-rate apartments shared among groups of people who already know each other.

The housing market in Serbia does not sufficiently meet the residential needs of its population, particularly among young individuals striving for independent living. Niš, Serbia's third-largest city with a population of 249,501 [7], reflects these dynamics. As home to a growing IT sector and a transient student population centered around its university, the city presents unique housing pressures. In response, this study explores the feasibility of implementing the coliving housing typology in the context of Niš. The analysis draws on survey data collected from local residents aged 18 to 44 (about 50% of population in Niš), representing the study's target generational cohort. The survey explored key motivations, perceived barriers, and design preferences related to Coliving. By contextualizing global housing innovations within the realities of a mid-sized Serbian city, this research aims to inform future urban policy and contribute to the broader discourse on housing transitions in Southeast Europe.

2. METHODOLOGY

This study employed a quantitative-dominant, mixed-methods approach to assess the feasibility and public perception of Coliving in Niš, Serbia. A cross-sectional online survey was conducted in March and April 2025, targeting individuals aged 18 to 44, representing the generation most affected by housing precarity and most likely to engage with alternative living models. A total of 90 respondents participated in the survey. The study was conducted in full compliance with ethical research standards. Participation was entirely voluntary and anonymous, with no personally identifiable information collected. The confidentiality and privacy of all participants were rigorously maintained throughout the research process.

A 17-item online questionnaire developed using Google Forms, structured into six sections:

1. **Introduction** - This section introduced participants to the research topic. It provided a brief explanation of coliving as a contemporary housing model, supported by visual materials

such as infographics and photographs of international examples to ensure clarity and engagement

2. **Basic informations (Demographic)** - Collected basic data such as age, employment status, housing situation, and duration of residence in Niš

3. **Awareness and Perception of Coliving** - This section assessed participants' prior knowledge and exposure to the concept of coliving, including whether they had heard of it, understood it, or personally experienced it. Additionally, it explored how attractive the idea of coliving is to them and which specific aspects (such as affordability, community, flexibility, or amenities) they find most appealing

4. **Housing Preferences and Comparisons** – This section investigates participants' choices between traditional housing and coliving. It explores the key factors influencing their housing decisions, such as cost, privacy, location, and community aspects. Additionally, it measures their willingness to try coliving as an alternative living arrangement

5. **Prices and Expected Services** – This section examines participants' expectations regarding the cost of living in a coliving space and the essential services and facilities they consider important. It aims to identify acceptable price ranges and key amenities such as furnished rooms, utilities, Wi-Fi, cleaning services, coworking spaces, and social events

6. **Cultural and Social Perceptions** – This final section explores respondents' willingness to live in culturally diverse groups and share common facilities with other residents. It also gathers opinions on whether coliving could realistically function and be accepted in the local context of Niš.

This survey serves as a preliminary instrument for collecting essential data aimed at understanding the current state of the housing market in the city of Niš, with a specific focus on young adults. By examining respondents' familiarity with and attitudes toward the concept of coliving, the study provides an initial exploration of this emerging housing typology within a post-socialist urban context. As the first investigation of its kind in the region, the research establishes a foundation for further academic inquiry while assessing the level of public awareness and acceptance. The findings are intended to inform future initiatives and offer strategic directions for promoting coliving as a viable housing alternative among local residents.

3. RESULTS AND DISSCUSION

The survey of 90 residents aged 18 to 44 in Niš reveals important insights into the local housing preferences and attitudes toward coliving.

3.1. Demographic Profile

The majority of respondents were young adults aged 18-24 (76.7%), predominantly students (65.6%), reflecting the city's significant student population. Most currently live with family (46.7%) or alone in rented apartments (23.3%).

This demographic profile highlights a crucial opportunity for coliving in Niš. The dominance of young adults, particularly students, suggests a high demand for transitional and flexible housing options. The fact that nearly half of respondents still live with family points to potential economic constraints or a lack of suitable independent housing alternatives. Additionally, the relatively high percentage of those already living alone in rented apartments

indicates a segment of young people actively seeking autonomy—an audience likely to be receptive to the affordability and semi-independent structure that coliving offers.

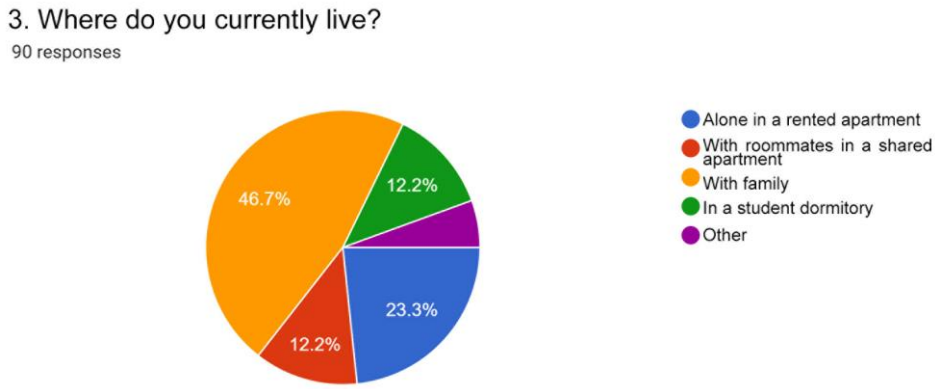


Figure 1. Pie chart, housing status

3.2. Awareness and Perceptions of Coliving

Over half of respondents (53.3%) are familiar with coliving, though only a small portion (12.2%) find the concept very attractive. The largest group remains neutral (38.9%), indicating uncertainty or limited experience with this housing model.

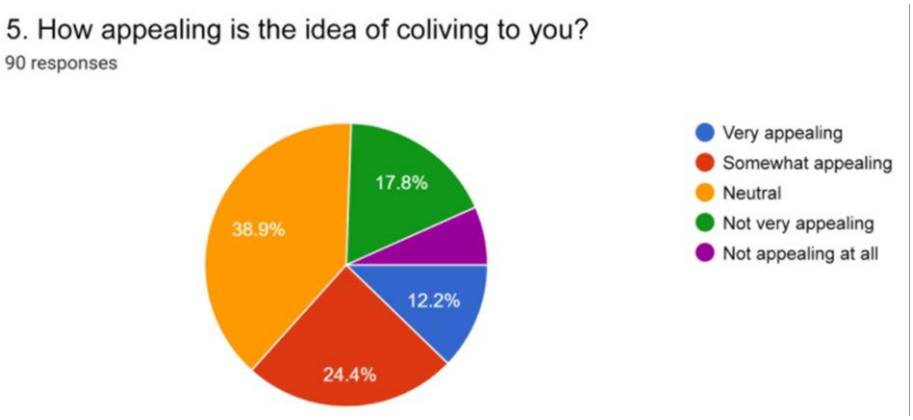


Figure 2. Pie chart, housing preferences

This data suggests that while awareness of coliving is relatively widespread among young adults in Niš, deeper understanding or enthusiasm for the model remains limited. The fact that only 12.2% find coliving very attractive, despite over half being familiar with it, reveals a potential gap between recognition and genuine interest—possibly due to cultural reservations, unfamiliarity with its practical benefits, or a lack of local examples.

The neutral stance held by 38.9% of respondents highlights a crucial opportunity: with targeted education, promotion, and well-adapted pilot projects, many individuals in this group could potentially shift toward a more favorable perception. This neutrality should not be viewed as rejection, but as an open field for further engagement, particularly if coliving is framed as both a practical and socially enriching alternative to traditional housing.

3.3. Key Incentives

Affordability (64.4%) and social interaction/community (43.3%) were the leading motivations for considering coliving, alongside the appeal of fully furnished spaces (38.9%) and additional services such as cleaning and events (44.4%). Flexible lease options and coworking spaces also attracted interest.

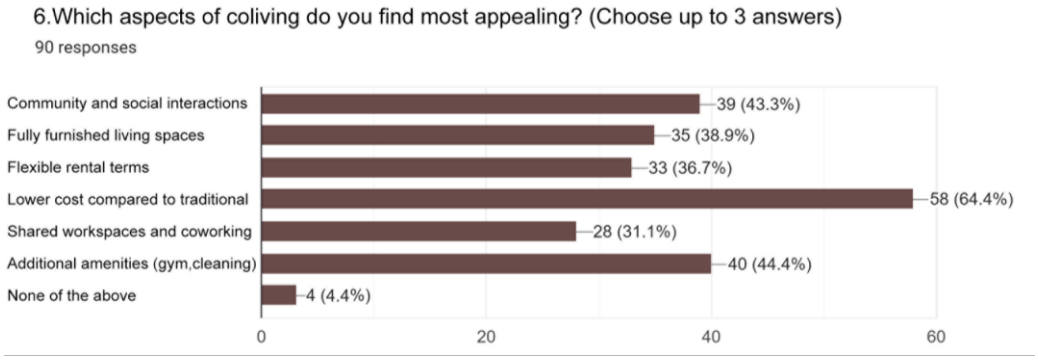


Figure 3. Key Incentives

This highlights the need for careful planning and thoughtful design in future pilot projects. Sustainable models must be developed to keep coliving costs affordable, more budget-friendly than traditional renting. At the same time, these models should encompass a wide range of amenities, as this remains a significant motivator for many residents.

3.4. Main Barriers

Privacy concerns (80.0%) and discomfort with sharing living spaces with strangers (74.4%) emerged as the most significant obstacles. Noise and lack of personal space (65.6%) further highlight the preference for privacy and individualism. Cultural differences and unclear rules/responsibilities were lesser but notable concerns.

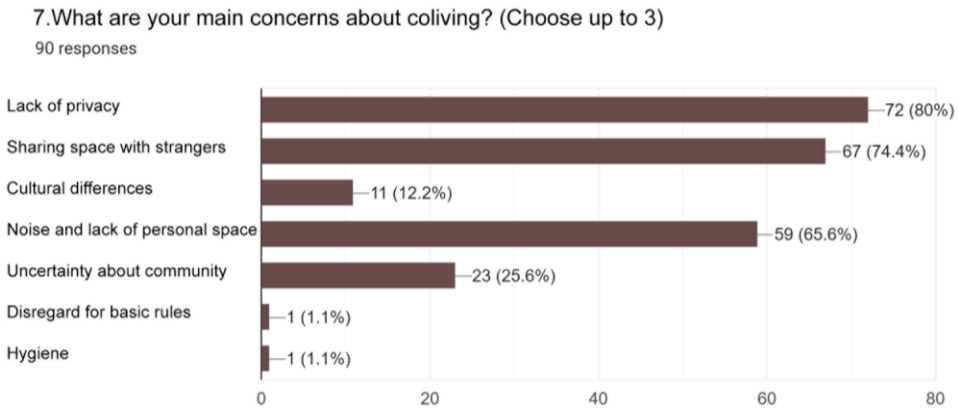


Figure 4. Main Barriers

Therefore, architectural and operational solutions should prioritize private rooms and, where possible, private bathrooms. Sound insulation, well-defined boundaries between personal and communal areas, and optional participation in social activities can help residents maintain their autonomy while still benefiting from the shared aspects of coliving.

3.5. Housing Preferences

Traditional renting remains the dominant preference (60.0%), with only 12.2% opting for coliving. Privacy (84.4%) and location (83.3%) are the highest priorities in housing decisions, outweighing community aspects.

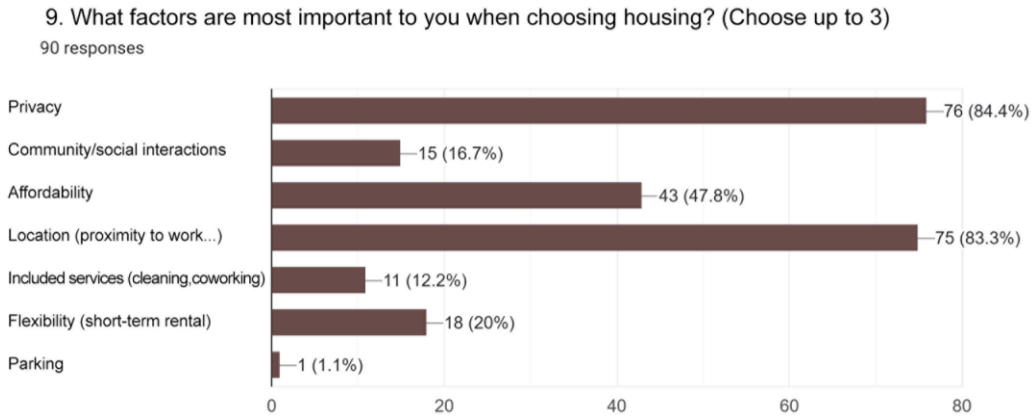


Figure 5. Key factors in housing choice

At first glance, these results may seem concerning, particularly regarding the percentage of respondents willing to choose coliving. However, there is considerable potential in the substantial number of undecided participants—especially given that coliving remains a relatively new and unfamiliar housing typology. These findings underscore the importance of raising awareness among young people about coliving and introducing short-term trial periods in future coliving communities. Such non-binding trial opportunities could encourage greater participation and help mitigate initial hesitation.

In addition to privacy, which emerged from the questionnaire as the most significant barrier, a large number of respondents identified location as an important factor when choosing housing. This indicates that coliving developments should be situated in areas attractive to young adults, particularly near universities and other amenities relevant to this demographic.

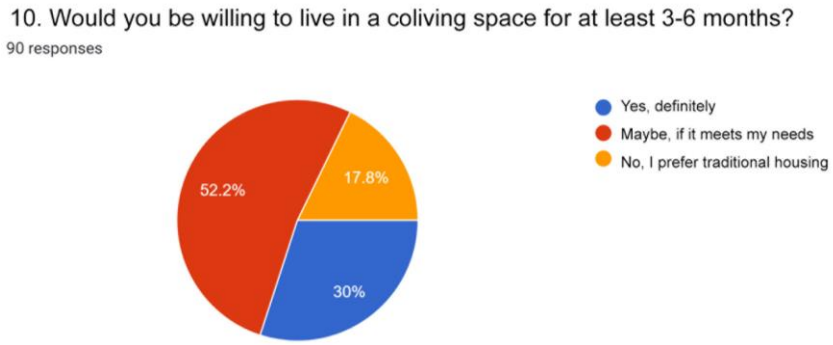


Figure 6. Pie chart, Willingness to Try Coliving

A considerable number of respondents expressed openness to coliving, with 30% willing to try it for a period of 3–6 months and 52.2% responding with “maybe.” In contrast, only 17.8% were not interested. This positive balance suggests a clear interest in more modern forms of living and a readiness among young people to explore new housing experiences.

3.6. Pricing Expectations

Around half of respondents (50.0%) are willing to pay €150–€250 for an all-inclusive coliving option, while 17.8% are willing to pay €250–€350.

These results indicate that the majority of respondents are only willing to pay up to 250€ per month for coliving services. This suggests that potential coliving models in Niš would need to be cost-effective to meet the expectations and financial capabilities of the target population. The relatively low willingness to pay may be influenced by current income levels and perceptions of value, and could represent a challenge for developers or investors aiming to establish coliving spaces with higher operating costs.

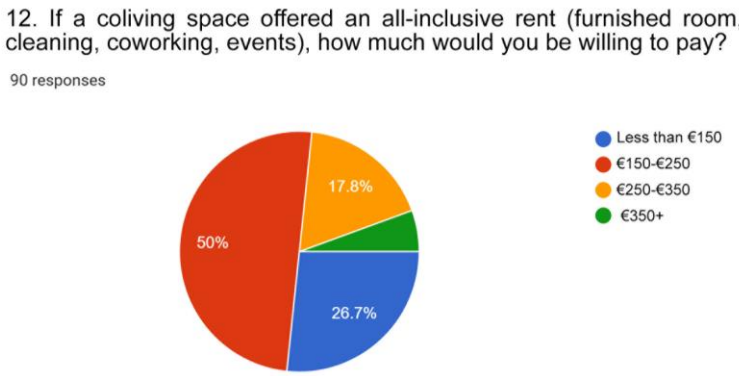


Figure 7. Pie chart, Pricing expectations

3.7. Essential Amenities

A vast majority prioritize private rooms (94.4%) and bathrooms (84.4%), emphasizing the need for hybrid coliving models that balance privacy and community. Shared social spaces, cleaning services, and wellness facilities received moderate interest.

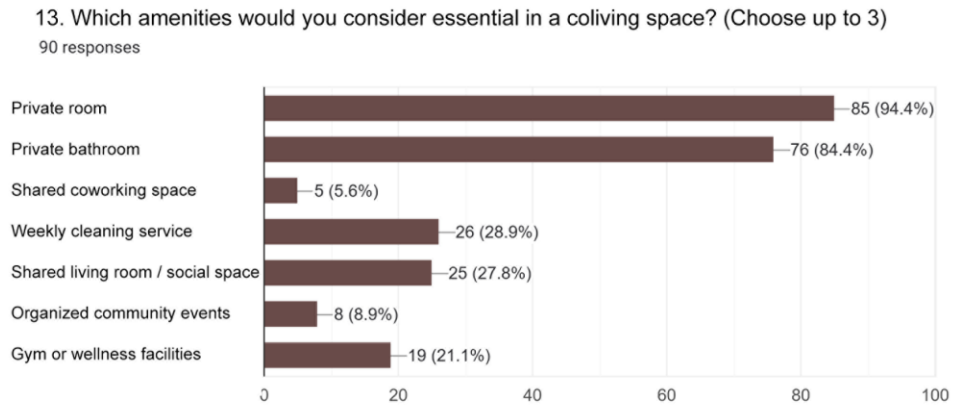


Figure 8. Essential Amenities

3.8. Social and Cultural Attitudes

Only a small percentage (8.9%) feel comfortable sharing spaces, while the majority (58.9%) remain neutral—indicating that their comfort depends on the behavior and

compatibility of other residents. A significant portion (32.2%) explicitly feel uncomfortable with the idea of shared living areas.

This highlights a key challenge for coliving implementation: while there is openness to shared living, it must be carefully managed through thoughtful design, clear community guidelines, and possibly options for more private or semi-private shared zones to accommodate different comfort levels.

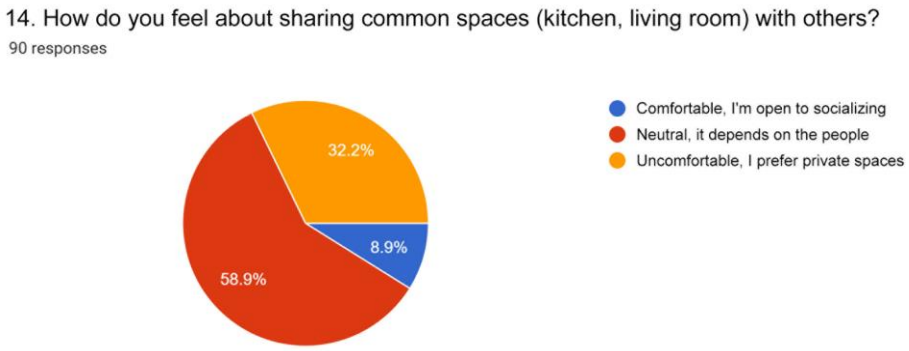


Figure 9. Openness to sharing common spaces

A significant portion of respondents (64.4%) maintain a neutral stance toward living in a multicultural environment, suggesting that openness depends on individual preferences. Meanwhile, 20% of participants expressed full openness to such a living arrangement. This reflects a generally inclusive attitude among young adults in Niš, which could support the development of coliving spaces that bring together diverse groups.

3.9. Perceived Viability

While only 25.6% of respondents believe there is already a market for coliving, the overwhelming majority (66.7%) express conditional support, stating that coliving could work with better understanding and adaptation.

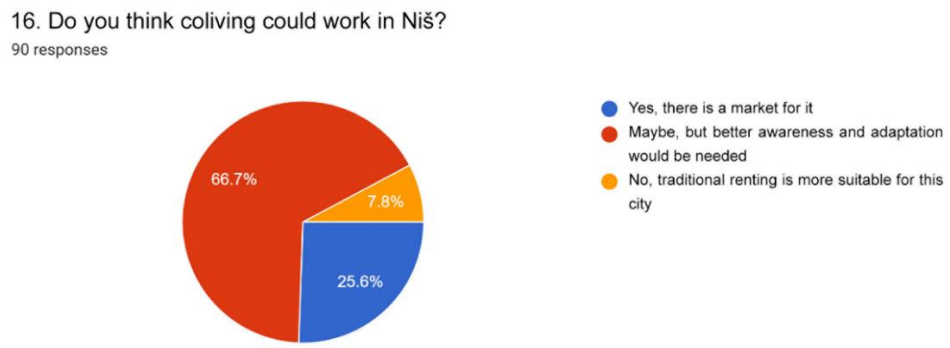


Figure 10. Perceived Viability of Coliving in Niš

This suggests that although awareness and acceptance are not yet fully developed, there is strong latent interest that could be activated through targeted education, promotion, and pilot projects. Notably, only a small minority (7.8%) outright prefer traditional renting, highlighting an openness among the population to explore alternative housing models like coliving if implemented thoughtfully.

4. ARCHITECTURAL IMPLICATIONS OF THE SURVEY FINDINGS

The results of the survey allow for the formulation of specific architectural guidelines for designing coliving spaces adapted to the local context of Niš. While the data indicates a degree of openness toward alternative housing models, the broader acceptance of coliving will depend largely on how spatial organization addresses the cultural values, habits, and practical needs of potential residents.

The most prominent concern among respondents is privacy—with 80% expressing discomfort over a lack of private space, and 94.4% identifying private rooms, and 84.4% private bathrooms, as essential. These findings point to the need for hybrid coliving models that combine individual living units with optional shared amenities, rather than fully communal arrangements.

Architecturally, this implies the development of residential units that allow for a high degree of adaptability—both in terms of length of stay and level of engagement with shared spaces. Spatial strategies that can help increase the acceptance of coliving in this context include:

- Sound insulation between private and shared areas
- Clear physical boundaries between public, semi-public, and private zones
- Flexible access to shared amenities (e.g., kitchens, coworking spaces, lounges)
- Retreat zones within communal areas, offering intimacy and personal space

Moreover, a large proportion of respondents (83.3%) highlighted location as a crucial factor in housing decisions. This suggests that coliving developments in Niš should be strategically located—close to universities, IT hubs, and public transportation—to support daily routines and reduce stress related to commuting.

The desire for short-term stays (with 30% of participants willing to try coliving for 3–6 months) further emphasizes the importance of designing easily maintainable, efficient living units that can accommodate high turnover, fast onboarding, and flexible leasing.

In summary, architectural design for coliving in Niš must respond to three core demands:

1. Ensuring a high level of privacy
2. Offering quality but optional shared amenities
3. Providing adaptability in location and duration of residence

In this way, coliving can become not only a socially and economically viable housing alternative, but also an architecturally sustainable model tailored to the real needs of young people living in post-socialist urban environments.

5. CONCLUSION

This study investigated the feasibility and social acceptance of coliving as an alternative housing model in Niš, Serbia, through a survey-based analysis targeting young adults. By contextualizing the findings within broader theoretical frameworks such as the sharing economy and housing precarity, the research highlights both the potential and limitations of implementing coliving in a post-socialist urban environment.

A key paradox emerged between the appeal of affordability and the challenge of privacy. While 65.6% of respondents cited cost-effectiveness as a primary motivator, a significant 80% expressed concerns about privacy—underscoring the need for coliving models that strike a careful balance between community and autonomy. Cultural hesitation also played a

role, with 25.5% of participants preferring to live with people from similar cultural backgrounds. These findings point to the importance of culturally sensitive strategies for social integration, such as optional communal activities and structured onboarding.

From an architectural perspective, the results suggest a strong need for hybrid spatial models that respect the individual's need for privacy while offering the option of community interaction. Future coliving developments should prioritize private rooms and bathrooms, enhanced soundproofing, and clearly defined spatial boundaries between private and communal areas. Additionally, the importance of location—particularly proximity to universities, technology hubs, and transportation—emerged as a central factor in housing preferences, guiding where coliving projects should be situated within the city.

The adaptability of coliving spaces—especially for short-term stays of 3–6 months—was another significant insight. This points to the necessity of modular and flexible architectural designs that can accommodate different lifestyles and durations of occupancy. These architectural responses are critical in making coliving both practically functional and socially acceptable within the context of Niš.

In sum, the successful implementation of coliving in Niš hinges on context-sensitive architectural and urban planning solutions that respond to local cultural norms, economic realities, and evolving lifestyles. By adapting global coliving principles to the specific needs of mid-sized post-socialist cities, this study offers a pathway toward sustainable urban housing models that are both inclusive and resilient.

ACKNOWLEDGMENTS

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Research paper

COMPUTATIONAL ANALYSIS OF FREE-EDGE EFFECTS IN COMPOSITE LAMINATES USING ABAQUS

Milica Živković[1], Emilija Jočić[2], Miroslav Marjanović[3]

Abstract

The free-edge effects are related to singular stress states at the interfaces between dissimilar layers in the vicinity of geometrical or mechanical discontinuities within the laminar composite. Stress concentration at free edges can further lead to delamination and a significant drop in stiffness, with fracture occurring at lower loads than expected. The paper deals with the computational (finite element) modeling of free-edge effects in cross-ply composite laminates. For this purpose, Abaqus software package has been used and two solid finite element types have been applied. Free-edge stress field of laminar composites under axial extension has been analyzed. Several numerical examples of cross-ply composites with various stacking sequences have been presented, and the results are compared against the existing analytical solutions based on the improved first-order shear deformation theory. Additionally, a parametric study has been conducted, focusing on the variation of τ_{yz} stresses through free edges as a function of plate thickness.

Key words: *Free-edge stresses, laminate, composite, plate, axial loading*

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1. INTRODUCTION

Because of their exceptional strength, stiffness and corrosion resistance, laminar composites have found an extensive application in construction of mechanical, aerospace, marine and automotive structures, typically demanding high reliability levels. When subjected to tension, they may fail through various scenarios, such as fiber breakage and pull out, matrix yielding and cracking, among others. Their ultimate strength and failure mechanisms depend on geometrical factors and material properties; therefore, a detailed study of their failure behavior is a crucial step towards the safe and reliable structural design [1].

Since the adjacent layers cannot move independently when loaded, normal and shear stress concentrations occur to satisfy the displacement compatibility conditions in the presence of different Poisson's ratios, elastic and shear moduli and thermal expansion coefficients of the adjacent layers. These stress concentrations are pronounced at the free edges of a laminar composite, which can further lead to delamination and a failure at loads significantly below the expected limit level. The stress concentrations decrease with distance from the free edges of the plate, gradually diminishing to negligible values. Their magnitude is also a function of layer orientation, layer thickness, boundary conditions, and loading type, as well. Under axial strain, the stress concentrations at the free edges are generally lower when compared to laminar composites in bending or torsion [2, 3].

Starting from the earliest work on this topic by Pipes and Pagano [4], various numerical and approximate analytical solutions have been derived so far to accurately identify and evaluate interlaminar stresses associated with the free-edge effect. A comprehensive review of different approaches can be found in [5, 6].

Exact analytical solutions for free-edge stress singularities are typically limited to simplified layups and loadings. Becker [7] proposed closed-form solutions using higher-order plate theory for free-edge stresses in cross-ply laminates. Nosier and Bahrami [8] and Nosier and Maleki [9] applied both the improved first-order shear deformation theory (FSDT) and the layerwise theory (LWT) to study free-edge effects in angle-ply and general laminates, incorporating reduced constitutive relations and traction-free boundary conditions. Beside the limited number of analytical solutions, a number of numerical solutions has been derived, such as 3D FEM-based solution by Wang and Crossman [10].

In this paper, the Abaqus [11] software is used to analyse the stress state near the free edges of a layered composite. Abaqus is a software application used for both the modeling and analysis of mechanical components and assemblies (pre-processing) and visualizing the finite element analysis results (post-processing). Abaqus has a large library of finite elements of different types, and two of them have been used for the purpose of this work. Using two different finite element types, interlaminar shear (τ_{yz}) and normal stress (σ_z) distributions are analyzed through the width of a layered composite, in the vicinity of free edges. Different stacking sequences are analyzed. For σ_z, the stress distribution through the plate thickness is also studied for a composite with an conventional cross-ply stacking sequence. Finally, a parametric study is performed to investigate the influence of layer thickness on the through-the-width distribution of the interlaminar shear stress τ_{yz}.

The obtained results are compared with analytical solution based on the first-order shear deformation theory, proving the high accuracy of applied numerical models, and the appropriate conclusions are derived.

2. MODELING OF LAMINAR COMPOSITE USING ABAQUS

For modeling purposes, the rectangular laminated composite plate is first created as a homogenous body (prism). By using a separation tool, several layers of the same height are created within the solid body (part). Therefore, a tie-constraint between the layers have been introduced. The linear elastic orthotropic material is modeled by specifying 9 independent engineering constants: moduli of elasticity E_i, shear moduli G_{ij} and Poisson's ratios ν_{ij}. Appropriate layer orientation is assigned by rotating local coordinate systems of the material within 90º layers. Uniform axial strain is assigned by applying translational displacements along the free edges, $u(a) = \bar{U}$ and $u(0) = -\bar{U}$, in order to achieve the strain of $\varepsilon_x = 10^{-6}$.

For the analysis of free-edge effects, meshing is performed by using two different types of solid finite elements. The **C3D8R** is a general-purpose linear brick element with reduced integration. It has one integration point in the center of the finite element. Nodes are located at the corners, and each node has 3 generalized displacements (24 degrees of freedom in total). The **C3D10** is a quadratic general-purpose tetrahedral element, with nodes in corners and mid points of the edges (see Figure 1). Each node has 3 generalized displacements (30 degrees of freedom in total), while the integration is performed in 4 integration points [12].



Figure 1. C3D8R and C3D10 finite elements in Abaqus, with their respective nodes and integration points (red color)

3. NUMERICAL RESULTS AND DISCUSSION

This section presents the obtained results from the conducted numerical analyses. The calculated free-edge stresses are compared with those obtained analytically [2]. Distibution of stresses is analyzed through the width and through the thickness of the considered plate-like models, with different stacking sequences.

3.1 Considered model geometry

For the analysis, a 4-layers rectangular laminated composite plate with dimensions $a \times 2b$ has been analyzed (Figure 2). Plate length is $a = 10h$, width is $b = 2h$, while layer thickness is $h_k = h/4$, where h is the total plate thickness. Each layer is a unidirectional reinforced composite made of material with the following properties in material coordinates: $E_1 = 137.9$ GPa, $E_2 = E_3 = 14.48$ GPa, $G_{12} = G_{13} = G_{23} = 5.86$ GPa, while $\nu_{12} = \nu_{13} = \nu_{23} = 0.21$. Three stacking sequences have been considered: two symmetric ones, $[0º/90º]_s$ and $[90º/0º]_s$, as well as the conventional cross-ply [0º/90º/0º/90º] sequence.

For the through-the-thickness interpolation, three sub-laminate discretizations have been considered, including P=1, P=2 or P=4 sublayers through each material layer, respectively.

This leads to the total of 4, 8 or 16 sublayers through the entire plate thickness. For the in-plane discretization, three mesh densities have been considered, including element sizes of *h*/4 (Mesh 1), *h*/8 (Mesh 2) and *h*/16 (Mesh 3). Table 1 elaborates the number of sublayers in each material layer, for each considered mesh density.

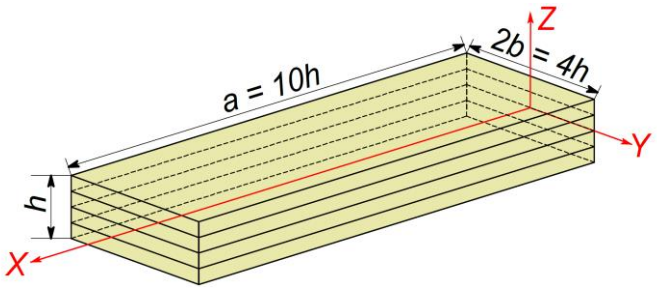


Figure 2. Considered laminated composite plate with four layers

Table 1. Number of sublayers depending on FE dimensions

FE dimension	h_k	h_k / 2	h_k / 4
number of sublayers (P)	1	2	4

3.2. Distribution of the interlaminar shear stress τ_{yz}

In Figure 3, the distribution of τ_{yz} through the width of the plate with $[90^o/0^o]_s$ and $[0^o/90^o]_s$ stacking sequences is displayed. Interlaminar shear stress is near zero in the middle and increases toward the free edge where it reaches its maximum values. The displayed results were measured at $z = h_k$ interface. The C3D10 elements (red lines) showed better accuracy against the C3D8R (blue lines) in predicting both the position and the value of the maximum stress, when compared against the analytical solution [2] (black line). As expected, mesh refinement led to the convergence to analytical solution.

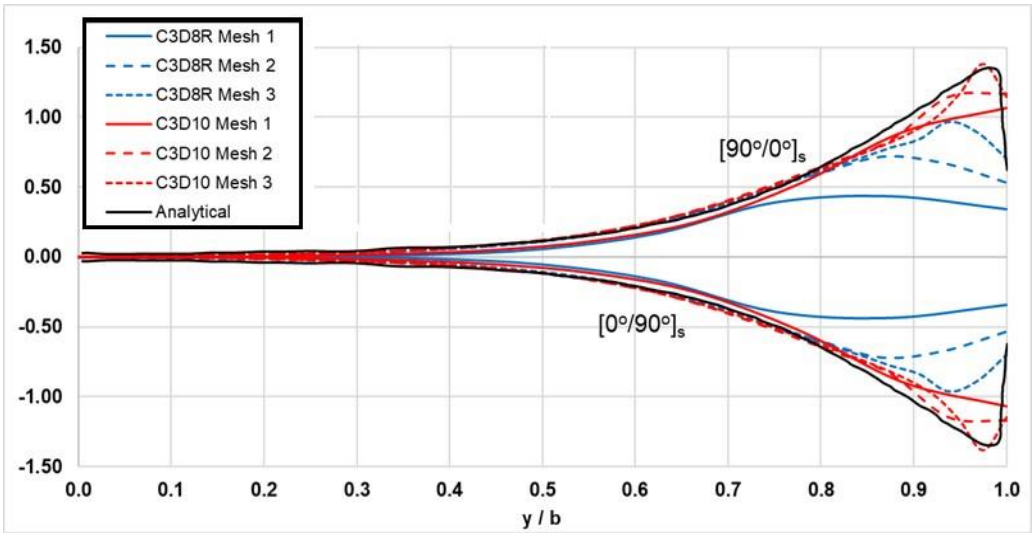


Figure 3. Dimensionless interlaminar shear stress (τ_{yz} / ε_0)×10^{-6} [kPa] distribution along the 0º/90º interface of the $[0^o/90^o]_s$ and $[90^o/0^o]_s$ laminates under uniform axial strain, considering different mesh densities compared to analytical solution [2]

3.3. Distribution of the interlaminar normal stress σ_z

In Figure 4, the distribution of σ_z through the width of the plate with $[0^o/90^o]_s$ stacking sequence is shown. Results from different models in Abaqus are compared with analytical solution [2], for the interface at $z = h_k$. In the middle of the plate, the stress is close to zero, while the stress values are greatest close to the free edge with the maximum being reached exactly at the free edge. For the $[0^o/90^o]_s$ laminate, mesh refinement leads to the increase of the σ_z along the free edge. As in previous case, the C3D10 finite element provided results that are significantly more similar with the analytical ones.

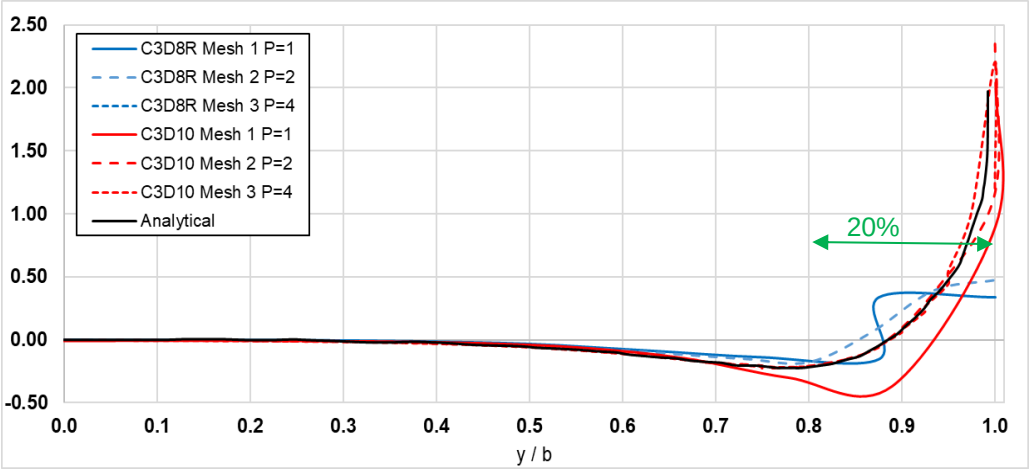


Figure 4. Dimensionless interlaminar normal stress (σ_z / ε_0)×10^{-6} [kPa] distribution along the 0º/90º interface ($z = h_k$) of the $[0^o/90^o]_s$ laminate under uniform axial strain, considering different mesh densities compared to analytical solution [2]

In Figure 5, the distribution of σ_z through the width of the plate with $[90^o/0^o]_s$ stacking sequence is displayed, for $z = h_k$ interface. The stress is close to zero in the middle of the plate width, gradually increasing towards the edges and sharply rising in the last 20% of the half-width, where it also changes the sign from positive to negative. This trend is also observed in the analytical solution.

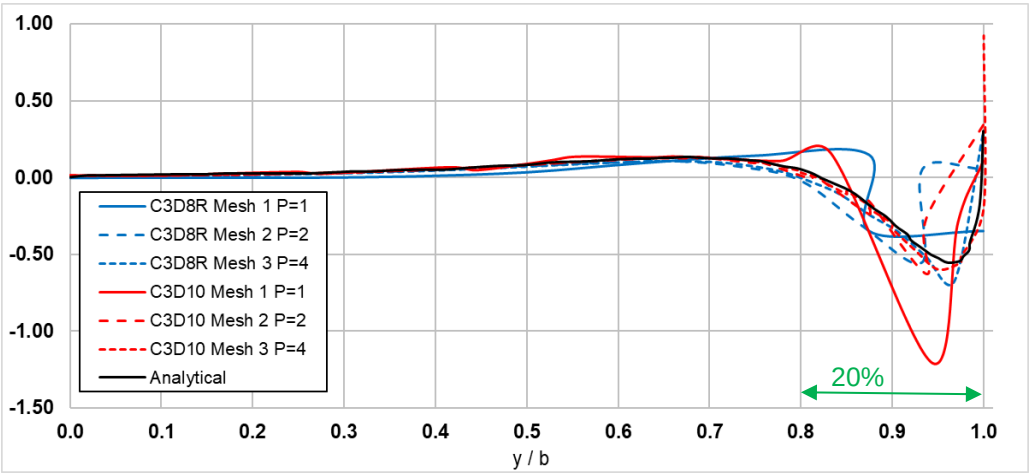


Figure 5. Dimensionless interlaminar normal stress (σ_z / ε_0)×10^{-6} [kPa] distribution along the 90º/0º interface ($z = h_k$) of the $[90^o/0^o]_s$ laminate under uniform axial strain, considering different mesh densities compared with analytical solution [2]

3.4. Distribution of σ_z through the plate thickness

Figure 6 shows the distribution of interlaminar normal stress σ_z through the thickness of the plate with [0º/90º/0º/90º] cross-ply stacking sequence. The results are obtained by using the C3D8R finite element and considering different mesh densities (P=2 and P=4). The results show that σ_z reaches its peak values at the interfaces of two layers with different fiber orientations. It is also shown that the used meshes greatly underestimate the maximum values of σ_z stress when compared against the analytical solution. This means that mesh refinement should be adopted at least in the zones covering ~ 20% of the plate's half-width along the free edges (see Figures 4-5), to accurately predict the extreme values of σ_z which may cause delamination.

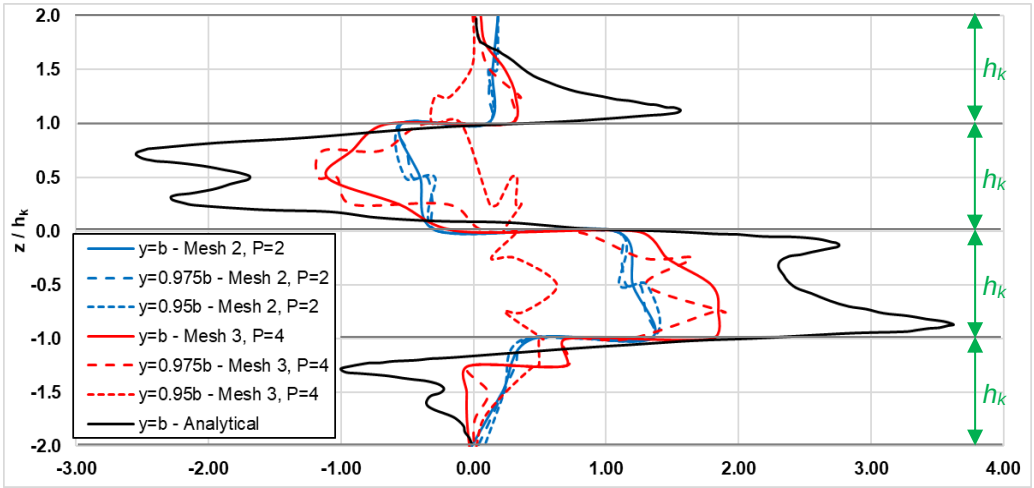


Figure 6. Dimensionless interlaminar normal stress (σ_z / ε_0)×10^{-6} [kPa] through the thickness in [0º/90º/0º/90º] laminate under uniform axial strain, considering different mesh densities compared to analytical solution [2]

3.5. Parametric study

As a benchmark study, a parametric anaysis on the influence of the plate (layer) thickness has been conducted. For this purpose, both C3D8R and C3D10 elements have been used. A 4-layers rectangular laminated composite plate with dimensions $10h \times 4h \times 4h_k$ has been analyzed (see Figure 2), where h_k is the layer thickness. The adopted material properties are the same as in the previous analyses, while only the stacking sequence $[0º/90º]_s$ has been considered. Four different plate thicknesses have been analyzed: 0.75h, h, 1.25h and 1.75h. For the through-the-thickness interpolation, two finite elements per layer have been adopted (P=2). For the in-plane discretization, the same element size has been adopted (h_k/2).

Interlaminar shear stress is near zero in the middle and increases toward the free edge where it reaches its maximum values. In the zone of around 70% of the plate's half-width, the element type selection does not play the important role because the obtained stress values are nearly the same (Figure 7). In the last 30% of the plate's half-width, the differences occur (see gray dots in Figure 7). For all considered plate thicknesses, C3D10 element provided slightly higher values of the interlaminar shear stress (red lines in Figure 7). For the C3D8R element, all selected plate thicknesses resulted in almost the same maximum value of the dimensionless interlaminar shear stress τ_{yz}.

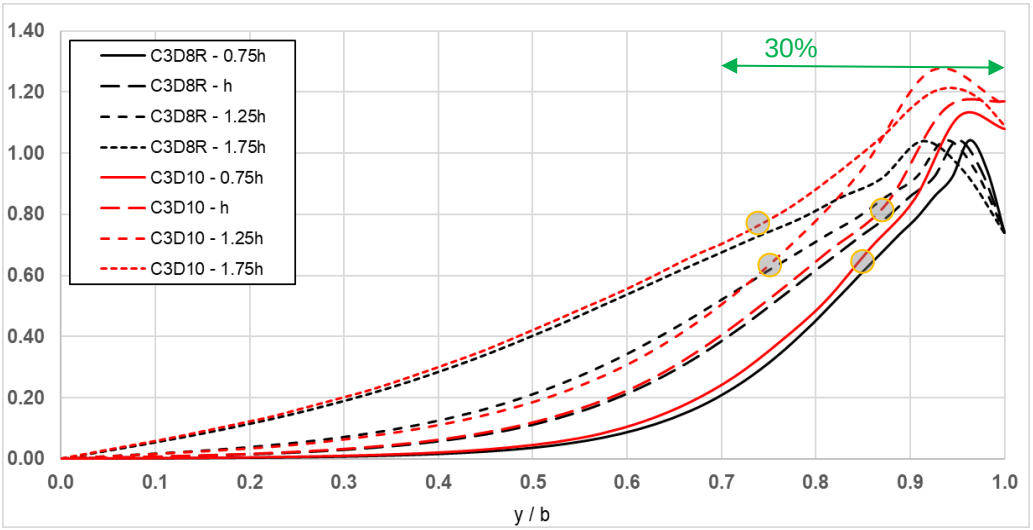


Figure 7. Dimensionless interlaminar shear stress (τ_{yz}/ ε_0)×10^{-6} [kPa] distribution along the 0º/90º interface of the [0º/90º]$_s$ laminates under uniform axial strain, considering different plate thicknesses and different finite elements. Gray dots denote the points where higher differences in results from selected elements start to occur.

4. CONCLUSIONS

In the paper, two solid finite element types in Abaqus software have been used to evaluate the interlaminar shear and normal stress state near the free edges of a layered composite, under uniform axial extension. The distributions are analyzed through the width and through the thickness of a layered composite, considering different stacking sequences. Finally, a parametric study is performed to investigate the influence of layer thickness on the through-the-width distribution of the interlaminar shear stress τ_{yz}. The obtained results are compared against the analytical solution, proving the high accuracy of applied numerical models.

The distribution of τ_{yz} through the width of the plate, at layer interface, expectedly predicted the near-zero values in the middle and increase of τ_{yz} toward the free edge where it reaches its maximum values. The C3D10 elements showed better accuracy against the C3D8R in predicting both the position and the value of the maximum stress.

The analysis showed that in the middle of the plate, interlaminar normal stress σ_z is close to zero, with the greatest values close to the free edge and the maximum being reached exactly at the free edge. Mesh refinement led to the increase of the σ_z along the free edge. Again, C3D10 provided better agreement with the analytical results. For [90º/0º]$_s$ stacking sequence, σ_z is also close to zero in the middle of the plate widthe, increases towards the edges and sharply rises and changes sign in the last 20% of the half-width (also observed in the analytical solution). For all above scenarios, mesh refinement led to the convergence of results to analytical solution, as expected. The distribution of interlaminar normal stress σ_z through the thickness shows that σ_z reaches its peak values at the interfaces of two layers with different fiber orientations. However, the used meshes greatly underestimate the maximum values of σ_z when compared against the analytical solution.

The benchmark study on the influence of the plate thickness on the interlaminar shear stress distribution, showed that τ_{yz} is near zero in the middle and increases toward the free

edge where it reaches its maximum values. In the zone of around 70% of the plate's half-width, the element type selection does not significantly influences the results. In the remaining 30%, the differences occur. For all considered plate thicknesses, C3D10 element provided slightly higher values of the interlaminar shear stress when compared against C3D8R.

Future research will include the derivation of free-edge stresses using the original software based on the LWT, under complex load scenarios, such as bending and torsion.

ACKNOWLEDGMENTS

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Research paper

SOME ASPECTS OF ELECTROKINETIC SOIL TREATMENT

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Abstract

One of the innovative and promising approaches to the stabilization of fine-grained soils with low bearing capacity is electrokinetic treatment which can be integrated with other techniques to enhance soil properties. This method could involve applying a low direct current through electrodes inserted into the soil while simultaneously introducing stabilizers through the electrokinetic process. The stabilization achieved in this way contributes to the improvement of the physical, chemical and mechanical characteristics of the soil. However, a significant challenge of this method is the corrosion of electrodes, which occurs due to electrochemical reactions at the interface between an electrode and the soil. When direct current is applied, oxidation and reduction reactions take place at the electrodes, leading to the dissolution of the electrode material. This can cause the reduction of the electrodes efficiency and longevity, impacting the overall effectiveness of the treatment. Consequently, it is important to examine the extent to which electrode corrosion can affect the flow of current and processes in the soil during the application of this innovative method. Therefore, the aim of this paper is to further elucidate the effects that occur when varying the parameters that affect the current flow.

Key words: *Electrokinetic Treatment of Soil, Direct Current, Electrode Corrosion*

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1. INTRODUCTION

Soil stabilization is a critical aspect of geotechnical engineering, particularly in areas where natural fine-grained soil conditions fail to meet the construction requirements. Furthermore climate change increases both the intensity and frequency of factors that influence the incidence of landslides, making them a more serious threat. The main reasons for the higher threat are increased precipitation, extreme weather conditions, prolonged droughts, permafrost melting and sea level rise. Namely, intense rains and longer periods of humidity saturate the soil with water, reducing its stability and increasing the risk of landslides. Also, more frequent storms, sudden downpours and longer periods of rain can cause erosion and destabilization of the terrain.Droughts can lead to drying out and cracking of the soil, which after heavy rains becomes unstable and prone to movement.In mountainous and cold areas, global warming causes permafrost to melt, which weakens the soil structure and contributes to landslides. Erosion of areas near coasts due to sea level rise can cause slope collapse and soil instability.

In addition to these global challenges the geotechnical properties of soils are of high importance in the performance and durability of infrastructure systems. In many cases, during the construction of large-scale infrastructure projects, the available locally fine-grained soil materials lack the necessary mechanical or physical properties required for safe and durable structural support. Consequently, the application of soil stabilization techniques becomes necessary to improve the engineering behavior of such materials and providerequired specifications.All this indicates the need to pay a special attention to methods that contribute to preventing the occurrence of landslides.

In response to these challenges, traditional methods, including chemical stabilization of soil, have been widely used. This chemical stabilization involves the addition of chemical agents (most commonly lime, cement, fly ash, or other pozzolanic materials) which react with the soil to enhance performance [1-7]. Regarding clayey soils, the chemical stabilization is especially effective and used, but there are limitations. Although this technique contributes to the permanent improvement of the physical, chemical, and mechanical characteristics of the soil, due to the method of application, it can only be used in surface, easily accessible soil layers.

On the other side, electrokinetic soil treatment has emerged as a novel and sustainable alternative [8-10]. This technique utilizes the principles of electrokinetics and involves applying a low-voltage direct current across electrodes embedded in the soil, generating electrical potential in the soil. The applied electric field induces the movement of pore water, dissolved ions, and fine particles through the soil. Given that the electrokinetic soil treatment can be performed at greater depths of the soil, and under existing structures, it seemed promising for drainage. Unfortunately, the effects of such treatment are not permanent. With new, more abundant rainfall, the water content in the soil increases again and the soil strength decreases.

Disadvantages of the previously mentioned soil stabilization procedures can be overcome with the innovative technique which might combine in some way the chemical soil stabilization and the electrokinetic soil treatment. In this way the improvement of the mentioned techniques could be achieved. During the possible procedure the, the introduction and movement of stabilizing agents through the soil could take place under the influence of the direct current, while the stabilization mechanism is based on the principles of chemical

stabilization.In addition, the inclusion of chemical additives such as lime or other reagents helps to improve chemical bonding, reduce plasticity, and increase soil strength.

Moreover, this technique for soil stabilizationcould offer precise control over the treatment process, allowing engineers to modify the treatment parameters, such as voltage gradient, electrode spacing, treatment duration, and chemical dosage, to specific site conditions. This level of control not only enhances the treatment efficiency but also can reduce the risk of over-treatment or under-treatment, which can compromise soil performance and structural integrity.Despite these promising attributes, this technique faces practical challenges, notably the pronounced corrosion of electrodes due to electrochemical reactions at the electrode-soil interface. This degradation can reduce the effectiveness of the process over time and increase operational costs. Understanding the underlying mechanisms of electrokinetic soil treatment and variables influencing the electrode corrosion is therefore essential for optimizing this promising technique for the soil stabilization and ensuring its long-term viability as a soil stabilization method.

2. PRINCIPLES OF ELECTROKINETIC SOIL TREATMENT

One of the key advantages of the electrokinetic soil treatment is its effectiveness in low-permeability soils, such as clays which is typically difficult to treat using conventional methods. These fine-grained soils show that there are limitations in the infiltration of chemical stabilizers when applied in traditional ways. As mentioned, during the electrokinetic soil treatment, when the voltage is applied to the electrodes, due to difference of potentials, direct current flows. The fundamental mechanisms of the electrokinetic soil treatment are based on electrokinetic phenomena, including electroosmosis, electromigration, and electrophoresis. When a low direct current is applied across electrodes placed in the soil, the movement of water in the soil from the anode to the cathode is enabled.

The process of electroosmotic movement of water, leads to a decrease in pore pressure that begins in the anode zone, and then spreads to the surrounding soil. The result of this process is a decrease in soil moisture and an increase in effective stresses in the soil, which results in the consolidation of the treated soil. In laboratory conditions, the water that is collected in the cathode zone during this process is collected in a container, whereby the amount of collected water is a measure of the effect of the applied electrokinetic procedure in terms of soil drainage. There is also a movement of ions towards the electrodes, where appropriate electrochemical reactions and deposition occur around the electrodes. At the same time, electrolysis and the formation of H^+ and OH^- occur in the immediate vicinity of the electrodes. The processes which are mostly active in a part of clayey soil under an electrokinetic treatment and strengthening and repair of slopes have been examined in studies in the previous period [11-14]. The described processes that occur during the conduction of the direct current and are of importance for the electrokinetic soil treatment are illustrated in Figure 1.

It should be mentioned that the oxidation occurs at the anode, creating an acidic front, while the reduction occurs at the cathode, creating an alkaline front. These reactions cause a decrease in pH at the anode and an increase at the cathode [14]. This pH gradient (often referred to as an acid/base profile) and its influences on the transport of species through the porous soil medium have been extensively investigated and well documented by many researchers.

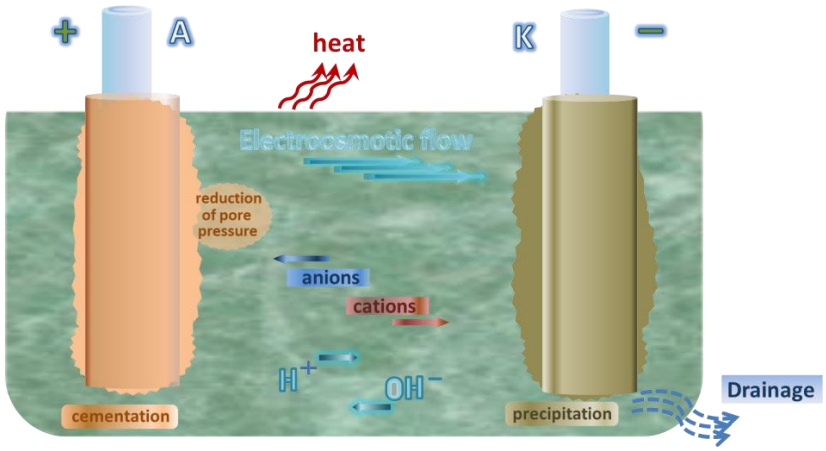


Figure 1. Mostly active processes that occur during electrokinetic soil treatment

In order to adequately predict which voltages and currents should be applied, the basic electrical characteristics of clay should be known. The specific resistance ρ of clay is usually taken to be from 10^2 up to 10^5 Ω•m for dry clay, and from 10 up to 100 Ω•m for wet clay. The specific resistance of clay depends on its mineral composition, water content, temperature and compactness. If precise values are needed for a particular type of clay, it is necessary to perform an experimental measurement under the conditions of interest, as was done during the experiment. Accordingly, a series of experiments is required under predefined laboratory conditions, during which specific parameters, expected to influence the electrokinetic stabilization process, should be systematically varied.

3. EXPERIMENTAL PROCEDURES AND RESULTS

Detailed research required experimental testing in controlled laboratory conditions, with validation through scientific methodologies.In order to conduct investigation, in laboratory conditions, on experimental models, the test was performed by applying predetermined voltages to the electrodes. In addition to the applied voltage levels, electrode spacing, numbers, and spatial configuration were adjusted and optimized throughout the testing process. Also, during the conducted experiment, the focus was on varying the water content of clay (*w*), as this can significantly affects its shear strength and compressibility.

Measurements were carried out under predefined voltage conditions using a direct current power supply DC Instek PSP-603, which is shown in Figure 2a. This used source provides the output voltage of 0 to 60 V and a direct current of up to 3.5 A. Since the applied voltages were varied up to 50 V, which is close to the limit value for safe work, measures were taken to secure the space where the experiment was conducted.

The electrodes were located in a test box, which contained clay with a predefined water content. The measurements were taken with electrodes inserted to a depth of 14 - 15 cm into the clay specimen, and on distance of 22.5 cm.The experiment was performed by applying five different voltages from 10 V to 50 V, and by measuring the intensity of the current flowing through the clay.



(a) (b)

Figure 2. Direct current power supply DC (a) and corroded electrodes (b)

In the first experimental phase, only new electrodes were used. Obtained results are presented in Figure 3. This figure presents the intensity of the electric current as a function of the applied voltage, for four different water contents (*w*) of 15%, 20%, 25% and 30%. It can be seen that the current increases in a continuous and uniform manner with increasing applied voltage and water content, which is consistent with theoretical expectations.The increase is more pronounced as the voltage and water content are higher, and with linear increase with different slope, what correspond to soil resistivity.

In general, during the electrokinetic soil treatment electrode the corrosion is a direct consequence of redox reactions at the soil-electrode interface. The anode typically undergoes oxidation and $M \rightarrow M^{n+} + n\, e^{-}$ occurs where M is the electrode material. On the other side, at the cathode, reduction reactions often produce hydroxide ions. The result is material loss at the anode and potential gas formation at the cathode, both of which compromise the electrode performance and the uniformity of soil treatment.The extent and rate of electrode corrosion is influenced by current density, electrode material, soil chemistry and when chemical additives are applied. Consequently, the electrode corrosion is a significant factor which can affect the electrokinetic treatment. Therefore, understanding the interaction between these factors is essential for optimizing the methods to be applied.

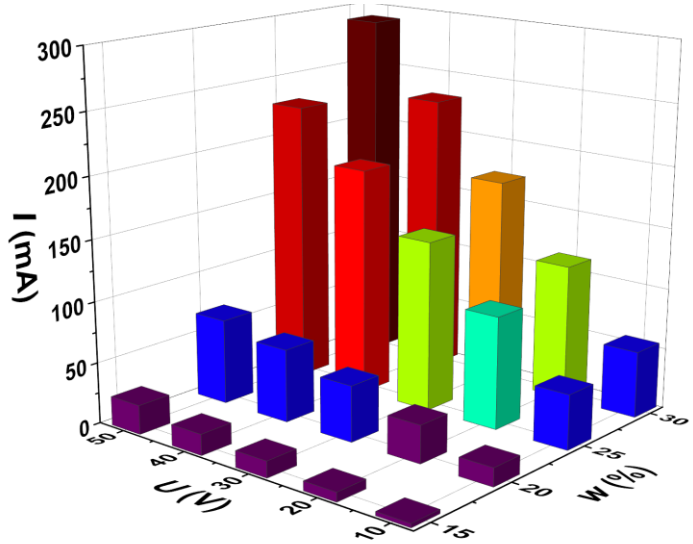


Figure 3. The intensity of the electric current as a function of the applied voltage, for four different water contents

That is why, during this part of the experiment, the influence of electrode corrosion that occurs over time was analyzed. For the samples in the test boxes, when there was clay with

a water content of 20 and 25%, additional tests were performed. Under the same conditions of the experiment, as previously presented, measurements were performed when corroded electrodes were used (Figure 2b). The results obtained are shown in Figure 4, where the increase in electric current intensity as a function of applied voltage can be seen, for two different water contents, for both new and corroded electrodes. As expected, in case of application of corroded electrodes, current flow is significantly reduced. However, it is interesting that there is a greater difference in the current readings when using new or corroded electrodes at the same water content of 30%, than between new electrodes at water content of 30 and 25%. In Figure 5 are presented the differences between the increase in the electric current intensity (as a function of the applied voltage) for both new and corroded electrodes, which are shown in Figure 4. For all values of the applied voltage, this Figure 5 shows the differences in measured currents when using new and corroded electrodes, and in both cases, when the water content is 25% or 30%.

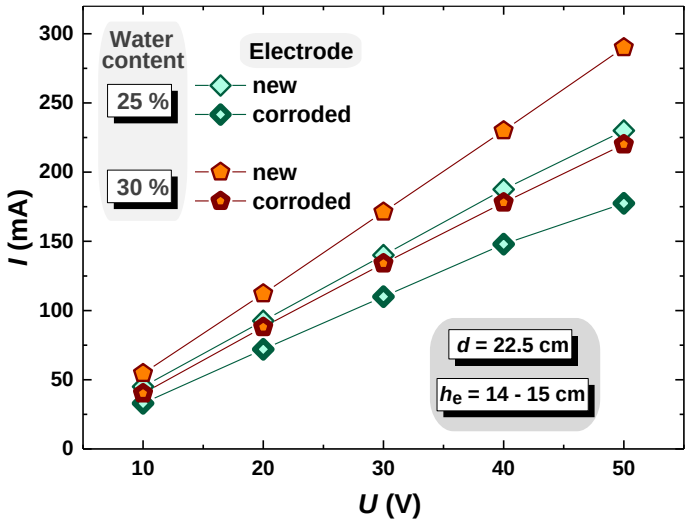


Figure 4. The increase in electric current intensity as a function of applied voltage for two different water contents, for both new and corroded electrodes

From Figure 5 it is clearly seen that the difference in the current flow between the cases when new and corroded electrodes are used is more significant when the water content is 30%, than when it is 25%. This difference becomes more pronounced with increasing voltage.It can be noticed that, for water content of 30%and an applied voltage of 50 V, the difference between the electric current intensity in the case when new and corroded electrodes are used is 70 mA. On the other hand, when only new electrodes are used at the applied voltage of 50 V,the electric current intensity is 60 mA higher in the case when the water content in the clay is 30% than when it is 25%.For all values of applied voltage, the trend is similar. Also, it can be seen that at all the applied voltages the smallest difference between the currents when the water content is 25% and when it is 30% is in the case when only corroded electrodes are used.This indicates that when the electrodes are corroded, the influence of the water content in the clay on the current flow is reduced. Obviously, in this case when only corroded electrodes are used, the specific resistivity of the clayey soil plays a relatively reduced role, i.e. the increased electrode resistance is more pronounced. These effectsare more noticeable at higher voltage values applied.

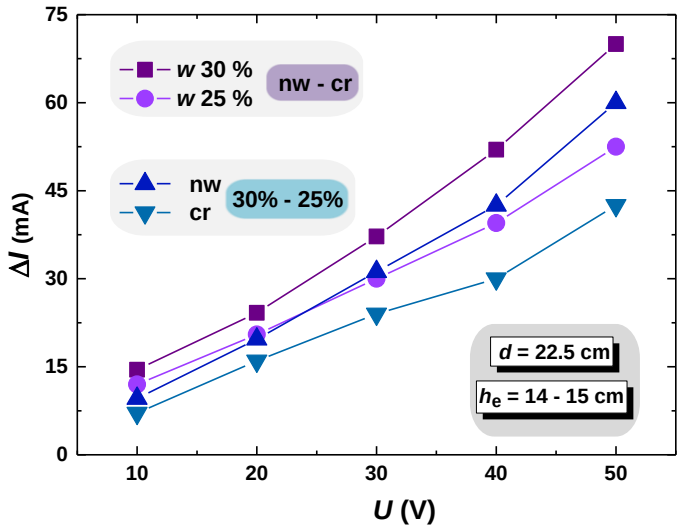


Figure 5. The difference between the increase in electric current intensity as a function of applied voltage for two different water contents, for both new and corroded electrodes

Obviously, the obtained results indicate a significant influence of electrode corrosion on the flow of electric current, and thus on electrokinetic soil treatment. Therefore additional research was performed in order to provide a more detailed analysis. The following sequence of experiments was carried out under the similar conditions. The test was carried out in the same test boxes, with a distance of 22.5 cm between the electrodes and a depth of clay to which the electrodes were inserted which was 14 - 15 cm, but with a successive increase of water content from 20% to 35% with an increase of 5%. The results of this sequence of experiments are presented in Figure 6.

For all cases of this additional experiment, which include samples of clayey soil with four different water contents, significant reduction in measured electric current intensity between electrodes embedded in clayey soil was observed. Table 1 shows the differences in the electric current intensity obtained during this part of the experiment, when new and corroded electrodes used for the highest and lowest values of water content percentage (20% and 35%). Based on the presented values can be seen that reduction of current was 21%-32% at applied 30 V, while at applied 50 V, it was 22%-38%.

As expected, the use of corroded electrodes leads to a significant reduction in electric current flow through the clay sample. This is due to the compromised conductivity at the electrode surface caused by electrochemical reactions that, over time, result in the formation of corrosion products (e.g., oxides, salts), a reduction in the effective electrode surface area, and an increase in contact resistance between the electrode and the clayey soil.Namely, the condition of the electrodes (new vs. corroded) has a more pronounced impact on the system's conductivity and the efficiency of the electrokinetic treatment than a percent change in clayey soilwater content. This is interesting, considering that the water content directly influences the ionic mobility and the overall electrical conductivity of the soil, and it is typically expected that even small changes in the water content would affect the current flow.However, the experimental results suggest that the electrode corrosion is an even more dominant factor.

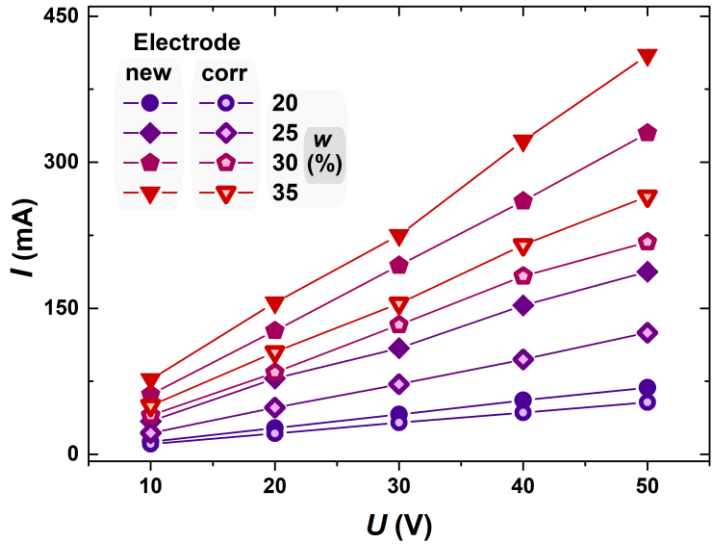


Figure 6. The increase in electric current intensity as a function of applied voltage for four common different water contents, for both new and corroded electrodes

Observed results imply that corroded electrodes not only reduce the efficiency of the current transmission but may also disrupt the uniform distribution of chemical stabilizers during a potential treatment. Since electrokinetic processes rely on the continuous and stable current flow to drive the electroosmosis and electromigration, any reduction in the current can negatively impact the overall effectiveness of the soil treatment.

Table 1. The difference in electrical current intensity obtained when new and corroded electrodes were used for the highest and lowest values of water content percentage

w (%) \ Voltage	10 V	20 V	30 V	40 V	50 V
20	2.4	5.5	8.5	12.5	15
35	27	51	70	107	145

These findings clearly indicate that electrode corrosion is a critical parameter that can have a greater influence on the treatment success in addition to certain physical properties of the soil, such as water content. Therefore, a special attention must be given to the selection of electrode materials, maintenance practices, and potential strategies for corrosion protection in electrokinetic systems.By implementing these approaches, the operational lifespan of electrodes can be extended, making the electrokinetic soil treatment more viable for a large-scale or long-term application.

4. CONCLUDING REMARKS

This study highlights the potential of the electrokinetic soil treatment as a promising technique for stabilizing soils, especially where traditional methods are insufficient or environmentally unsuitable. The findings demonstrate that while parameters such as the soil water content are important for the effective current flow and treatment outcomes, the condition of the electrodes, particularly the extent of corrosion, plays a significantly more critical role in the overall performance of the system.

The observed reduction in the current flow when using corroded electrodes, even at an optimal water content, emphasizes the detrimental impact of electrode degradation on the electrokinetic process. The fact that the corrosion caused a more substantial decrease in the current than a 5% variation in soil moisture underlines the importance of electrode maintenance, material selection, and corrosion mitigation strategies in practical applications.

Given that electrokinetic stabilization relies heavily on the sustained and consistent current, the electrode corrosion emerges as a limiting factor that can compromise the treatment efficiency, duration, and cost-effectiveness. As such, future work should focus on the optimization of treatment parameters to reduce the electrochemical degradation, and the potential implementation of protective measures such as pulsed current techniques. Concerning that the electrokinetic soil treatment holds a great promise it can be further optimized for broader, more reliable use in geotechnical and environmental engineering.

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Review paper

BIOMIMETIC FORMS IN ARCHITECTURE: DEFINITION, APPLICATIONS AND CHALENGES

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Abstract

The implementation of biomimicry as a design approach in architecture is still in its early stages. Biomimicry is defined as a solution to design problems inspired by natural patterns and has a wide range of applications in architecture, from materials, form, to regenerative ecosystem level. The primary purpose of this paper is to investigate the development of biomimicry in architecture from the aspect of form, through a bibliometric review. In this study, articles published in the Web of Science database (2014–2024) were analyzed. VOSviewer software was used to conduct the bibliometric analysis and to represent the analysis results. In order to increase the knowledge of biomimicry, this study also analyzes how biomimetic forms can be applied in architecture and explores the various challenges in their implementation. The challenges of implementing biomimicry in architecture are grouped based on social and technological challenges. Emphasizing the importance of the need for biomimicry in the design of contemporary architectural forms is the goal of this study. Based on the results, future research directions and practical recommendations were presented to support the successful deployment of innovative design approach.

Key words: *Biomimicry (BM), Form, Architecture (AR), Bibliometric analysis*

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1. INTRODUCTION

In the last few decades with the application of digital technologies, progress has been achieved in the development process of architectural design. At the same time, new ideas and approaches began to emerge that provide architectural solutions based on forms from nature. Recognizing the qualities of such forms, architects have always strived to imitate nature. Architects and designers refer to nature-based design using interpretations of several bio-related keywords, such as biomimicry, biomimetics, bionics, biomorphism, ecomimicry and organic design [1]. Biomimicry is a promising emerging research field defined as a solution for design problems inspired by natural models, systems, and elements [2]. The term was coined by Janine M. Benyus in 1997 and is a junction of the Greek words 'bios', meaning 'life', and 'mimesis', meaning imitation [3]. In particular, 'biomimicry' stresses the interconnectedness of systems to solve complex problem in design and today's environmental challenge [4]. In the flora and fauna, it is possible to find a large number of geometric shapes and forms that have developed in response to the limited resources of the environment. Biomimicry offers completely new ways of approaching design so that the whole system can be optimized and a radical increase in resource efficiency can be achieved.

Development processes and systems based on digital engineering, as well as on complex geometry and biological principles, are connected in contemporary architectural design. Digital tools, robotic prefabrication and additive manufacturing have enabled new progress in expanding the boundaries of the theory of architectural phenomenology, from the representation of space to the representation of systems.

Recent years have seen an increase in studies on digital design and state of the art manufacturing methods in biomimetic architecture. However, despite the increased interest in biomimetic research in architecture, the concept itself is still ambiguous for many practitioners and researchers.

When there is an increased level of interest in an emerging concept or technology, there may be a risk of increased confusion due to the fragmentation of the presented knowledge about this concept and its application. Bibliometric analysis play a vital role in bringing together previous studies' results. To answer specific research questions, a systematic literture review was used, ensuring the inclusion of only related literature, identifying what is known and unknown about the topic under study.

With the aim of contributing to the increased understanding of the role of design methodology and technology in biomimetic architecture, the current study uses the bibliometric analysis approach to answer the following research questions:

- How to transfer biomimetic morphological principles to architectural design?
- What are the potential and current applications of biomimetic forms in architecture?
- What are the main challenges facing the adoption of biomimicry in architecture from the social and technological perspective?

The structure of this study is as follows: after this section, Section 2 presents the research methodology, then Section 3 presents the literature characterization and bibliometric findings with visualization performed using VOSviewer. The findings are discussed in the same chapter. In Section 4 are presented the conclusions, limitations and implications of the study.

2. RESEARCH AND METHODOLOGY

The essential purpose of this paper is to survey publications and research directions in the field of biomimetic forms in architecture using the scientific literature database. Web of science is recognised as one of the databases with the most extensive data sources for a wide range of topics. To define the current trends, characteristics and potential applications of biomimetic forms related to architecture, the methodological approach of this study is a systematic literature review (SLR) [5]. There are three main phases in SLR research methodology, which are the identification, screening, and eligibility to decide what should be included in the review process. The following terms were used in the identification phase on Web of Science database: “biomimetics” OR “biomimicry” AND “architecture” OR “architectural design” AND “forms” AND “computational design” OR “robotic manufacturing”. The search included only scientific articles, conference papers and reviews written in English. The search result consists of 353 studies; among them, 35 were duplicated and removed. In the screening phase, the search was for studies that included defined terms in the title, abstract or keyword list, in order to ensure the use of studies directly related to the studied topic.

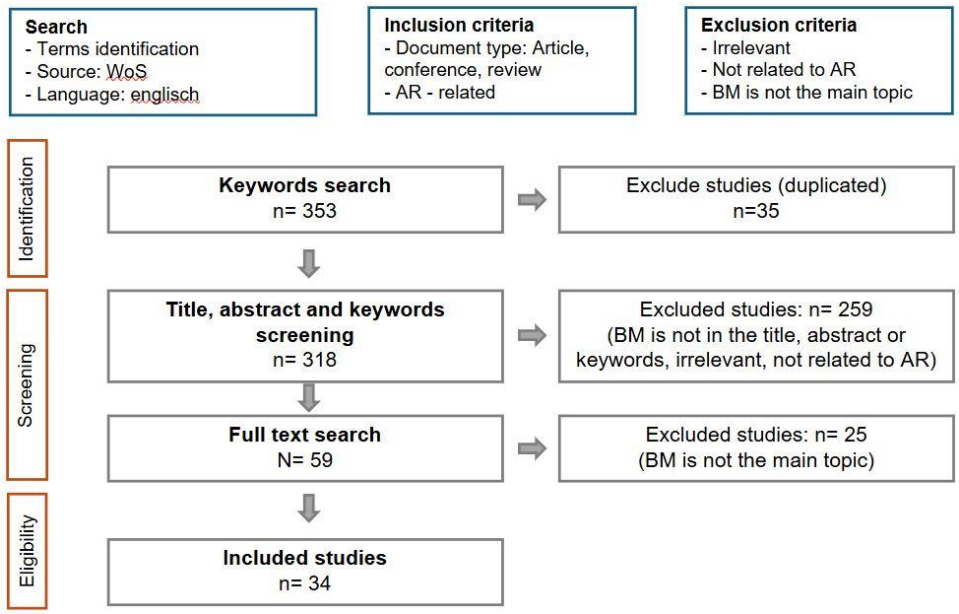


Figure 1. Methodological framework of the research

Studies that are irrelevant to biomimetic architecture from the aspect of form and computational design are excluded. In the continuation of the research, a full text search was performed. In this step studies not related to architectural form and computational design in biomimetic architecture were excluded (e.g. studies that mentioned computational design and robotics in biomimetic architecture as a future recommendation in the abstract). Accordingly, 34 studies were selected to be included in this study. Bibliographic data from the Web of Science database were analyzed in VOSviewer Software Tool. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the

relationships between the most repeated keywords about the studied topic, and then cluster them accordingly [6].

3. RESULTS AND DISCUSSION

Articles from the Web of Science database were studied to identify bibliometric indicators in the research, such as thematic classification, annual publication analysis, geographic area analysis, keyword co-occurrence, citation by source and authorship analysis.

3.1. Biomimetic form in relevant research areas

Figure 2 presents a diagram illustrating the thematic classification of biomimetic form in architecture. Based on the diagram, it can be concluded that in the field of Construction Building Technology, biomimetic form is the most researched topic with a number of papers of 122. It is important to highlight significant studies in fields such as Engineering (99), Materials Science (55), Architecture (34) and Energy Fuels (8).

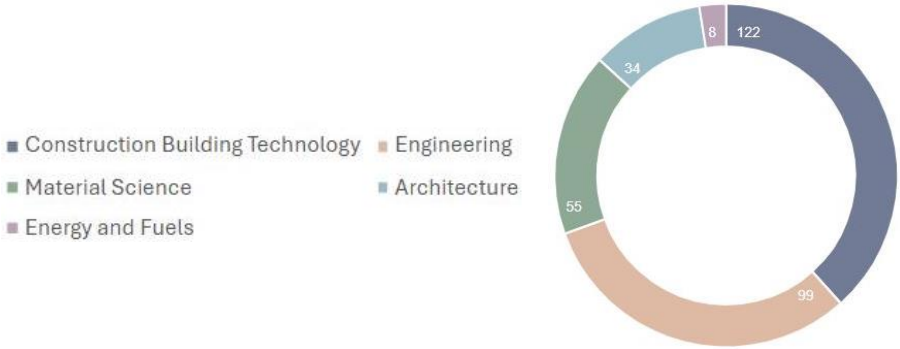


Figure 2. Subject area distribution of the related literature in biomimetic architectural forms

3.2. Anual publication analysis

Based on Figure 3, there is an evident increase in the number of published scientific papers and interest in the topic of biomimetic form in architecture. The chart covers the period from 2014 to 2024. The distribution of publications by year indicates the relevance of the topic and the need for designers and practitioners to turn to innovative approaches to support sustainability. This review included 34 papers related to studied topic. As of the date of this review (April 2025), the largest number of papers was published in 2022 (12 papers) and 2024 (10 papers). This very rapid increase in the number of studies each year may show some signs of awareness of the potential of biomimetic form in architecture and confirms the need to clearly explain the meaning of biomimicry and identify possible challenges for its application. The increased interest in biomimicry can also be seen in the number of papers that included case studies or pavilions.

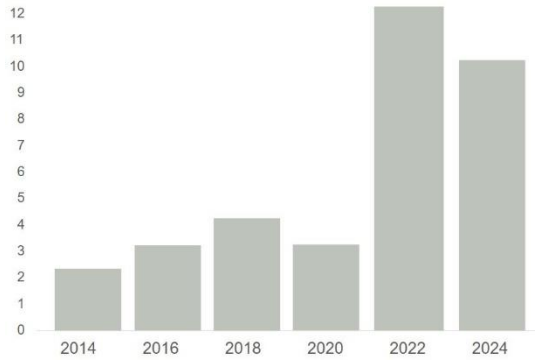


Figure 3. Annual number of publications related to biomimetic architectural forms

3.3. Geographical location

Figure 4 shows the results of the bibliometric analysis based on co-authorship using countries as the unit of analysis. The minimum number of documents in a country is set to 1. The results show that 12 countries meet the thresholds in the data inclusion phase, but only countries with more documents are selected for the co-author network. The results show that only 8 countries meet the thresholds. Figure 4 shows four clusters. Cluster 1, colored green, includes the United States, Germany, and India. Cluster 2 (red) includes China, Australia, Italy, and England. Finally, cluster 3 (blue) refers to the Netherlands, which is the only country in this cluster, but has links to at least 6 countries. The size of the bubbles shows that the United States and Germany have more documents on the topics analyzed in this study.

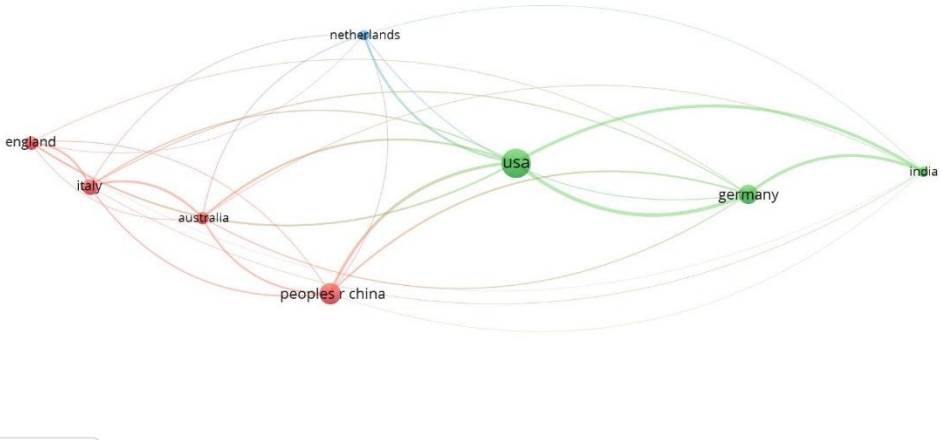


Figure 4. Network visualization of co-authorship by country. The size of nodes represents the frequency of occurrence, the lines between the nodes represents the co-occurrences of the co-authorship

3.4. Key word corelation – bibliometric analysis

To identify patterns of publications about biomimetic architectural forms and current trends in the international scientific literature, keyword co- occurrence was conducted using VOSviewer. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the relationships between the

most repeated keywords about the studied topic, and then cluster them accordingly [6]. Before conducting the co-occurrence analysis on VOS viewer, keywords with similar meanings were merged. Each map is characterized by nodes connected by the lines; the size of the bubbles indicates the frequency of occurrence or citations, while the lines represent the connection between the two concurrent keywords, creating a network map. The keywords analyzed were words that were repeated at least five times in the selected articles.

As a result, 44 keywords were obtained in 7 groups (clusters): biomimicry and sustainable construction (green), bio-inspired and computational design (red), building envelope performance (dark blue), sustainability and adaptation in architecture (light blue), design related to plant behavior and soft robots (purple), behavior and growth through model (yellow), biomimetics related to animals, actuators and movements (orange). This study found that the autors preferentialy used the keywords “Biomimetics” and “Biomimicry”.

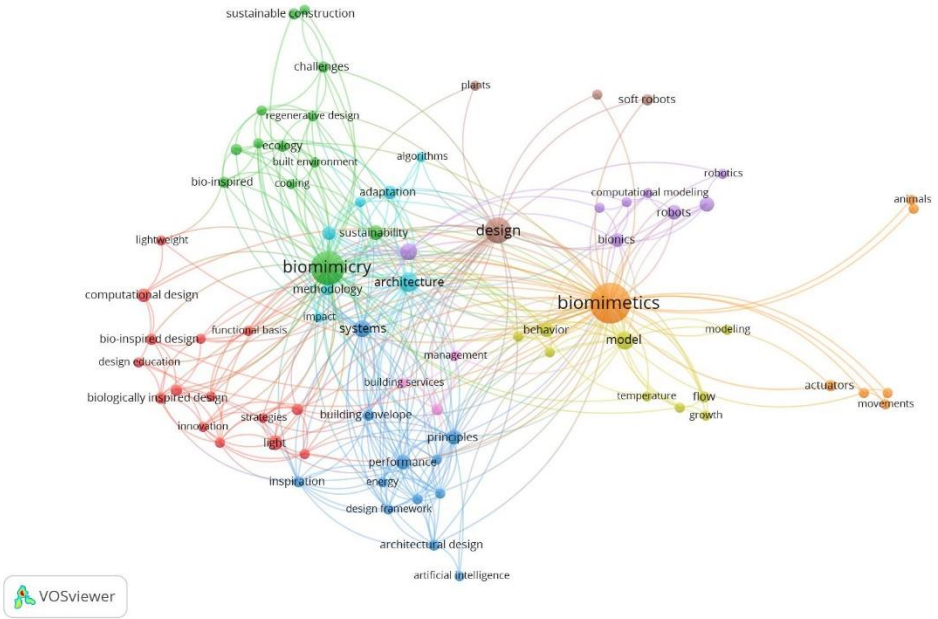


Figure 5. Network visualization of keywords co-occurrences of data included

3.5. Publicion source

Figure 6 shows the bibliographic analysis by document source and the relationship between publications and citations. The minimum number of documents is set at 1. The size of the node is proportional to the number of publications. The journals with the most documents are "Biomimetics" (5) and "Architectural design" (3). They are followed by "Bioinspiration and Biomimetics", "Sustainability" and Buildings.

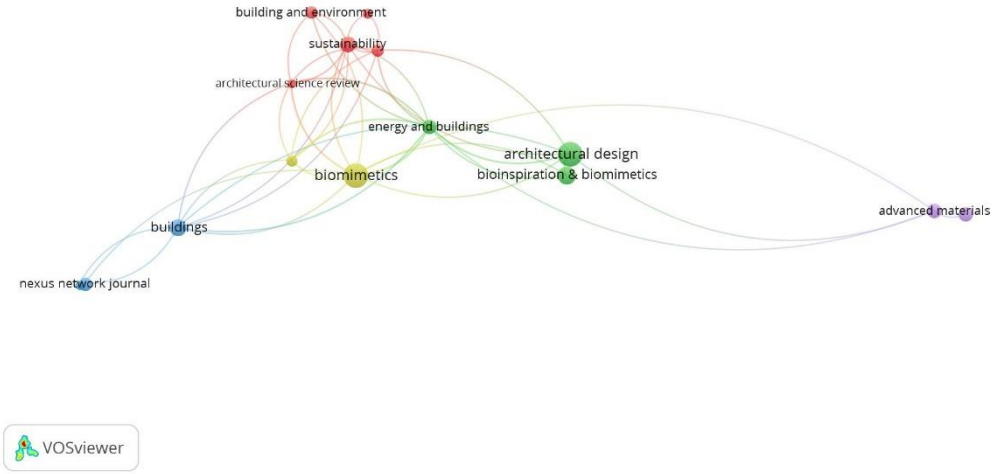


Figure 6. Visualization of publication sources' citations

Table 1 shows the distribution of documents and citations in the different journals (only sources with more than 1 document are considered in this table) and the total link strength, which is the total strength of links from one journal to other journals. The distribution of articles classified as biomimetic form and architectural design are mostly published in listed journals.

Table 1. List of journals with more than one publication about biomimetic architectural forms

Source	Documents	Citations	Total link strength
Biomimetics	5	138	16
Architectural design	3	152	12
Bioinspiration and Biomimetics	2	94	9
Sustainability	2	73	24
Buildings	2	68	18

3.6. Autorship analysis

In this chapter, the most cited authors whose articles are related to the topic of this paper are analyzed. Figure 7 shows the 6 authors with the most citations of their articles related to biomimetic form and architectural design. The highest number of citations (267), with a total link strength of 26, belongs to Achim Menges, based on the results from the cluster network. The other 6 authors with the most citations and their link strength are also shown in Table 2.

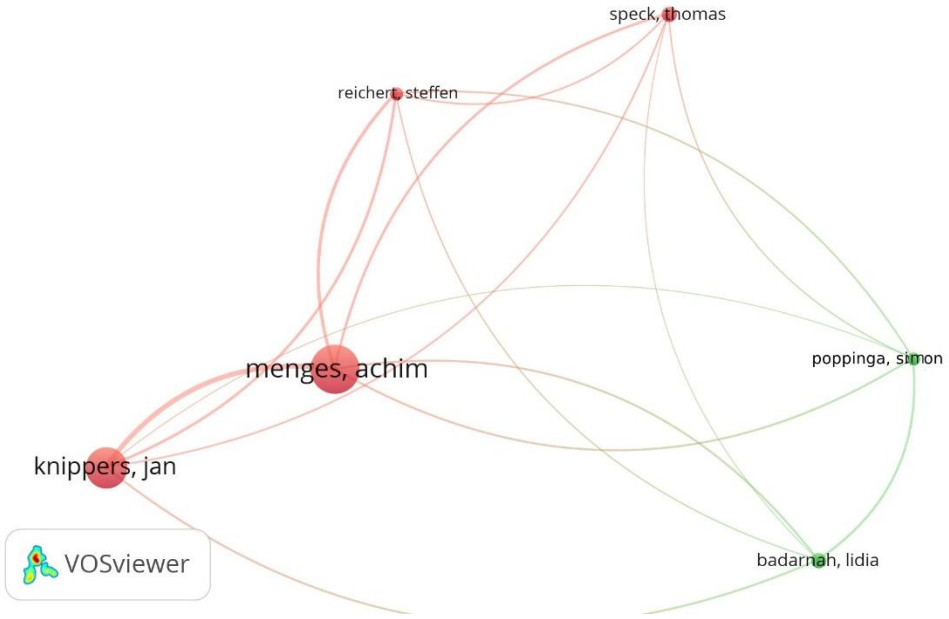


Figure 7. Visualization of the most cited authors

Table 2. List of authors with more than one publication about biomimetic architectural forms

Rank	Author	Document	Citation	Total link strength
1	Menges, Achim	7	267	26
2	Knippers, Jan	5	196	21
3	Speck, Thomas	4	165	13
4	Badarnah, Lidia	3	202	9
5	Poppinga, Simon	3	165	9
6	Reichert, Steffen	2	267	19

4. APPLICATIONS AND CHALLENGES

Based on the analyzed studies, it is evident that the largest number of studies represent the exploration of biomimetic architectural form through the design and fabrication of pavilions or building envelopes. A smaller number of studies deal with the methodology, review and challenges of biomimetic design [7-14].

4.1. Design strategies, tools and targeted performance in analyzed projects

Analyzed public building projects are generally characterized by scarce participation of biologists during the design process. The motive for applying the biomimetic approach was to provide a design with neutral to a positive impact on environmental issues, but almost none of them evaluated the final impact of the realized design. Kinetic building envelopes, ventilation or water regulation systems in buildings driven by technical equipment and operational energy have been recognized as bioinspiration. However, these cases lack an

interdisciplinary approach that involves the inclusion of biomimicry as a discipline and its methods in the initial design phase [15-23].

On the other side, academic projects present a strong correlation with biological contribution in their design process. These are mostly ephemeral structures - pavilions. Researchers from the Universities of Stuttgart and Freiburg are a perfect example of interdisciplinary collaboration [24-33].

It is important to identify common strategies and tools for successful transfer of biomimetic morphological principles to architectural design. What all academic projects have in common for a successful outcome is use of these transition tools and strategies:

1. Involving biologists and biomimetic tools in the initial design phase to understand principles from nature and their transfer into technology
2. Applying generative-performative design and parametric tools, where the building envelope is viewed as an intelligent adaptive system that reacts to the environment [34, 35]
3. Expertise in the field of building materials (bio-based materials) and their behavior, applying augmented reality, additive manufacturing, robotic manufacturing with a high degree of precision [36, 37].

Targeted performance achieved and applications:

1. Thermal comfort
2. Structural performance (less material), lightweight design
3. Indoor climate regulation (ecologically sensitive architectural surface)
4. Co2 reduction, less material waste

4.2. Challenges in implementation of biomimetic design approach

When it comes to such complex and developing approaches, one must talk about the challenges in its implementation. Based on the literature reviewed, this research defines the following groups of challenges:

1. Methodological challenges
2. Social challenges
3. Technological challenges

Some of the reasons explaining the low number of biomimetic products in architecture are the lack of a clear methodology, the difficulties of interdisciplinary work, and the complexity of biology as a model. In order for appropriate biomimetic design concepts to be generated with potential for commercialization, the systematic transfer of biological knowledge into technology needs to be facilitated and methods presented.

Similar to any new concept, people may show high level of resistance to change. Low level of technology acceptance, fear of working with unfamiliar practices, and heavy reliance on traditional practices are some of the main reasons for this resistance.

For the successful adoption of biomimetic buildings, stakeholders should focus on clearly demonstrating their sustainability credentials, rather than relying on their biomimetic nature as a stand-alone means of persuasion. Educational campaigns and public communication strategies should prioritize factual evidence of benefits, explicitly addressing environmental, economic, and social dimensions. There is no “biomimetic design language” that allows laypeople to judge biomimetic buildings or other products as inspired by living nature based on the characteristics of those buildings/products. The results highlight the importance of evidence-based communication of specific benefits and suggest that successful promotion

of biomimetic or bioinspired technologies requires a more nuanced understanding of public conceptualizations of sustainability [7].

Biomimetic strategies that integrate the structure, form and material of complex adaptive systems into a single heuristic process are one of the models in the research of digital morphogenesis in architecture. Digital tools expand the boundaries from the representation of space to the representation of systems. The main challenges in terms of technology and digital tools for biomimetic forms relate to bringing the language and symbols of new techniques of space representation closer to the user - the architect. A generative approach to modeling requires cognitive predispositions, and architects need an affinity for programming for such an approach to form generation [38].

5. CONCLUSION

Biomimicry is one of the most innovative approaches to energy-efficient design, and little research has been conducted in this area when it comes to architectural form. With the aim of better understanding this approach, presented review attempted to analyze the potential applications of biomimicry from the aspect of architectural form and identify the challenges that may be faced in adopting and implementing this approach.

The significant growth in the number of publications on this topic in recent years is shown by the Web of Science database, and the University of Stuttgart stands out in the number of publications and citations. Their example shows that cooperation between experts in biology and architecture is necessary to promote interdisciplinarity and achieve better results. According to this findings, architecture, biology and technology are deeply intertwined and multidisciplinary studies are inevitable.

The results of this study are relative given the rapid development of technologies and the possibility of introducing AI into the entire design process. Future studies could also address the evaluation of the most serious challenges in implementing a biomimetic approach in the design of architectural forms.

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Review paper

DIFFERENT ASPECTS OF THE APPLICATION OF OLD SHIPPING CONTAINERS IN THE CONSTRUCTION OF MULTI-STOREY BUILDINGS

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Abstract

Application of old shipping containers in the construction of different kinds of buildings is increasingly popular in the world and in our country as well. This is an economically and ecologically sustainable option. Containers, which were originally designed for transportation, after they have served their purpose, can be used to build modular buildings due to their high resistance, speed of construction and relatively low cost. These buildings are modern and flexible solutions in the construction, which use containers as modular units. Containers can be combined according to different modular schemes, which enable creative and functional architectural solutions. The paper discusses the application of old shipping containers in the construction of multi-storey buildings from several of the most important aspects in architecture and civil engineering.

Key words: *Shipping Containers, Container Buildings, Modular Construction, Multi-Storey Buildings, Sustainable Architecture*

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1. INTRODUCTION

The application of old shipping containers in the construction of different kinds of buildings is an innovative approach that offers very fast, cost-effective and environmentally friendly solutions. This construction method has experienced its expansion at the beginning of the 21st century. Shipping containers that were originally designed for transportation now are used as large modular blocks for building construction.

Shipping ISO containers, Standard 20' and Standard 40', with their lengths of 6.06 m and 12.2 m, and width of 2.45 m, allow flexibility in design. Their own steel structure makes them very strong and resistant to various kinds of loads. The container walls can be cut, which enables creation of larger spaces. The only design limitation is their height, which is 2.59 m, but there are also tall containers that have a height of 2.89 m. It is an innovative and economical way of construction, which enables creative and functional solutions. It is possible to build different types of buildings, from houses and cottages to business spaces, industrial and residential complexes. Solutions with large glass areas and roof terraces are popular, too. There are many examples of the integration of green roofs, which have shown significant environmental benefits, creating spaces that improve both aesthetic appeal and ecological balance, by promoting energy efficiency. The sustainable potential of buildings made of old shipping containers cannot be ignored.

Containers can be connected and placed in different configurations, either horizontally or vertically, which enables the construction of more complex buildings with multiple floors. The design takes advantage of modular architecture, utilizing shipping containers as building blocks to create highly efficient and adaptable structures [1]. Cost-effectiveness is another key advantage of "container" buildings, as they are popularly called. Reusing containers as building material not only reduces waste, but also reduces overall material costs.

Therefore, the idea of using old shipping containers for the construction of modular buildings has appeared primarily because of their high resistance, modularity, speed of construction, relatively low costs and ecological characteristics. Buildings constructed in this way have become an economically and environmentally sustainable option. In 1987, Phillip C. Clark obtained a patent for modifying shipping container boxes for habitable and productive buildings. Through this patent, shipping container architecture were established by attaching one or more container boxes on a foundation with all infrastructural elements such as inner side walls, roofs, ceilings, doors and windows [2].

2. EXAMPLES OF MULTY-STOREY CONTAINER BUILDINGS

"Container City 1" is the first multi-storey container building in the world. It was built from recycled shipping containers in 2001 in London, Fig. 1.(left) This building was originally high three-storeys. Now, it is a four-storey building that is used for residential and commercial purposes, including art studios and offices. Shortly after its construction, the "Container City 2" building was built in 2002, Fig. 1.(right), by the same company.



Figure 1.Container City 1 (left) [3], Container City 2 (right) [4]

This project has became the forerunner of many other innovative buildings made of containers around the world. To name only a few: "Container Building" in Santiago, Chile Fig. 2.(left), "The Stow-Away Hotel" in Waterloo, London, England, Fig. 2.(right), "Keetwonen" in Amsterdam, Netherlands, Fig. 3 .(left), "Cité A Docks" in Le Harve, France, Fig. 3 .(right), "Local Studio's IDA" on McKinley, Phoenix, the tallest container building in the USA, Fig. 4.(left).



Figure 2. Container Building (left) [5], Keetwonen (right) [6]



Figure 3.Drivelines Studios (left) [7], Cité A Docks (right) [8]

The world's tallest building made of shipping containers, called "118 VR", was planned to be built in London, Fig. 4.(right). Planning permission was obtained in 2019. This office building was supposed to be 26 m high (9 floors), and have a load bearing steel framework.



Figure 4. Local Studio's IDA (left) [9], 118 VR (right) [10]

There are also extreme examples of container architecture, such as the conceptual design of container skyscrapers. Two the most specific are the "Radical Shipping Container Skyscraper", and the "Containerscrapers", Fig. 5. Both examples are focused on providing temporary homes in Mumbai, India.



Figure 5. Radical Shipping Container Skyscraper, [11,] "Containerscrapers", [12]

3. ENVIRONMENTAL ASPECT

One of the major problems of environmental pollution is the accumulation of various types of waste, which is constantly increasing from year to year. Rapid economic development and intensive construction, primarily of residential buildings, significantly affect the environment. We must be aware that architecture and civil engineering are the areas that have a great impact on the environment, especially during the construction time, and therefore require the mandatory application of the principles of sustainable development. In addition to the application of clean and energy-efficient, green technologies, the world's modern trends in architecture and construction also include the use of ecological, non-polluting and recycled materials, renewable energy sources, reduction of construction waste, reduction of water and energy consumption, more rational use of construction land, application of modern technologies and construction systems, and improvement of living and working conditions in all buildings in general [13].

The use of old shipping containers in the construction of buildings is just one way to contribute to sustainable development. All over the world, in various places, often inappropriate, and especially near major ports, there are piles of old shipping containers that have ended their long transportation life, which usually lasted from 7-15 years. However, many of these disused containers are a result of a recent, alarming trend toward single-use container shipping [14].

The reuse of shipping containers for other purposes, such as the construction of different types of multi-storey buildings, would significantly reduce the amount of waste as well as the need for the production of new construction materials. Shipping containers contain much more steel than is needed to build a house, for example. In addition, air pollution due to CO2 emissions during the steel recycling process in smelters would be reduced. Construction of buildings, especially residential ones, by reusing shipping containers is also an environmentally sustainable option. We give a new purpose to an old and worn-out thing and thereby contribute to the preservation of the environment [15].

4. ECONOMIC ASPECT

The use of old shipping containers as modular units in the construction of multi-storey buildings can, in certain cases, become an alternative solution, especially when it comes to the speed and cost of construction. It is well known that the two most significant advantages of modular construction are faster construction and cost savings. Construction time can even be shortened by half compared to conventional construction, and cost savings are directly related to time savings.

The shortening of the construction time is closely related to the preparation of the construction site itself and the foundation construction, while at the same time modifying of the modules takes place off-site. By using old shipping containers as modules, since the containers are already factory-made, the speed of construction is additionally increased because they are only modified in the workshop and require less construction work. In addition, the modules are quickly assembled on site and are functional in just a few weeks. Due to the increasing demands and innovations, construction processes are evolving. In recent decades, the construction industry has undergone significant industrialization and

adopted various methods of construction. As a result of this evolution, off-site construction has become an established practice as an alternative to traditional on-site construction [16].

Assembly on the construction site includes stacking the modules horizontally and vertically and connecting them to each other. If there is a supporting steel structure, the assembly includes inserting modules into that structure and connecting them to it. In addition, it is necessary to connect the previously assembled installation components on the construction site. Certainly, the whole process is much faster than the classic construction method. Also, there are no construction delays due to bad weather conditions at the site.

The cost of the containers themselves is low, while the conversion costs such as the assembly of insulation and installation and structural adjustments can increase the total cost. However, due to less need for the heavy equipment and faster construction, this is still a more affordable option compared to traditional buildings.

The use of all shipping containers is, therefore, a very economical option. In addition to faster construction and savings in construction time and costs, there is also a significant saving in material for the construction itself, considering that the containers are only modified.

5. STRUCTURAL ASPECT

Shipping containers are made of a special type of steel, called “corten” steel, which makes them very durable and resistant to weather conditions. Unpainted corten steel will form an outer layer of rust that reduces deeper rust spreading. Shipping container experts favor corten steel for its protective qualities. Corten steel structure is a key reason why we are confident that shipping containers will become a suitable and cost-effective building component for off-site construction [17]. Also, due to their very structure, they have great strength, so they can withstand heavy impacts and are often more resistant to seismic activity.

Structurally, each shipping container consists of four steel columns at the corners and beams that connect them longitudinally and transversely, at the base and at the top. There are also longitudinal and transverse wall panels and top and bottom plates. The floor structure as well as the walls between two adjacent modules or two adjacent modular assemblies are duplicated, which further contributes to the strength of this system.

Multi-storey modular container buildings belong to the cellular structural system. Considering that, they can be built by stacking containers (modules) directly one above the other without additional supporting elements, or by installing modules into a load bearing steel frame [18, 13]. Examples of the buildings built in these two ways are shown in Fig. 6.(left) (Stow Away Hotel, a building with directly stacked containers one above the other) and Fig. 6.(right) (City of the Sun, a building with load bearing steel framework). A combination of these two solutions is also possible. Modules or cells are usually prefabricated business or residential units consisting of only one or more connected containers that make up a modular assembly. It is important that their weight and dimensions do not exceed the allowed values for transport and assembly. In the phase of the conceptual design of the building it is also important to look at both possibilities and determine which solution is more profitable, taking into account all the advantages and disadvantages.



Figure 6.Stow Away Hotel (left) [19], City of the Sun (right) [20]

The main advantages of a solution where the containers are stacked directly on the top of each other without any additional supporting structure is that there is no need to insulate the containers on all six sides and the construction speed is higher. Therefore, this is a cheaper solution, since there are no costs for additional insulation and for construction of the supporting structure. On the other hand, the possible number of floors of these buildings is smaller, because the containers themselves carry all the loads, which limits the number of floors and resistance to external forces.

Container buildings with an additional supporting steel structure are a more advanced version of shipping container buildings. Steel structure provides additional strength, flexibility and safety. This system has multiple advantages, especially when it comes to the loads acting on the building. Containers are placed inside the steel frames. The steel frames carry all the loads and increase the stability of the entire building when affected by wind, earthquakes and possibly other external forces. Considering that, in this way it is possible to build container buildings with more storeys than in a system without an additional structure in which the modules carry themselves. Precisely, in that case, the modules in the lower floors carry the entire weight of the building. Due to the greater load capacity and stability, it is possible to install additional equipment, such as solar panels or heavier loads on the roof, depending on the purpose of the building.

Also, the application of this system allows a greater flexibility in design as it facilitates the placement of larger windows, terraces or extensions that would weaken the containers themselves. In a system without additional structure, the containers are supported by their basic form, so the removal of walls is limited, as this could reduce their load-bearing capacity. Creative solutions such as consoles, open spaces or asymmetrical layouts are easier to implement. If additional bracings are needed to increase the stability for a higher number of storeys, they are easy to add. Buildings with additional steel structure are more suitable for larger, longer-term and more complex projects (residential buildings, business and public buildings) where a greater number of floors and larger spaces are required. Unlike them, container buildings without an additional steel structure are a good choice for smaller, temporary projects (work camps, temporary housing facilities, warehouses or summer cottages), where the budget is limited.

The main disadvantage of the solution with a supporting structure is that the modules (modular assemblies) must be completely waterproof and completely insulated on all six sides, which requires higher costs. The construction of the load-bearing steel structure increases the total cost of the building and the complexity of the project. Maintenance is also more expensive because steel requires regular corrosion protection.

When it comes to the construction of container buildings, the connections between the containers, and the connections between the containers and the steel structure are very important. The containers themselves have corner castings on the corners (Figure 7) which are used to connect the containers to each other by using twistlocks (Figure 8) or bridge clamps (Figure 9) to prevent the containers from overturning during ship transportation or storage of goods, when they are stacked on the top of each other in multiple levels. However, in the case of building construction, especially those that are not of a temporary nature, it is necessary to make bolt connections or welding.

All the rules for joints and connections defined by Eurocode 3 [21] must be applied, considering that this is a steel structure, both of the supporting structure and of the containers themselves.

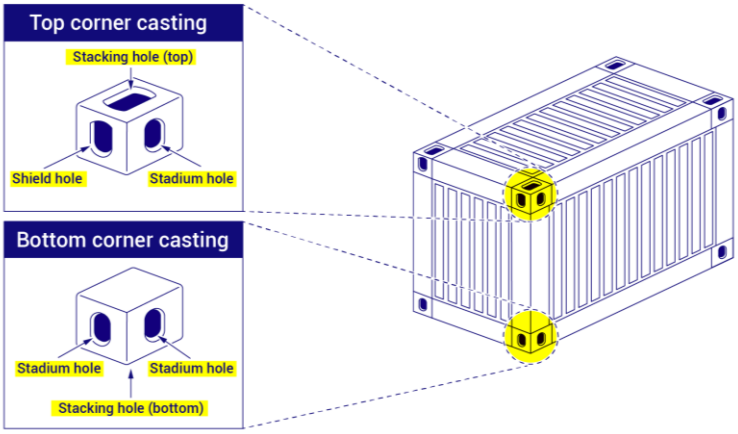


Figure 7. Corner castings, [22]

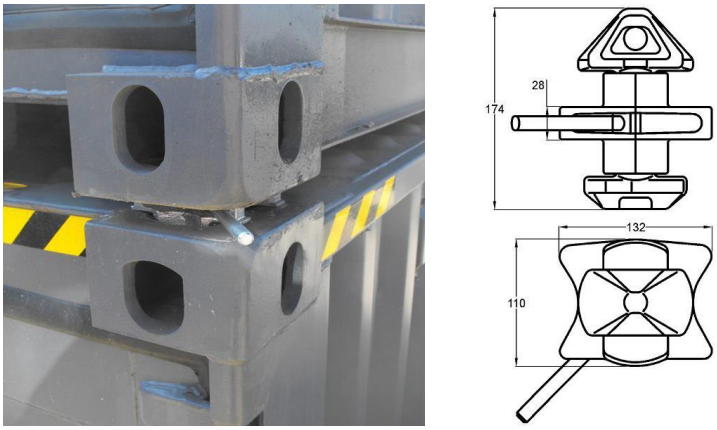


Figure 8. Corner castings and twist-lock, [23]



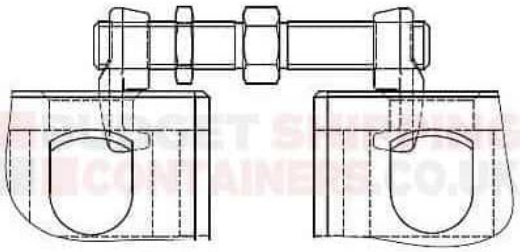


Figure 9. Bridge clumps, [24]

Connections between shipping containers and the supporting steel structure, which are made with bolts or welding, must be designed to ensure stability, safety and durability. For temporary buildings, it is necessary to make bolt connections for easier disassembly.

The connections must withstand all static and dynamic loads, including the weight of the structure, wind and earthquakes. All the basic components of the joints must be made of high-quality corrosion-resistant steel. At the connection spots, thermal and sound insulation must be installed properly, in order to prevent energy losses. Since the connections are exposed to weather conditions, it is necessary to use anti-rust coatings. The basic criteria for choosing the connection method are, first of all, the question whether the structure is temporary or permanent, then the size of the structure itself, the type and intensity of the load on the connections, the required resistance to external influences, the possible later need for expansion or disassembly, as well as the available budget.

Here, only basic notes are given on the ways of making connections in multi-storey container buildings. A more detailed analysis goes beyond the scope of this paper.

6. ARCHITECTURAL ASPECT

In architectural terms, buildings made of old shipping containers are challenging from several aspects. From the aesthetic aspect, container buildings can appear as industrial or unsightly without additional exterior finishing works. Architects around the world have enthusiastically embraced the idea of reusing shipping containers for construction, although it is still repulsive to some of the general public. Opinions are divided, both among experts and among ordinary people, but considering the rapid advancement of technology and architecture, it seems that more and more people are accepting this concept. Today we have a lot of multi-storey buildings built from old shipping containers that are far from what we can see by looking at the worn and scrapped containers, such as shown in Fig. 10.



Figure 10. Roundhouse Administration Building (left) [25], Clipper House (right) [26]

Therefore, the appearance of shipping containers can be a challenge, but with proper design and processing, they can become aesthetically appealing and modern. Containers can be painted or covered with different materials, such as wood panels, to achieve the desired look. Also, there are solutions with large glass surfaces and green roofs.

In addition to the reshaping of the external appearance, the finishing works also include the replacement of the original container floors with wooden or laminate floors and ceramic tiles and the installation of interior wall coverings, the installation of doors and windows in previously installed metal frames and the assembly of installations.

The modular characteristics of shipping containers enable the design of creative and functional spaces. Considering that the walls of the container can be cut, and the containers can be joined and stacked both horizontally and vertically, it is possible to form larger functional units with the necessary comfort. Their flexibility enables the design of various types of multi-storey buildings, most often residential, but there are also commercial buildings, business premises, public and industrial buildings.

From the energy efficiency aspect, metal containers are poor insulators due to the high thermal conductivity. In order to ensure the living comfort and reduce energy losses, it is necessary to provide the adequate thermal insulation. Polyurethane foam is most often used. It adheres to the walls of the container and prevents condensation, so using it solves two problems. Also, due to the metal construction of the container, good protection against the moisture and corrosion is required, as well as the provision of the adequate ventilation and air conditioning. Considering that they are made of metal, containers can be quite noisy, so it is necessary to provide adequate sound insulation, usually made of rubber, between adjacent units.

7. CONCLUSION

Shipping containers, originally designed for the transportation and storage of goods, after the end of their useful life end up in piles, most often near large ports, creating huge amounts of waste that is not acceptable for the environment. Besides the fact that they can be recycled in steel smelters, at the beginning of the 21st century, they began to be massively used for construction, firstly for one storey buildings of various purposes, and then increasingly for the construction of multi-storey buildings. Their reuse in architecture has emerged as a more sustainable solution.

The material they are made of, their structure and dimensions, make them ideal modules for construction of contemporary buildings. Due to the high speed of construction

and lower costs compared to conventional methods, as well as due to the environmental aspect, this innovative approach can in some cases be a good alternative solution. Although part of the public and the professionals do not accept them due to their unattractive, industrialized appearance, there are many realized projects in the world. Also, they often win prizes at competitions and contests for the conceptual design. The progress of architecture and technology today enables significant modification of containers so that their appearance becomes interesting and aesthetically acceptable. Shipping containers are inherently robust, designed to withstand the harsh conditions of global transit. This durability translates into resilient structural components for high-rise buildings. Their modular design allows for unparalleled flexibility in construction, enabling architects and builders to create multifaceted spaces that accommodate various needs [1]

Certainly, the most important aspect of the application of old shipping containers is their sustainability, but equally important are the structural and architectural aspects, especially when it comes to more complex projects of multi-storey buildings. This thoughtful approach to design embodies a vision of the future for urban architecture, presenting a sustainable and socially responsible model for future development.

The findings of this research can serve as a valuable foundation in the creation of public strategies that promote the principles of circular construction. Local authorities could support such an initiative through financial incentives, simplified legal procedures or strategic integration into social housing, emergency infrastructure or temporary facilities. With such strategies, this innovative approach to construction could promote greener and more adaptive cities. As such, it can offer, not only architectural and engineering innovation, but also a practical response to global challenges in housing, waste reduction and climate adaptation, creating a socially responsible path toward more sustainable cities.

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Research paper

ENHANCING PEDESTRIAN CIRCULATION: QUANTIFYING SPATIAL INTEGRATION IN URBAN EVENT SPACES

Tanja Mitrovic[1]

Abstract

Circulation within urban spaces refers to how people move through environments, and it plays a vital role in the design of pedestrian-friendly areas. The concept of circulation in architecture and urbanism is frequently equated with communication, as it enables the easy movement and connection between various elements of the urban landscape. Understanding how spaces function as integrated units allows for better design solutions that enhance both movement and comfort. In this context, spatial integration is crucial in determining how well different parts of a space function as a cohesive whole. When spaces are well integrated, they promote smooth interaction between different areas, facilitating walkability and contributing to a more connected urban landscape. However, the challenge lies in effectively assessing the integration of urban space, particularly in areas shaped by temporary structures or urban furniture during public events. Here it is shown that calculating the convex hull of the surface area of the space provides a reliable method for quantifying spatial integration, which directly impacts pedestrian circulation. The study used the Convex Hull tool in Grasshopper software to analyze key public spaces. By comparing the surface area of the original geometry to the convex hull, an integration index was calculated, with values ranging from 0 to 1. High integration was observed when fewer fragmented spaces existed, facilitating smoother pedestrian movement. These findings provide a quantitative approach to optimizing public spaces, leading to improved user experience by minimizing fragmentation and promoting spatial cohesion. This method offers immediate opportunities for architects and urban planners to design more efficient, user-friendly spaces.

Key words: *Circulation, Spatial Integration, Public Events, Temporary Structures, Spatial Layout*

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1. INTRODUCTION

The way people move through urban space has changed over time, influenced by social and economic shifts, regulations, and technological progress. Although industrialization and the growth of car use have shifted the focus toward vehicle traffic, often at the expense of pedestrians, walking still remains the most essential and common way people interact with the urban environment. As Diaconu [1] emphasizes, walking is not only a basic mode of locomotion but also a rhythmical, often unconscious activity that fosters a sensory and affective relationship with the city. Through movement and tactile perception, people develop a personal understanding of urban space, which transforms walking into a deeply aesthetic and exploratory experience.

The movement of people within cities has always been a key focus in architecture and urban planning. In contemporary urbanism, the concept of circulation, referring to how individuals and groups move through built environments, has emerged as a key factor in shaping the design of walkable, accessible, and socially engaging spaces [2, 3, 4]. As the movement of people becomes increasingly central to discussions on urban livability, understanding the spatial conditions that enable or hinder circulation is more crucial than ever. Circulation is not merely a matter of physical movement; it also embodies a form of communication, linking spatial elements and enabling interaction across various zones of the urban fabric [5].

The communicative aspect of circulation becomes especially important when viewed through spatial integration, a concept that shows how well different parts of an environment work together. Highly integrated spaces allow smooth movement, easy navigation, and effortless interaction between areas, making them more walkable and user-friendly. As Penn et al. [6] have argued, spatial integration serves as one of the most reliable predictors of pedestrian flow and density along pathways in urban space. It is seen as a quality that allows a space to be immediately comprehensible to individuals, even those with no prior knowledge of its overall layout [7]. On the other hand, fragmented or poorly integrated spaces create barriers both physical and perceptual that limit accessibility and reduce spatial coherence. Therefore, the integration of spatial layout is not just a qualitative issue but a measurable aspect of urban design that directly affects the user experience. The quality of public spaces depends not only on how well they support movement, but also on how they encourage people to gather and interact. As Shaftoe [8] points out, good public spaces allow for informal and spontaneous social activities. In event settings, the way standing areas are arranged can strongly influence both how easily people move and how they connect with one another.

Despite its importance, assessing the integration of urban space, particularly with temporary structures and urban furniture during public events, presents a methodological challenge. These temporary elements can significantly change the flow and perception of space, making traditional spatial analysis tools inadequate for capturing the temporary changes in how people move through space. As a result, new approaches are needed to assess how temporary spatial arrangements affect pedestrian movement and connectivity.

The aim of this research is to propose and test a computational method for quantifying spatial integration using the convex hull as a geometric index, thereby offering a reliable and adaptable tool for evaluating possibility of pedestrian circulation in urban environments shaped by temporary structures.

This paper presents a method implemented in the Grasshopper environment that uses the Convex Hull as a geometric metric to compare a space’s original footprint with its minimal

enclosing shape. By applying this method to event-configured public spaces, the study offers urban designers a data-driven tool to assess spatial cohesion and improve navigability.

In summary, this research introduces an innovative, quantitative tool for assessing and optimizing spatial integration in rapidly changing urban spaces. While the tool provides measurable insights, its results should be interpreted with an awareness of the methodological boundaries. The intention is not to offer a fully comprehensive model of spatial experience during events, but to establish a structured basis for evaluating spatial coherence as one dimension of a complex and time-sensitive urban phenomenon.

2. METHODOLOGY

To ground the methodological approach in a real-world context, the study was applied to a representative urban square frequently used for hosting diverse public events.

2.1. Site Context and Event Dynamics

The study focuses on Liberty Square, located in the central urban core of Novi Sad, Serbia. Surrounded by iconic architectural structures, the square accommodates a large pedestrian traffic and remains deeply rooted in the city's cultural and civic identity. Its central location and accessibility make it an ideal setting for hosting various large-scale public events that activate the space throughout the year. Over the past decades, Liberty Square has evolved into a multifunctional event space, supporting a broad spectrum of public activities, including cultural festivals, trade fairs, concerts, national celebrations, sporting events, and civic gatherings.

To validate the relevance of this site and ensure the representativeness of the spatial layouts evaluated, the research draws upon empirical data collected by Mitrovic et al. [9], who analyzed 17 events held at Liberty Square between 2017 and 2022. The dataset includes details on event types, durations, the use of temporary structures, and their typical spatial configurations. The analysis revealed that trade fairs and festivals accounted for 53% of all events hosted during the observed period, followed by entertainment and music events (each at 17.6%), and sports events (11.8%). Notably, trade fairs and festivals typically span over two weeks, generating more extensive and enduring spatial transformations compared to short-term events. The most commonly used temporary structures include exhibition stands and kiosks.

2.2. Theoretical Framework for Spatial Integration Analysis

This study introduces a geometric approach for evaluating the spatial cohesion of urban public spaces affected by temporary structures, using the convex hull as the core analytical tool. By comparing the surface area of functional pedestrian zones to the area of their convex hull, a simple spatial integration index is derived, reflecting the degree of continuity and connectivity in the spatial layout.

While conventional spatial integration analyses often rely on graph-based techniques such as axial or visibility graph analysis, this research adopts a more geometric and flexible approach, better suited to the dynamic nature of event environments. The convex hull is used as an indicator of spatial cohesion and navigability. This interpretation aligns with principles from space syntax theory, which associates spatial openness and continuity with higher

levels of integration. Space syntax, developed to explore how spatial configurations affect human behavior, particularly movement, interaction, and accessibility, defines integration as a topological measure indicating how close a space is to all others within a spatial system. It is typically calculated as the inverse of the average depth from one space to all others, making it a proxy for centrality and spatial accessibility [10, 11].

2.3. Analytical Workflow and Methodological Tools

The analysis was conducted using the Grasshopper plugin within the Rhinoceros 3D, which offers parametric design capabilities and real-time computation of geometric relationships.

The workflow consists of the following key steps:

1. Spatial Input Preparation:
   The first step involves defining the boundaries of the event space and placing temporary structures based on event-specific layouts. Access zones between these structures are then identified. The remaining areas, intended for active or passive use such as gathering, pausing, or informal interaction, are designated as standing zones. These zones are modeled as closed planar surfaces in Rhinoceros 3D based on the spatial configuration of the site.
2. Convex Hull Calculation:
   For all resulting standing surfaces, the Convex Hull component was used to generate the smallest enclosing convex polygon. This envelope represented the theoretical limit of spatial cohesion for the given configuration.
3. Spatial Integration Index Calculation:
   The area of the geometry of the identified standing zones was compared with the area of its convex hull. From this, the integration index (I) was derived using the formula:
   $$\mathrm{I} = \frac{Aoriginal}{Ahull} \quad (1)$$
   This ratio ranges from 0 to 1, where values closer to 1 indicate high spatial integration, reflecting a strong correspondence between the occupied space and its convex boundary, while lower values suggest fragmentation and discontinuity.
4. Weighted Index of Integration Calculation:
   To evaluate the overall integration index of the entire event space, a weighted average method was applied. Rather than treating each standing area equally, the calculation considers the relative surface area of each zone. This ensures that larger spaces, which have greater capacity for user movement and interaction, exert a proportionally higher influence on the final result. Total integration index (I_{total}) is calculated by multiplying the integration index value (I) of each standing surface by its corresponding area ($A_{original}$), summing the results, and then dividing by the total area of all standing surfaces:
   $$\mathrm{Itotal} = \frac{\Sigma Aoriginal(i)\ x\ I(i)}{\Sigma Aoriginal(i)} \quad (2)$$
   This approach provides a more accurate reflection of spatial cohesion and user experience across the entire layout.

The analytical process began by importing the 2D layout of the event space from AutoCAD into Rhinoceros 3D, ensuring that real-world dimensions were preserved. Once imported, the geometry served as the basis for parametric analysis in Grasshopper. Within

Grasshopper, custom definitions were created to determine key spatial parameters and calculate the integration index based on the convex hull method. Parameters such as the position and shape of temporary structures, their dimensions, the distances between them, and the space occupation ratio were used to define the base geometry. These inputs enabled the generation and manipulation of spatial configurations in a parametric environment. The tool also provided real-time visual feedback and allowed iterative adjustments to the spatial layout. After the analysis was completed, visual outputs were returned to Rhinoceros 3D for further refinement, documentation, and presentation.

3. APPLICATION AND EVALUATION

The method was applied to different layouts of temporary structures on Liberty Square in Novi Sad. Four different configurations were analyzed, each containing 36 temporary structures. Layout 1 presents a grouped arrangement consisting of a single cluster with four

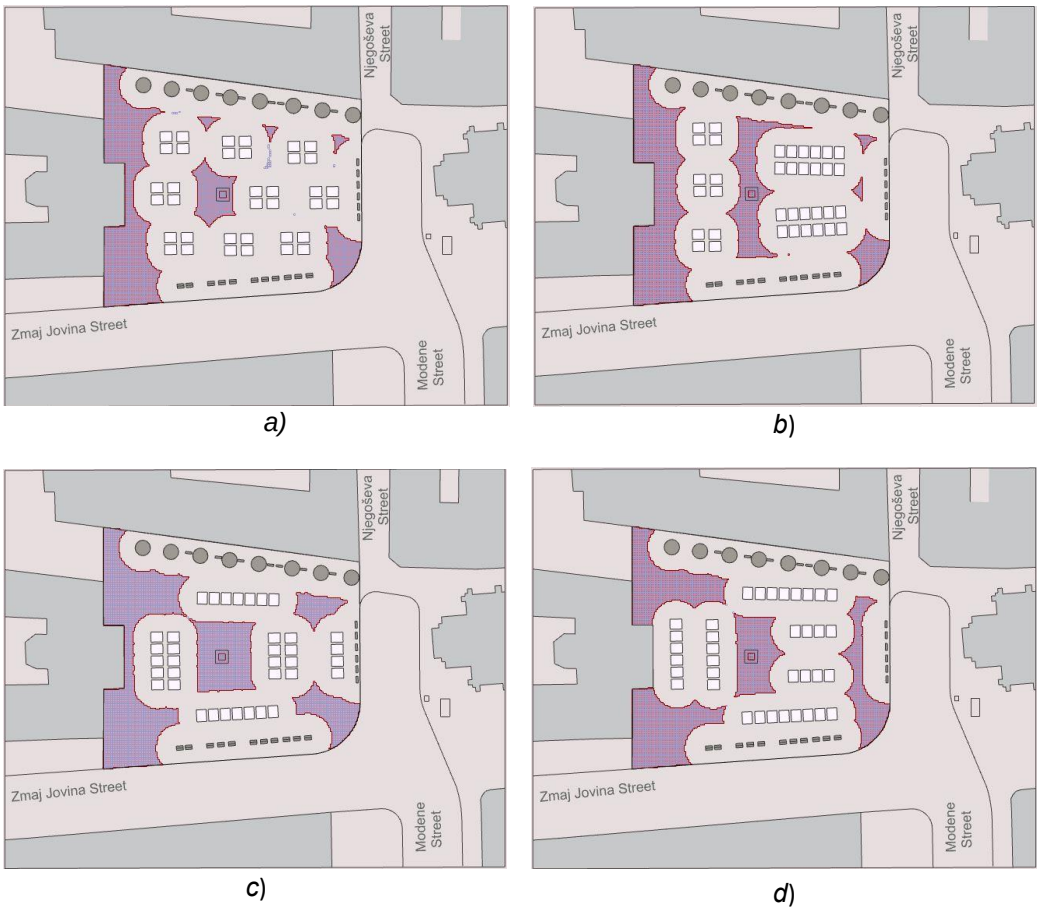


Figure 1. Visualization of standing area configurations corresponding to the following temporary structure layouts: a) Layout 1 b) Layout 2 c) Layout 3 d) Layout 4, source: author

temporary structures. Layout 2 includes three dominant groups composed of 4 and 12 structures, respectively. Layout 3 combines both linear and grouped arrangements, while Layout 4 follows a fully linear configuration. The boundary of the analyzed area was defined based on years of practice in placing temporary structures within a specific part of the square. Initially, standing areas were identified by leaving an access space of 2 meters on each side of the temporary structures, as illustrated in Figure 1.

After identifying the standing zones, their spatial configuration was analyzed using the Convex Hull method. This technique involves constructing the smallest convex polygon that completely encloses each standing zone, effectively capturing the outer boundaries of the usable space. The results of this process are shown in Figure 2.

The analysis offered insight into how temporary interventions reshape the spatial structure of public areas. These findings are further supported by numerical data, as evidenced by the integration index presented in the following tables (Table 1, 2, 3, 4). The index was calculated for each identified standing area according equation (1).

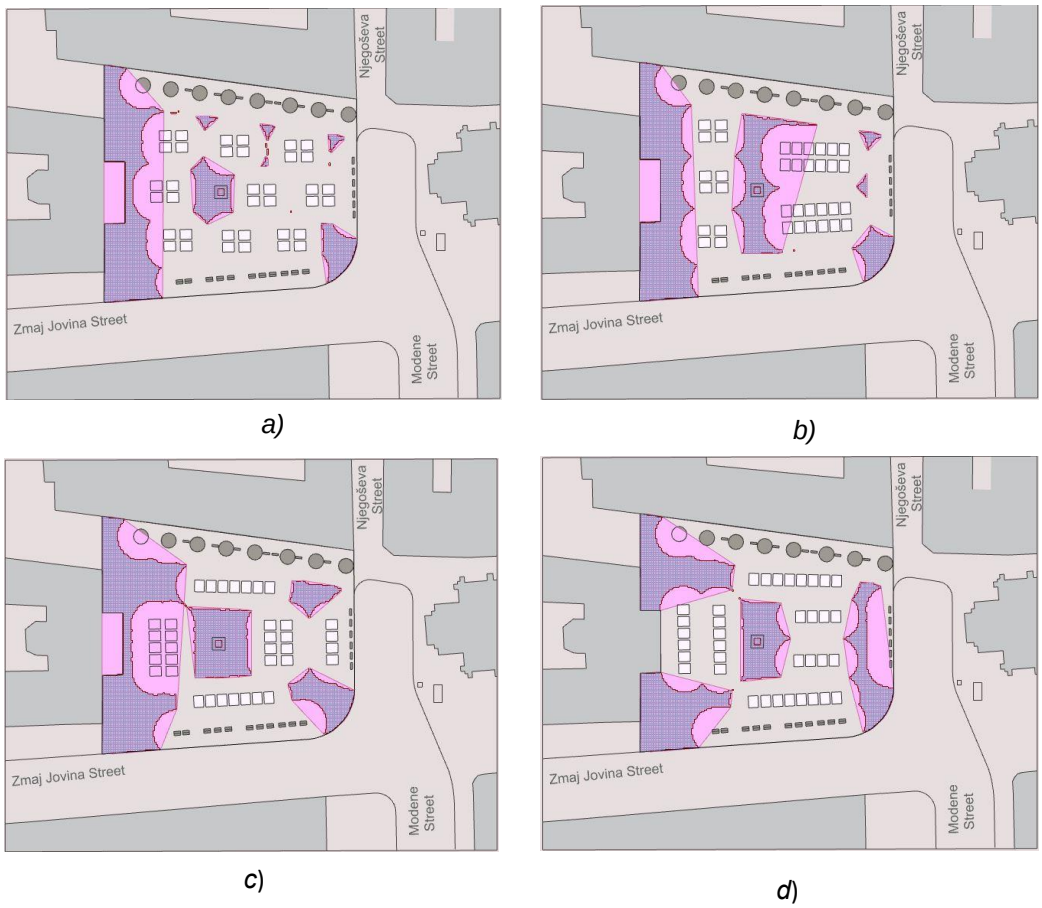


Figure 2. Implementation of the Convex Hull approach to analyze standing surfaces across the following temporary structure layouts: a) Layout 1 b) Layout 2 c) Layout 3 d) Layout 4, source: author

Table 1. Calculation of the integration index (I) for each identified standing surface (A_i) in Layout 1

Layout 1	A_1	A_2	A_3	A_4	A_5	A_6	A_7
$A_{original}$ (m^2)	489.33	111.41	8.62	6.37	2.24	80.61	8.50
A_{hull} (m^2)	847.59	149.13	12.05	9.59	3.23	97.61	13.02
I	0.58	0.75	0.72	0.66	0.69	0.83	0.65

Table 2. Calculation of the integration index (I) for each identified standing surface (A_i) in Layout 2

Layout 2	A_1	A_2	A_3	A_4	A_5
$A_{original}$ (m^2)	541.26	220.71	71.76	7.55	10.27
A_{hull} (m^2)	788.99	563.40	96.17	9.94	16.28
I	0.69	0.39	0.75	0.76	0.63

Table 3. Calculation of the integration index (I) for each identified standing surface (A_i) in Layout 3

Layout 3	A_1	A_2	A_3	A_4
$A_{original}$ (m^2)	592.84	235.81	121.45	63.26
A_{hull} (m^2)	1097.14	276.39	176.62	80.53
I	0.54	0.85	0.69	0.79

Table 4. Calculation of the integration index (I) for each identified standing surface (A_i) in Layout 4

Layout 4	A_1	A_2	A_3	A_4
$A_{original}$ (m^2)	260.24	281.72	178.92	160.63
A_{hull} (m^2)	410.84	370.45	229.40	343.25
I	0.63	0.76	0.78	0.47

Based on the integration index values presented in the tables above, the total integration index (I_{total}) for each layout was calculated using the weighted average method, as shown in equation (2). This approach takes into account both the degree of integration and the area of each individual standing area, ensuring that larger and more spatially significant areas are proportionally represented in the final index. The resulting values are presented in Figure 3.

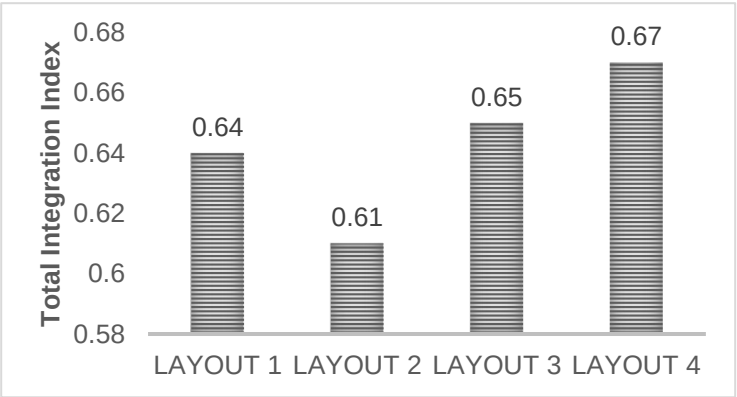


Figure 3. Graph illustrating total integration index of standing areas for each temporary structure layout, source: author

These results present the integration values of standing areas based on the application of the Convex Hull method across different configurations of temporary structures. Among the examined layouts, Layout 4 achieved the highest total integration index of 0.67, suggesting that its linear arrangement supports a more cohesive and accessible spatial structure. This layout appears to reduce fragmentation, and enhance overall spatial legibility.

In contrast, Layout 2 recorded the lowest integration index of 0.61, indicating a more fragmented spatial configuration. It is also noticeable that layouts with a smaller number of identified standing spaces (Layout 3 and 4) have a higher value of the integration index.

The variation between these results highlights the crucial role that spatial configuration plays in enhancing or hindering integration. Even relatively small changes in the arrangement of temporary structures can significantly impact the overall cohesion of public space. Consequently, these findings highlight the need for thoughtful design strategies that prioritize spatial integration, especially in event-based or temporarily transformed urban environments. Such approaches not only improve navigation and user experience but also support the creation of more inclusive and functionally efficient public spaces.

4. DISCUSSION

The analysis of the integration index in four different layout configurations reveals the key role of spatial layout in influencing the cohesion and usability of event spaces. The study demonstrates that temporary structures, despite their impermanence, have a significant spatial logic that can either facilitate or hinder movement, visibility, and intuitive orientation. These findings contribute to an expanding body of literature emphasizing the dynamic interaction between event-specific design and the performance of public space [3, 10].

Layout 4, with its linear structure, produced the highest total integration index. This finding reinforces the notion that spatial continuity, particularly when aligned with natural pedestrian flows, enhances spatial legibility and coherence. These results are consistent with established principles in space syntax theory [11, 12, 13], where spatial integration is closely associated with pedestrian movement and spatial comprehension, even in short-term or unfamiliar spatial contexts [6].

In contrast, Layout 2, composed of large, clustered groups, displayed the lowest integration values indicating a fragmented spatial experience. This underscores how even subtle changes in spatial configuration, such as the spacing or grouping of temporary elements, can significantly impact space cohesion. Such observations coincide with findings in research on pop-up urbanism [14], where ephemeral spatial arrangements can dramatically alter user experience and behavior depending on their spatial logic.

While the integration index offers useful insight into navigability and cohesion, it captures only one layer of public space performance. The quality of experience in public space is inherently multidimensional, encompassing not only circulation and movement but also opportunities for social engagement, psychological comfort, inclusivity, and spatial adaptability [3, 4].

The variation in integration levels across layouts reinforces the idea that even small changes in spatial configuration can lead to measurable shifts in spatial performance. These results resonate with studies in space syntax research [5, 7], which have consistently demonstrated that the configuration of elements within a system has a direct impact on how space is experienced and used. Although much of this literature focuses on permanent urban

form, our findings suggest that similar principles apply to temporary settings, where the logic of layout remains crucial to spatial efficiency.

Moreover, by applying a weighted index that takes into account the area of each standing surface, the analysis advances conventional integration metrics by integrating both spatial quality and quantity. This methodological adjustment ensures that larger, highly efficient surfaces contribute proportionally more to overall spatial performance. While similar techniques have been used in architectural modeling and simulations [15], their application to temporary urban layouts remains limited, making this study a novel contribution.

Ultimately, this discussion positions the proposed method as a bridge between theoretical frameworks like space syntax and real-world design needs in dynamic urban contexts. By doing so, it lays the groundwork for more responsive, evidence-based strategies in designing adaptable public spaces.

5. CONCLUSION

This study introduces a geometric approach to assessing spatial integration in public spaces during events by applying the convex hull method to analyze different layouts of temporary structures. The results highlight the significant impact that spatial configurations can have on pedestrian movement and overall spatial efficiency. While the values derived from this analysis should not be regarded as absolute or definitive, they hold particular value in comparative assessments. The strength of the method lies in its simplicity, adaptability, and ease of implementation, making it particularly useful for evaluating temporary or frequently reconfigured urban environments. This has practical relevance in contexts where urban spaces are frequently reconfigured for temporary uses such as markets, fairs, festivals or civic gatherings, and where permanent redesign is not always feasible.

However, the applied method of measuring spatial cohesion has limitations, particularly in capturing more complex spatial dynamics such as user clustering, edge conditions, or visual barriers. Additionally, the changing nature of events may affect the consistency of the results across different settings. Events vary not only in their physical configuration but also in their rhythms, durations, crowd dynamics, and intended programs, all of which shape how space is experienced.

Despite its limitations, this study advances the discourse on flexible urbanism by offering a structured method for assessing how temporary layouts affect movement and integration. It provides a practical tool for improving navigability and coherence in event-based spaces. Future research should expand the empirical base with behavioral data and test the method across varied contexts, while also integrating metrics like visibility, proximity, and spatial entropy to enhance its robustness.

In conclusion, this research offers a significant contribution to understanding how temporary spatial configurations influence the coherence and navigability of urban environments. With further methodological refinement and application in varied urban environments, future studies can support more inclusive and efficient design strategies in public space planning.

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Research paper

DEVELOPMENT OF PUBLIC OPEN SPACES IN MULTI-FAMILY HOUSING IN POST-SOCIALIST CONTEXT: EFFECTS OF LAND RESTITUTION

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Abstract

Large housing estates were the dominant form of housing in socialist cities, with more than half of the urban population residing in them – sometimes even exceeding 80%. While the primary focus in housing construction was on efficiency and quantity, attention was also given to the quality of living. The layout of the estates, featuring detached buildings surrounded by expansive green spaces, was designed to create optimal microclimatic and sanitary conditions while also providing recreational areas in close proximity to the apartments. After the fall of socialist regimes, cities in Central and Eastern Europe (CEE) and Southeastern Europe (SEE) went through multilayered transformations known as the post-socialist transition. The transition period was marked by the return of property rights over real estate – buildings and land – through processes of privatization and restitution. Large housing estates as integral parts of the urban structure of socialist cities underwent significant changes during the post-socialist period.

The paper examines the impact of post-socialist changes on the development and transformation of public open spaces (POS) in inherited multi-family housing areas in selected countries of Central and Eastern Europe (CEE) and Serbia, with a particular focus on the influence of land restitution. By analyzing these examples, the paper aims to establish a relationship between land ownership and the state of the POS and to identify the potential for their future development and management in a post-socialist context.

Key words: *public open space, multifamily housing, post-socialist transformation, land restitution*

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1. INTRODUCTION

After World War II, many socialist countries faced acute housing shortages due to war destruction, urbanization, and rapid industrialization. The ruling governments, emphasizing collectivism and state responsibility, undertook vast housing projects to provide affordable and standardized living conditions for workers and their families. Although the focus in housing construction was on efficiency and quantity, there was also a strong emphasis on the quality of housing.

The spatial arrangement of building clusters within large housing estates was primarily determined by the necessity to establish optimal microclimatic conditions and ensure adequate hygienic standards within residential units, as well as to provide accessible outdoor recreational spaces in close proximity to housing. Extensive greenery surrounding the detached buildings emerged as a fundamental component of these residential environments. Vegetated areas played a crucial role in enhancing the microclimate, supporting public health, and offering opportunities for rest and leisure, while simultaneously contributing to the formation of a distinctive and coherent urban landscape. On average, green spaces accounted for approximately 40–45% of the total area of such estates [1]. The planning principles underlying housing estates are grounded in three key concepts: providing extensive and easily accessible green spaces; positioning and orienting buildings to ensure sufficient sunlight reaches the dwellings; and organizing traffic circulation to enhance pedestrian safety and mobility [2]. Most socialist housing estates were built on land that had been nationalized after World War II. State control over urban construction land enabled planning and land use with less economic constraint [3] which made it possible for socialist neighborhoods to be exceptionally well equipped with parks and other open public spaces[4].

After the fall of socialism in the 1990s, a transition toward a capitalist social order began, accompanied by the restoration of property rights through processes of privatization and the restitution of property to pre-war owners. As a result, undeveloped areas within socialist housing estates also became subject to restitution. During the transition period, socialist housing estates faced numerous challenges, including the deterioration of the building stock, neglect and degradation of open spaces, aging population, etc.

The aim of this paper is to: (1) identify the similarities and differences in the development of public open spaces (POS) within inherited large housing estates (LHE) in countries of the region; and (2) examine how the chosen model of restitution has influenced the development and management of public open spaces.

2. POS IN POST-SOCIALIST TRANSFORMATION

With the rise of the Communist Party to power across the region, means of production were nationalized or collectivized, with the exception of agricultural land in some countries. Most residential and industrial property were nationalized, and constitutional amendments introduced various forms of ownership. For example, the 1947 constitution of Bulgaria established a conventional socialist classification of property: social, cooperative, and individual ownership [5]. As a result of nationalization and confiscation, the state acquired significant ownership of land and housing stock in urban areas [6]. The construction of socialist housing estates began in the 1950s and was mainly carried out on the outskirts of

cities, where large areas of state-owned land were suitable for mass prefabricated construction.

The transition that affected the countries of the region in the 1990s began with political changes, followed by institutional, socio-economic, and urban structure transformations, which represent the final and longest phase of the transition. The transition period was marked by the restoration of property rights over real estate – buildings and land – through privatization and restitution processes. With regard to housing, the most significant changes included the withdrawal of direct state financing for new housing construction, the privatization of the previously public housing stock, and the restitution of housing to private owners that had been nationalized during communist rule [7].

Restitution occurred through:

- the return of actual property (e.g., land, buildings, businesses) to its rightful owner - "in kind" and "in rem" restitution;
- compensation through coupons (vouchers);
- a combination of these two models (see Marcuse, 1996).

Restitution was carried out in different countries of the region at varying speeds and within different legal frameworks, but also with varying degrees of success.

After the return of land to pre-war owners, ideal conditions were created for new construction on the space between existing buildings. The restitution laws were interpreted in such a way that, as long as there were no buildings on the land, it was eligible for restitution [8] which meant that neighborhood open spaces became legally eligible for private development. Stanilov notes that the privatization of property through restitution had the greatest impact on the loss of public spaces in socialist cities [9].

Socialist housing estates in the post-socialist period face problems primarily related to the lack of coordinated policies for future development. Creating clear development policies for socialist housing estates is highly complex due to the lack of agreement among various potential stakeholders in the development process, the unclear legal status of properties involved in the restitution process, and the lack of financial resources necessary for maintaining and improving buildings and infrastructure that are rapidly aging [9].

In addition to the return of land, urban planning, which was not adapted to new conditions, played a crucial role in the appropriation of open spaces within socialist housing estates. Socialist urban plans, for instance, classified entire urban blocks into vague categories, such as "complex residential development" [4] without defining open spaces as a separate category.

2. METHODOLOGY

This paper explores the impact of post-socialist changes on the development and transformation of public open spaces in inherited areas of multi-family housing, with particular attention to the influence of land restitution.

To assess the impact of restitution on the condition of public open spaces in inherited LHE the paper first analyzes two case studies from countries that implemented different restitution models: (1) Hungary (case study: Budapest) – which carried out restitution through compensation in vouchers, and (2) Romania (case study: Bucharest) – which implemented in-kind restitution; and how these approaches affected POS within LHEs.

Following this, the paper examines the management of POS in inherited LHEs in Serbia (case study: Niš), which also applies in-kind restitution, albeit with a delay of 20 years.

The analysis of the regional cases is based on a review of existing literature, while the Serbian case draws on legal and planning documents, available land data, and on-site field observation.

3. EXAMPLES OF NEIGHBORING COUNTRIES

3.1. Hungary

Model of restitution

Unlike most countries in the region that chose to pursue in-kind restitution for housing properties, in Hungary, the real estate property was not restituted in-kind. Pre-war owners that were still living in Hungary in 1990 were only entitled to symbolic compensation in the form of coupons or agricultural vouchers [5]. The maximum compensation available was approximately USD 21,000 (HUF 5,000,000), determined on a sliding scale relative to the property's assessed value. In rem restitution was not offered to the owners [10]**.** This way, public open spaces, including those in inherited LHEs, remained the property of the municipality and were not fragmented by returning the nationalized land to owners.

The state of public open spaces in large housing estates

The construction of large prefabricated housing estates (lakótelep) in Hungary began in the 1960s, first in Budapest, then in larger regional center. Therefore, Budapest serves as a suitable case study for analyzing the post-socialist development of LHE.

The treatment and development of POS in inherited LHEs in the post-socialist period differs depending on LHEs characteristics—first of all, period of construction and location within the city. Some neighborhoods that occupy strategic positions in the city are being revitalized. For example, Kelenfold, the first LHE built by panel technology, is today one of the most developed residential areas in Budapest. Due to its good position next to the historic urban core of Budapest, infrastructure development, and social structure, new housing developments appeared in Kelenfold, which is rare in LHEs that are often exposed to stigmatization and shrinkage [11]. Most of inherited LHEs face numerous problems, both within the buildings and in the surrounding areas: devastation, bad condition of green areas, playgrounds and street furniture, and a lack of parking spaces. For instance, Havana, one of the largest housing developments in Budapest, located on the outskirts of the city began to show signs of slumming in the 1990s.

Even though the flats were mostly privatized at the beginning of the 1990's, the state of the open space remained unchanged, i.e. it belongs to the district municipality as a public territory. This situation resulted in various problems related to maintenance cost, change of space use, accessibility, parking shortage, security etc. [12].

Development strategies and programs

The planning system and administration in Budapest are both characterized by duality. The dual-municipality system consists of 23 district municipalities and the Municipality of Budapest. Urban planning consists of framework planning regulations at the level of the Municipality of Budapest and detailed physical planning at the level of district municipalities [7]. According to the National Urban Planning and Building Requirement (NURBP), green areas are marked as "areas not intended for construction" together with transportation, utility

placement, communications areas, forest areas, agricultural areas, etc. The NURBP classifies public green spaces into two subcategories: the public park and the public garden, and regulates the fundamental features, physical parameters, and ecosystem services of public green spaces. Since they are legally defined as public green areas, they are included in the zoning plan as a regulated zoning category. Unlike public parks and gardens, residential and institutional green spaces are not recognized in NUPBR and mapped in the Zoning Plan, regardless of their size and frequency of use, because they are owned by either a community (residential estate) or an institution [13].

After a decade of neglect, in 2000 Hungary introduced a national program for renovation of residential buildings, so called “Panel Programs” which was primarily focused on the technical renovations aimed to improve energy-efficiency of buildings. The situation changed slightly in 2003 with the introduction of the possibility of complex renovation, which encompasses a complete renovation of a building and its surroundings, potentially including the rehabilitation of green areas. In this case, state funding may cover up to 50% of the total costs, with the condominium and local government each contributing 25% [14]. Complex projects require a detailed plan, close cooperation between the municipality and the owners, well-organized owners, and, most importantly, the financial ability of both local administration and private owners to participate, so the local governments and the residents more often choose to apply for partial physical renewal. Hungary's admission to the European Union in 2004 gave the country the opportunity to apply for various EU urban projects [15].

Although some regeneration projects were launched at the national level, improving the environment and the living conditions in the LHEs remains mostly a local task. This is, first of all, due to decentralization and the shift of responsibilities for LHEs from the state to local authorities - in the case of Budapest to district municipalities [5]. In addition, despite the high proportion of condominiums and cooperative-run buildings, public space between the buildings is owned exclusively by the municipalities. Since the district authorities are the owners of the green areas in LHE, they try to "share" the responsibility for maintaining large open spaces with the residents in the form of a public-private partnership. Large green areas remain the responsibility of the municipality, while residents are offered to maintain green space next to the buildings in the form of semi-public spaces (community gardens) [16].

3.2. Romania

Model of restitution

Romania is one of the countries that implemented „in-kind“ restitution, which was formaly initiated in 1991 with the adoption of the Land Law (Law No. 18/1991). The law categorized land into five types: agricultural, forest, urban, water, and industrial, primarily focusing on the restitution of agricultural land. Later amendments to the law permitted in-kind restitution of urban open spaces, including spaces between buildings, which led to the loss of POS (parks, children’s playgrounds, school grounds, and green spaces) and densification of urban fabric, without any planning procedures for public consultation [17].

The state of public open spaces in large housing estates

LHEs development in the post-socialist period can be most easily followed by the example of Bucharest, “the city of many housing estates” [18].The privatization of state-owned housing stock in LHEs transferred the responsibility for buildings from public authorities to the owners. The Land Law introduced definitions of communal areas of shared residential buildings that are inseparable from individual apartment ownership, such as the land under the building,

courtyards, the building's structure, etc. In practice, these communal areas most often consist of a narrow strip of land, 90 cm wide, encircling the building [19], while the rest of the common space is in the public domain or in the ownership of the local council. In some neighborhoods, the undeveloped land became a host to various unwanted contents set up without permits, or with temporary or fake permits [20] . Due to the lack of clear guidelines for acquiring publicly owned space for private use, residents started using various strategies to create private or communal areas resembling private gardens. This led to tensions with other residents who were unable to make similar arrangements and were left without access to outdoor seating [19]. The commercialization of POS in inherited LHEs gained full momentum at the end of the 1990s, when foreign companies began to enter the Romanian market and chains of supermarkets and gas companies started to appear on the undeveloped land of LHEs [20]. The return to national identity and religion, after the end of communist period, resulted in increased construction of churches in POS, including those in LHEs, making them a mixture of incompatible contents (market place, gas station, church).

Development strategies and programs

The development of POS in inherited LHE faces strategic, planning, and institutional shortcomings. As stated by Niță et al. [21] green areas are frequently accounted for in strategies for city development, but mostly in a descriptive and theoretical manner, without a clear delineation of the benefits or challenges of their management. Green areas, especially in large cities, are often seen as undeveloped land and, as such, available for further development.

The planning treatment of POS (public open space) in LHE (large housing estates) can best be understood through the example of Bucharest. At the city level, there is no adequate planning framework specifically addressing LHE. The regulatory framework of the General Masterplan (PUG – Plan Urbanistic General) is too broad to offer appropriate solutions for these areas. On the other hand, they are often subject to derogatory, lower-level planning documents that operate at the scale of a single plot. These documents are typically initiated by private investors and adopted at the lower administrative level (Local Council), without consideration for the broader context of the LHE [19, 22].

Similar to two-tier planning system, the responsibility for the development and maintenance of public open spaces in Bucharest is divided between two administrative levels. General Municipality of Bucharest is in charge of the management of the main public spaces (parks, boulevards, etc.), while Local Public Authorities are responsible for the open space of LHEs - those in the close vicinity (gardens around the buildings, playgrounds, parking spaces) as well as POS within LHEs such as streets, parks, and public gardens [19]. There is no unified development strategy for LHEs, including POS, at either the national or municipal level. Instead, individual ad-hoc interventions emerge, which do not take into account the broader urban context.

4. MANAGEMENT OF PUBLIC OPEN SPACES IN NIŠ, SERBIA

Model of restitution

Similar to Romania and other countries in the region, Serbia implements “in-kind” restitution. Restitution in Serbia began 20 years after the process had started in other countries in the region, with the adoption of the Law on Restitution of Seized Property and Compensation [23]. This law regulates the conditions, manner, and procedure for the return

of confiscated property and compensation for confiscated property that was taken from individuals and certain legal entities after March 9 1945, and transferred to public, state, social, or cooperative ownership (Article 1). The subject of return is construction land in public ownership of the Republic of Serbia, autonomous provinces or local self-government units, as well as construction land in state, social or cooperative ownership. Construction land on which public areas are located or where the planning document envisages the construction of public facilities shall not be returned to the previous owners (Article 22).

The Law doesn't recognize POS, but recognizes only "undeveloped construction land in public ownership". The term "undeveloped construction land" means land on which no buildings have been built, on which buildings have been built contrary to the law, and land on which only temporary buildings have been built (Article 3).

The process of returning the property according to the applications submitted until 2014 is still ongoing, and only after the resolution of all applications will the ownership of all undeveloped construction land for which the applications have been submitted be known.

The condition and management of POS in inherited multi-family housing

In the 1990s, public housing was massively privatized in cities in Serbia, but the status of the land under and around the buildings has remained unclear to this day. The problem of POS management in inherited residential blocks, is complex and involves numerous factors: legislation, ownership structure, the competence of local authorities and public institutions, public finances, urban planning documents, etc. As a result, these spaces are often exposed to devastation, fragmentation, insufficient maintenance, and appropriation for private purposes (parking spaces, cafe gardens, private gardens, etc.).

POS management is based on state-centred model, where planning and delivery of POS management services is provided by public-sector institutions, with minimum use of external input from private contractors or the voluntary sector. Local decisions on the maintenance of open spaces, are based on the Law on Planning and Construction which defines "areas of public use", and Law on Public Property, which defines "goods in general use in public property". Both terms are related to land in public ownership. In terms of management, jurisdiction is clear for land in private ownership, for which the owners are responsible, and for land in public ownership, which falls under the responsibility of the local government unit. The problem of space management and rights to space is present in cases of unclear ownership, which is often present in inherited areas of multi-family housing where various rights to the land exist (right of use, holder, property), as well as various rights holders (city, republic, private individuals) (see Table 1).

Similar to Romania, Serbia also lacks a planning level that specifically addresses public open spaces (POS) within inherited large housing estates (LHE). In the case of the city of Niš, it can be said that these spaces are not adequately recognized in the General Urban Plan of Niš 2010–2025 (Official Gazette of the City of Niš, no. 43/11). The construction area defined by the GUP Niš 2010–2025 is divided into: 1) areas of public use and 2) areas for other uses. Areas of public use include state-owned land, on which there are public facilities and associated areas of those facilities. Green and open areas of public use are: recreational areas, park greenery, park forest and protective greenery. For example, the kindergarten, park, and riverbank are designated as "areas of public use", while the open space around the buildings is classified under "other uses", effectively excluding it from formal recognition and protection as public space.

While GUP doesn't recognize these open spaces as "areas of public use", plans of general regulation use different terms for their description [24] :

- areas of public use for the needs of the functioning of buildings and plots within the block;
- public areas for the needs of the functioning of the block ;
- areas of public use for the functioning of buildings and plots within the block, where the construction of civil engineering objects only is allowed.

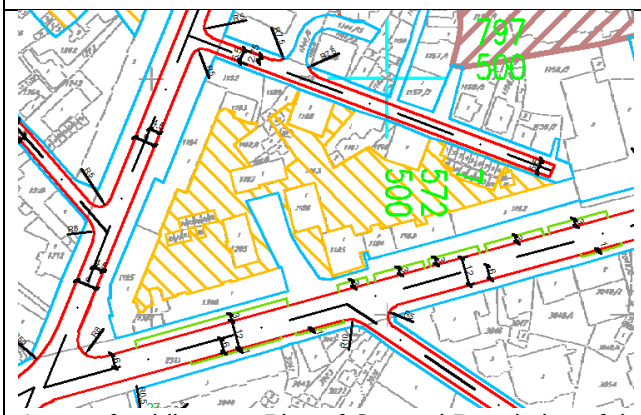
Table 1: POS in inherited LHE in Pantelej municipality, Niš

<table>
<tr><td colspan="2">Housing characteristics</td></tr>
<tr><td colspan="2">Inherited multifamily housing (1970s-1980s); open block
Cadastral status: each building is an individual cadastral plot ("building = c. p."), land around buildings – separate cadastral plot (c.p. No. 720)</td></tr>
<tr><td colspan="2">Public open space</td></tr>
<tr><td colspan="2">Cadastral plot No: 720
Cadastral municipality: Niš "Pantelej"
Land type: City construction land
Area: 8978 m2
Land culture: land next to building and other facilities</td></tr>
<tr><td colspan="2"> 
</td></tr>
<tr><td colspan="2">Cadastral plot rights holders</td></tr>
<tr><td>Name: Construction Company Građevinar DOO
Type of right: right of use
Form of ownership: -
Area: 8286/8978 m2</td><td>Name: private persons
Type of right: right of use
Form of ownership: -
Area: 266/8978 m2</td></tr>
<tr><td>Name: private persons
Type of right: holder
Form of ownership: state RS
Area: 426/8978 m2</td><td>Name: Republic of Serbia
Type of right: property
Form of ownership: state RS
Area: 8552/8978 m2</td></tr>
</table>

Although these spaces are recognized as a form of public-use area, their predominant land uses are usually designated as housing of varying densities within urban areas. Consequently, building rules for "other uses" (housing) become relevant for construction in the "area of public use".

The maintenance of public areas in Niš is entrusted to a Public Utility Company (PUC) as well as the maintenance of space around the buildings of inherited residential areas, which is currently in different forms of ownership.

Table 2: POS in inherited LHE in Medijana municipality, Niš

<table>
<tr><td colspan="3">Housing characteristics</td></tr>
<tr><td colspan="3">Inherited multifamily housing (1970s); semi–enclosed block; inner city area
Cadastral status: each building is an individual cadastral plot (“building = c. p.”), land around buildings –separate cadastral plot (c.p. No. 1163)</td></tr>
<tr><td colspan="3">Public open space</td></tr>
<tr><td colspan="2"> 
POS (c.p. No. 1163; orange) and “buildings- plots” (yellow)Source: Geosrbija (https://a3.geosrbija.rs/)</td><td>Cadastral plot No: 1163
Cadastral municipality: Niš “Bubanj”
Land type: City construction land
Area: 5276 m2
Land culture: land next to building and other facilities</td></tr>
<tr><td colspan="2"></td><td>Cadastral plot rights holders
Name: City of Niš
Type of right: property
Form of ownership: public
Share of ownership: 1/1</td></tr>
<tr><td colspan="2"> 

Areas of public use - Plan of General Regulation of the City Municipality of Medijana (Source: http://www.eservis.ni.rs/urbanistickiprojekti/)</td><td>Valid planning documents:
General Urban Plan of Niš 2010-2025 (Official Gazette of the City of Niš, no. 43/11)
Plan of General Regulation of the City Municipality of Medijana (Official Gazette of the City of Niš, no. 72/12) and amandments to the PGR Medijana
Land use: areas of public use for the needs of the functioning of buildings and plots within the block</td></tr>
<tr><td> 
</td><td> 
</td><td> 
</td></tr>
<tr><td colspan="3">The apearance of some parts of the public open space (numbers on the map above indicate the location of the photo). Source: Authors</td></tr>
</table>

Due to the unclear ownership structure and the ambiguous planning of POS in inherited LHEs, local regulations related to the POS maintenance mostly operate within the frameworks inherited from the period when state ownership of urban construction land was established, while all others parties including local self-government units, were merely holders of the rights to use urban construction land [25].

The maintenance of public areas is financed from the city budget. Although the PUC is responsible for the maintenance of public spaces, construction and reconstruction (development) is under the jurisdiction of the PE Directorate for the Construction of the City of Niš. In addition to budgetary funds, the Program for development of construction land and maintenance of municipal infrastructure [26] provides that development of public green spaces can be also financed from donations, aid, and unspent funds from previous years. This form of financing is rare and usually involves small-scale interventions (rain garden, equipping children's playgrounds, etc.) aimed at promoting private companies, rather than long-term improvement of the space.

Given that the city budget is limited, funds are rarely allocated for the reconstruction of the space between buildings and that is usually for spaces with a higher degree of public use and a higher number of users, such as open blocks from the socialist period. Smaller spaces in closed or semi-open blocks are often neglected and in very poor condition, even if located in the central city area and with clear ownership structure, as the POS shown in Table 2. Since the space is publicly owned, residents do not participate in its arrangement or maintenance, but instead appropriate the right to use the land, mostly for parking. This interpretation stems from the period when urban construction land was exclusively state-owned, and it was generally understood that the spaces around buildings were intended to support the functioning of the buildings. Moreover, the sale or transfer of publicly owned land was not permitted until the adoption of the Planning and Construction Law in 2009. The change in the status and ownership structure of urban construction land has led to conflicts regarding the rights and responsibilities associated with that land. Specifically, the question arises of how to motivate residents to engage in the improvement of public spaces when they hold no exclusive rights to their use. Additionally, under the current Law on Planning and Construction, publicly owned land can be alienated from public property, which further discourages residents from investing in the enhancement of their immediate surroundings.

5. DISCUSSION AND CONCLUSION

The analysis of case studies from neighboring countries, as well as from Serbia, shows that regardless of the type of restitution applied (in-kind or compensation), these countries still lack clearly defined models for the development and maintenance of public open spaces. However, certain differences can still be observed.

In the case of Hungary (Budapest), where ownership issues over POS in inherited housing areas were resolved early in the transition period, various national and international regeneration projects for LHEs have been initiated. These projects are characterized by clearly defined roles and responsibilities, specifying how different actors—such as the state, local administrations, and condominium associations—participate in the process.

On the other hand, Romania and Serbia still face unresolved issues related to restitution. Although in Romania (as seen in the case of Bucharest) the division of responsibilities for public spaces between the two-tiered administration is formally defined, there are significant

challenges stemming from the restitution process (namely, the return of parts of POS to pre-war owners) including the absence of a public space management strategy, derogatory planning at the level of individual plots within LHEs (e.g., changes in land use, enabling conditions for additional construction), encroachment on public areas, and isolated ad hoc interventions.

In the case of Serbia (Niš), issues of management and jurisdiction over public spaces have been examined in more detail. As in Romania, the challenges can be linked to the restitution, i.e. the return of property rights over areas of public use (such as POS in inherited LHEs) as well as the ongoing and incomplete restitution process, which leaves the legal status of POS land unresolved. This unclear land status directly affects urban planning, which serves as the foundation for making local decisions regarding the development and maintenance of these spaces.

The development of public open spaces (POS) in inherited large housing estates (LHE) depends on numerous factors, including regulatory frameworks, financing, administrative capacity, stakeholder involvement, and more. However, it is important to emphasize that the ownership structure of the land is one of the most critical elements in defining rights and responsibilities related to land use and management.

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Research paper

MODULAR SOLUTIONS FOR RESIDENTIAL BUILDINGS - KEY TO AFFORDABILITY AND SUSTAINABILITY

Konstantina Hristova[1]

Abstract

The global housing crisis, exacerbated by rising construction costs, land shortages, labour limitations and even climate change, has underscored the need to experiment with designs to deliver quality accommodation. Prefab construction technologies present a promising solution, targeting these problems by reducing construction time, material waste, and overall expenditures. This paper aims to explore the potential of modular housing as a key strategy for improving affordability and enhancing the comfort of the inhabitants of residential developments, with a focus on using different types of solutions.

The paper analyses the application of the three main types of modules, previously defined by the author - construction, spatial-functional, and planning module through several examples. Their flexibility, adaptability and contribution to the construction process is studied. Their advantages and limitations are evaluated. The study employs a qualitative methodology, including a review and comparison of case studies, to define several key findings highlighting that modular construction significantly reduces construction timelines and labour costs, with each type of module offering distinct advantages for different housing needs. However, challenges remain in terms of size of single units, customization, integration and blending with the existing built environment, as well as the amount of initial investment.

The significance of this study lies in its ability to demonstrate how pre-fabrication for housing can serve as a cost-effective and sustainable solution to the growing demand for accommodation, especially affordable one. By highlighting the practical applications and limitations of different module types, the study provides valuable insights into how modularity can be applied to maximize their effectiveness in addressing the contemporary residential crisis – both in terms of affordability and lack of housing due to different factors.

Key words: *pre-fabrication, modular constructions, residential solutions, housing crisis, affordability, experiments*

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1. INTRODUCTION

In the context of over-urbanisation and rapid urban population growth (with 54% of the world's population now residing in cities, which is expected to rise to 68% by 2050), the shortage of housing in large megacities is a serious problem, highlighting the contemporary housing crisis. In contrast to the 19th and 20th centuries, when the primary causes of urban migration were attributed to changes in people's livelihoods and warfare leading to significant destruction of housing stock, contemporary urban migration is predominantly driven by economic factors – search for better services, working conditions and payment. Locally in Bulgaria, this has resulted in abandonment of small towns and suburban parts, and higher attraction of individuals to urban centres and bigger cities, leading to lack of enough residential units in particular areas and huge number of empty apartments in others. In this scenario, a viable solution would be to construct housing from prefabricated elements, as the rationales for this pragmatic approach are rooted in the primary benefits associated with this construction method, namely:

- faster execution speed leading to reduced construction timeline.
- consideration of the construction method as an economical one, mostly due to the elimination of certain processes, which are unavoidable in the conventional construction process, as well as the possible typification of most of the elements.
- high degree of precision during constructing.
- the possibility of reduction in the maintenance and operating costs of buildings throughout their life cycle.

In contemporary practice, the use of different materials and lightweight constructions has created opportunities for more flexible planning solutions and interesting volumetric developments. The avoidance of wet processes and the reduction of construction waste, the unification of elements leading to more cost-effective solutions, are just some of the reasons why it has and should continue to stimulate the interest of researchers, planners and investors. The utilisation of "*eco-friendly materials ... advanced technologies for the design, construction and 'smart' management*" [1] of housing constitutes an integral part of contemporary practice in prefabricated housing.

The prevailing sentiment amongst our society, locally, is one with an initial hint of negativity towards prefabricated construction, largely attributable to historical memories and associations, compounded by the characteristics of national psychology. Despite certain traditions and past experiences, its utilisation is intentionally avoided, and contemporary solutions are regarded more as an exotic practice than as a widespread implementation.

The fundamental distinction is that until the 1990s, prefabricated construction, in its mass manifestation, was utilised in the construction of apartment housing on a substantial scale in the residential neighbourhoods built from the 1960s to the late 1980s. So currently it is facing certain controversial opinions, without considering its indisputable advantages. The prevailing economic conditions in the country, coupled with the relatively modest cost of man-labour, render monolithic construction financially viable under certain circumstances, thereby ensuring its preference and wider application. Prefabricated structures, predominantly composed of wood, find application in the construction of single-family dwellings, while prefab reinforced concrete and steel elements are primarily utilised in the erection of warehouse, industrial and hall buildings. However, this phenomenon is mostly local, and, in the interests of the wider community, it is considered better that it should be a transient one.

This paper explores the potential of modular systems as a strategic response to two of the most pressing issues in the housing sector: affordability and sustainability. Drawing from recent advancements in design and prefabrication technologies, the study highlights how modular construction methods can meet diverse residential needs while minimizing environmental impact. The contemporary potential of prefabrication does not constrain the functional or spatial configuration of an architectural entity. Instead, it facilitates the customisation of dwellings to align with the particular requirements of the occupants, while maintaining cost-effectiveness at a specific stage in their life cycle [2].

Previous studies have demonstrated the efficiency and ecological benefits of prefabricated structures; however, this research expands the discourse by further analysing the three distinct types of modules, as previously defined by the author [3]:

- modular solutions, based on a specific structural dimensions and proportions (structural/ construction module).
- modular solutions which combine both the space, the function and the structure in a single shape (space-functional module).
- planning module – not necessarily related to the shape or the structure.
- hybrid module – some or all the above combined in different ways.

These types, except for the simply planning module, will be studied through three selected case studies - The Urban Village Project by Space 10 & EFFEKT Architects for IKEA, The Puzzles of Complexity Project by Architectural Mythologems and the GOMOS system, developed by Summary in Portugal. The paper examines the practical applications of these modular types, evaluating their advantages and limitations in conceptual and real-world contexts. By identifying patterns in how, when, and why specific modular systems are applied, the study contributes to a deeper understanding of the role modularity can play in shaping the future of sustainable and accessible housing. The findings aim to inform architects, planners, and developers seeking effective solutions to contemporary residential challenges and eventually to support re-establishing and reviving the construction method in Bulgaria to a certain extend.

2. METHODOLOGY AND RESEARCH OBJECTIVES

The aim of this study is to explore the potential of modular construction as a viable solution to two major challenges in contemporary residential architecture: affordability and sustainability. The research seeks to identify how modular approaches can optimize building processes, reduce costs, and minimize environmental impact while maintaining flexibility and quality in residential design.

To achieve this, the study adopts a comparative case study methodology, analysing three residential projects, both conceptual and real, based on modular planning:

- Urban Village Project by Space10 & EFFEKT Architects.
- Puzzles of Complexity by Architectural Mythologems.
- GOMOS plug-in system developed by Summary in Portugal.

Each case could be listed under some of the defined by the author types of modular solutions. The research evaluates how these modules are applied, their integration into the design and construction process, and the resulting advantages and limitations in each context.

Data is gathered from architectural documentation and online published information about the projects. The analysis focuses on qualitative aspects such as environmental performance, adaptability and flexibility answering to user needs, architectural image and defining and creation of shared common spaces. Comparative conclusions are drawn to outline patterns of use and highlight best practices in modular residential developments.

3. ANALYSIS AND DISCUSSION

This section presents briefly the background, and the essence of the three modular housing case studies and finishes with their comparative evaluation, based on the above-stated four key criteria.

3.1. Space10 & EFFEKT Architects – The Urban Village Project - modular concept for IKEA

The Urban Village Project is a conceptual development born by the collaboration between Space 10 and Effekt Architects under the management of IKEA. It is "*a vision for creating shared living communities for people of all ages, backgrounds and living situations …. "* which *"objective is to enable a better everyday life through the multiple benefits of living in a tight-knit community, with shared facilities and services like day-care, urban farming, communal dining, fitness and shared transportation*" [4]. In accordance with the concept behind IKEA packaging it is supposed that the buildings materials are "*prefabricated, mass-produced and flat-packed*" [4] thus making the solution quite affordable. Both the construction and closing material is wood which gives high sustainability to the solution, reduces exploitation costs within its lifecycle and forms better living environment for the inhabitants.

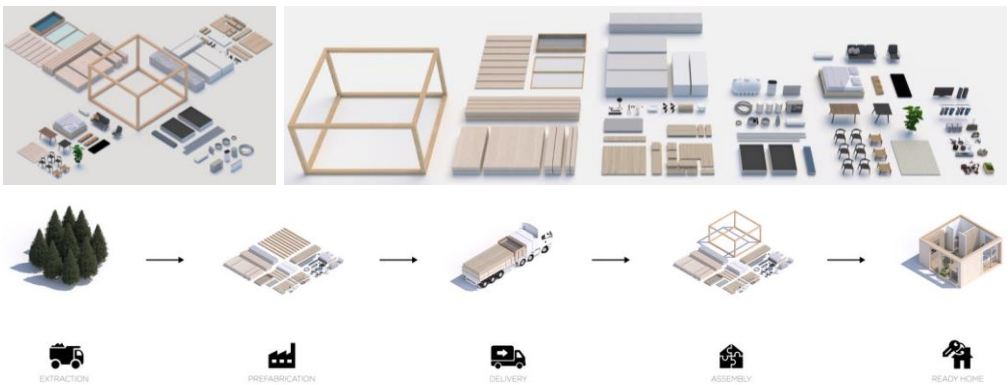


Figure 1. The Urban Village Project – elements of a single modular residential unit and creation of the unit – transition from the woods to the city; source [5, 6]

The development of the project is "*based on a standardized modular building system*" [4], which is a grid of squares with sizes 6 meters x 6 meters within which is proposed a possible separation of the single residential units with different sizes, starting from 36 sq. m., thus making them suitable for diverse in size and needs households (fig. 2). All of this provides great extent of flexibility of the project and could be considered a key benefit. In terms of usage of the defined types of modules it could be deliberated that the project is interpreting the structural type of module, tending to transform it into a hybrid type. This is created through the combination between a planning and construction type of module since it is developing

itself within a structural grid, which defines the shape, the sizes as well as the proportions of the units and the common spaces.

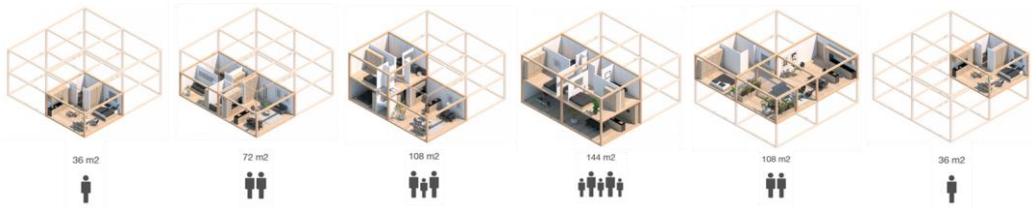


Figure 2. Different options for housing units – high-level flexibility depending on the size of the household and their personal needs, source [5]

Being on the boundary of creating shared and co-living spaces the project could find its multiple places within the city fabric both as a standalone construction and as a densification instrument in already built environment (fig. 3), thus serving as a possible restriction for the observed in the recent years, rapid urban sprawl. The architectural form is simple, minimalistic and compact, as it gives the possibility of creation transitional in-between spaces within the grid, in order to create a sustainable and quality living environment [7].



Figure 3. Possibilities to integrate the modules of the Urban Village Project within the urban fabric, source [5]

3.2. Architectural Mythologems – Puzzles of Complexity - modular housing in China – research and concept project

The Puzzles of Complexity project is a highly conceptual design proposed by the architects from Architectural Mythologems. The project's urban layout is inspired by a chessboard pattern, symbolizing binary principles foundational to computing [8].



Figure 4. Puzzles of Complexity – chess influence and appearance of the compact architectural form, source [8]

Similarly to the Urban Village Project it has grid-like arrangement and facilitates a visually articulate community structure, where the repetition of simple units ends in a dynamic urban

complex with a mixture of private, public and semi-public spaces. The design philosophy underscores the idea that complexity can emerge from the strategic assembly of simple elements. While the individual modules maintain a minimalist appearance, their collective arrangement results in a visually complicated architectural image (fig. 4).

This project's grid has sizes of 3 meters x 3 meters and is defining modular units with numerous possibilities for combinations. The solution could be listed, similarly to the Urban Village Project, as a hybrid type of module – a combination between structural and planning modules, since the residences occur within the framework of the structural lattice, which serves as the foundation on which residents are able to customize and expand their living spaces over time, according to their evolving needs, thus giving this project also a great extent of flexibility (fig. 5). This approach not only promotes affordability by enabling incremental construction but also supports sustainability through efficient use of materials and space. The minimalist aesthetic allows for scalability and adaptability. The smaller sizes of the grid give greater possibility for creating human scale and successful zoning [9] of the public and semi-public spaces incorporated within the project.

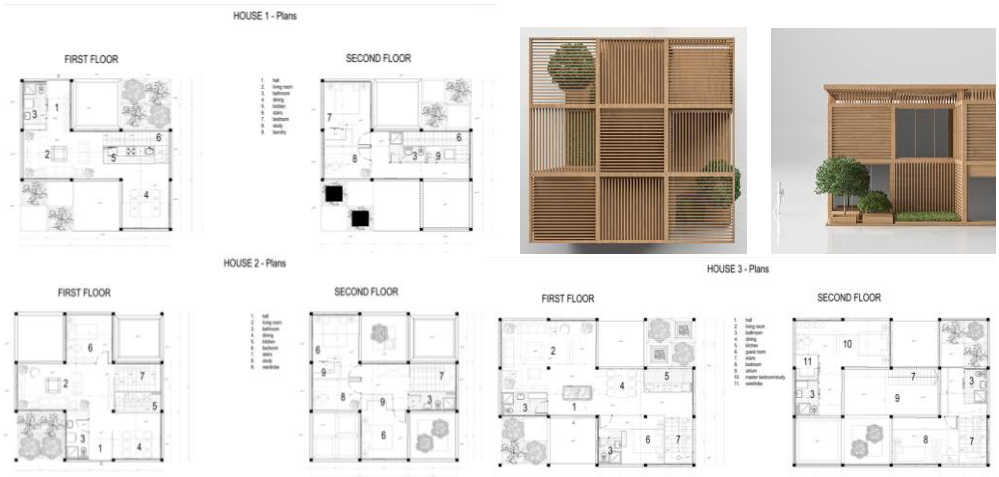


Figure 5. Puzzles of Complexity – floor plans and appearance of the tree types of residences, source [8]

3.3. Summary, Portugal - GOMOS modular system

The GOMOS System, developed by the Portuguese architecture studio Summary, led by architect Samuel Gonçalves, is a modular construction approach inspired by the assembly of concrete sewer pipe. This system reimagines such structures for residential use, maintaining their rapid assembly and structural stability. In its essence it is a concrete shell prefabricated to live-in and ready to be installed on-site.

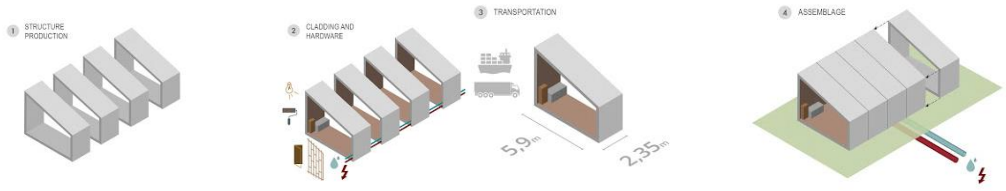


Figure 6. GOMOS modular system – shape and size of the prefabricated elements, source [10]

Elements could be defined as a space-functional module, according to the author's classification due to the fact that they are arriving on-site completed with their interior and exterior finishes, insulation, window frames, plumbing, electrical installations and fixed furniture – all incorporated within their specific shape (fig. 6). The system's design allows for adaptability to various programs beyond housing. Modules can be added post-construction to accommodate expansion, and the system can adapt to different land conditions, residents' requirements and needs.

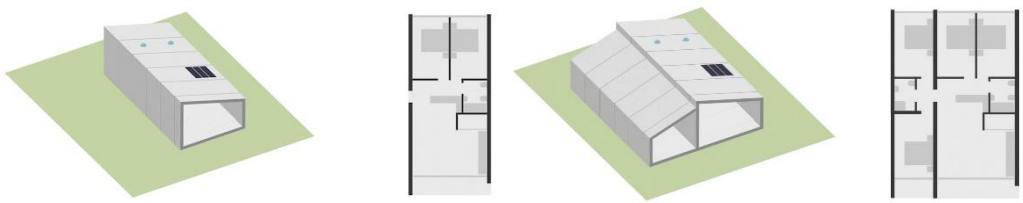


Figure 7. Possible solutions for the shape and the floor plan, using the GOMOS system elements - flexibility of the solution, source [10]

The construction process is divided into four phases – production of the structure, installation of finishes and facilities, transportation, and assembly. This streamlined approach allows for on-site assembly to be completed in just a few days. Module dimensions are optimized to comply with transportation regulations, facilitating easy delivery to construction sites (fig. 8). Design choices, including natural ventilation corridors and effective insulation, contribute to low energy consumption in GOMOS buildings. Factory production under controlled conditions ensures consistent quality and reduces the likelihood of construction issues commonly found in traditional building methods, although in some realizations using the system internal signs of leakages could be seen. This is showing some week points in the process of insulating the joints between different elements, especially in projects where the concrete structure is left visible, such as Vale de Cambra housing in Portugal, constructed in 2019 (fig. 8).



Figure 8. Phases of construction process – fig. 8 – left; internal problems with the connections between elements – fig. 8 - right, source [11]

The system is flexible enough and is tested in designing and creating different types of buildings without limiting its usage to residential constructions (fig, 9). It represents a significant advancement in modular construction, offering a solution that is both efficient and adaptable. Its emphasis on prefabrication, rapid assembly, and flexibility makes it a

compelling option for addressing contemporary housing challenges, particularly in contexts where affordability and sustainability are dominant.



Figure 9. The GOMOS system elements are used for constructing variety of buildings, including single family housing, apartment buildings, student dormitories, kinder garden as well as public buildings, source [11]

In the following table the three above-discussed projects are evaluated in accordance with the initially set criteria - environmental performance, adaptability and flexibility answering to user needs, architectural image, defining and creation of shared common spaces and usage of the different types of modules, defined by the author.

Table 1. Qualitative comparison and evaluation between The Urban Village project, Puzzle of Complexity and projects, adopting the GOMOS modular system

CRITERIA / PROJECT	Urban Village Project	Puzzle of Complexity Project	projects, adopting the GOMOS System
Environmental Performance	**HIGH** -based on circular design principles -usage of natural materials -reusability of materials – design for deconstruction -reduced footprint via shared resources.	**MODERATE** -modular structure -potential for reuse, -no clear information about the used materials.	**HIGH** -usage of prefabricated concrete modules -reducing site waste and construction time -good thermal mass for energy efficiency.
Adaptability & Flexibility to User Needs	**VERY HIGH** -possible reconfiguration, extension, and spatial personalization.	**MODERATE** -adaptable layouts -higher class living – closer to single family housing in a complex.	**LOW–MODERATE** -highly standardized units with minimal options for post-construction adaptation.
Architectural Image	-distinct and contemporary -strong design identity based on usage of the wood and the modularity within urban context -highly conceptual.	-blends modular logic with vernacular motifs or typologies -more anonymous in appearance but contextually responsive.	-minimalist and industrial -visually uniform -architectural identity comes from repetition and the usage of simple forms.

Common / Shared Spaces	**HIGH** -shared amenities are within the core of the concept (laundry, gardens, workspaces) -promoting community and reducing loneliness -shared/ open-air spaces could be integrated anywhere in the structure – ground floor and above.	**MODERATE** -shared corridors or courtyards where appropriate -not a primary focus but considered within the plans -shared spaces could be only on the ground floor.	**LIMITED** -projects are focused on self-contained living units -shared/ open-air spaces depend on external planning and layouts of regulated plots as well as the one of the particular building
Type of modules used, as defined by the author	**hybrid type of module** – mixture between structural and planning type of module	**hybrid type of module** – mixture between structural and planning type of module	**space-functional type of module**

Each project offers distinct advantages and challenges. The buildings which are using the GOMOS modular system excel in environmental performance due to the efficient, prefab process and simplicity, but are less responsive to user diversity and community integration. The Urban Village Project presents an ambitious model for future urban living, with high adaptability and sustainability, though it remains largely conceptual. It sets a visionary example for modular urban communities. The Puzzle of Complexity Project offers a tested, pragmatic balance between standardization and contextual responsiveness - incorporating some flexibility and shared use while being grounded in local needs and urban practicality, making it particularly relevant for rapidly urbanizing regions. All the studied examples present specific spatial structure which is generally defined by other authors as "*modular structure obtained through the combination of a sequence of typical... modular elements*" [12], which is a fundamental asset to the possibility for creation human scale and the proper organization of the shared spaces.

4. CONCLUSION

This study highlights the growing relevance of modular construction as a key strategy for addressing the dual challenges of affordability and sustainability in residential housing. The analysis of the three international case studies – each applying the types of modules, defined by the author, demonstrates that modular approaches can effectively reduce costs, shorten construction timeframes, and minimize environmental impact, while maintaining flexibility and architectural quality.

The comparative evaluation reveals that modular systems are most successful when tailored to local conditions, supported by clear planning strategies, and integrated early in the design process. The Urban Village Project by Space10 & EFFEKT Architects shows the value of systematized, replicable design; the Puzzles of Complexity Project illustrates rapid urban-scale implementation; and the projects built with the GOMOS system emphasizes

material and energy efficiency through prefabrication. All key features well-known in our local practices but seemingly forgotten long ago and being avoided in design and construction process at any cost. Although the fact that we have long-lasting traditions and know-how in prefabrication processes local architects and mostly contractors are evading the integration of prefabricated elements within the construction process of residential buildings, no matter that materials, such as wood and concrete, are locally produced and could be easily implemented, thus significantly reducing construction time and material transportation costs.

Despite the benefits, limitations such as design constraints, restriction in sizes due to transportation challenges, and regulatory hurdles persist. Future research should address the long-term performance of modular housing, user adaptability over time, and the integration of circular economy principles. In addition, broader quantitative studies on lifecycle cost analysis in modular systems would deepen the understanding of their environmental and economic impact.

Ultimately, this study affirms that modular housing is not a universal solution but a powerful tool – one that, when applied strategically, can contribute meaningfully to more equitable and sustainable living environment.

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Review paper

REVIEW OF METHODS FOR INTEGRAL SEISMIC AND ENERGY RENOVATION OF EXISTING MASONRY BUILDINGS IN SERBIA

Jelena Savić[1], Aleksandra Cilić[2], Jelena Stevanović[3], Miloš Nedeljković[4]

Abstract

The research of the methods for integral renovation of the existing architectural stock is necessitated by weak seismic resistance and poor energy performances of these buildings. Most of the existing buildings in Serbia are masonry buildings, which had been built before the first comprehensive seismic design code in the SFRY, that was issued in 1964, and also before the requirements regarding thermal protection were enacted. Today, technical regulations define the required level of load bearing capacity and safety that buildings should satisfy, as well as the appropriate level of energy efficiency, so that the quality of housing and the conditions of service of the building correspond to modern living standards. In practice, several separate techniques have been used for years for improving the thermal protection of existing buildings, and also for the rehabilitation and strengthening of structural elements in case of global and local interventions. The focus of the research is increasingly shifting towards integrated strategies that synergistically deal with the study of both aspects. The paper shows the methods of integrated renovation that are applied from the outside of the building, in order to facilitate their execution in buildings that are in use, with minimal disturbance of the building residents. The application of appropriate comprehensive and effective solutions is a process that still requires further research in order to optimize strategies.

Key words: *masonry buildings, seismic design, thermal protection, structural measures, integral improvement*

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1. INTRODUCTION

The aging of the building stock is a problem that affects many regions of the world. This means that a large proportion of existing buildings are considered energy inefficient, as they use a lot of energy for heating and cooling. In addition to this, a big problem is the weak resistance to seismic effects. Recent earthquakes have caused significant economic losses, mainly due to the vulnerability of older buildings that were not designed and built to modern standards.

Addressing seismic and energy performance with separate interventions is a common approach that is topical. However, to achieve better cost-effectiveness, safety and efficiency, a new holistic approach to building renovation is an emerging topic in the scientific literature and also in practice.

A holistic approach to building renovation could be a leading instrument for promoting renovation and ensuring the longevity of investments made to improve energy efficiency. Until recently, retrofitting and renovation efforts were mainly focused on improving the thermal protection, without taking into account the structural integrity of the building. Looking at the structure is crucial when it comes to renovation, because neglecting the structural integrity of the building can later lead to major damage and irrational ineffective finance spending.

In the scientific literature [1], [2] the topic of integrated seismic and energy retrofitting has become popular in the last five years. This topic entails the formation of an appropriate methodology for combined assessments of existing buildings, as well as for the analysis of potential benefits from integrated interventions. Observing the scope and complexity of interventions related to energy efficiency and seismic resistance, as well as their accompanying costs, and the assessment of the condition of existing buildings and their comprehensive analysis are of great importance for the formation of the process of deciding on the renovation of buildings. The feasibility of applying appropriate integrated retrofitting, available materials and production technologies is presented in the paper. The selection and implementation of the appropriate methods largely depends on the applied structural systems, the quality of the built-in materials, the condition in which the building is located and other characteristics of the buildings.

It is crucial to emphasize that the renovation of existing buildings not only extends the life of a particular building, but also significantly preserves natural resources. Improvements in energy efficiency in existing buildings lead to significant reductions in the energy required for heating and cooling, thereby reducing costs, and the economic aspect is also improved. In addition to the basic goals of such a comprehensive integrated renovation, it is important to emphasize the improvement of the comfort and quality of life of the users. It becomes evident that the benefits resulting from such a comprehensive renovation go beyond the basic goals and extend to other aspects, making this process even more complex and meaningful.

This paper shows the available methods, i.e. those that have the most common application in practice, when it comes to seismic strengthening and improvement of energy efficiency. Although not all available methods are presented here, the selected ones show the appropriate possibilities and advantages provided by the integration of structural and energy measures [2], [3].

2. MATERIALS AND METHODS

The research methodology consists of few stages. The first phase includes an analysis of the types of existing multi-family residential buildings built in the period of mass construction after World War II. Depending on the time of construction, different systems, structural assemblies and materials were applied, and very often these buildings were extended and reconstructed. A certain number of buildings, despite their solid structure, are damaged by sudden events, such as earthquakes, fires, explosions and the like. Earthquakes are external factors that cause damage to buildings, and they cannot be predicted. Depending on their severity, these damages can range from minor to devastating. The second step includes the analysis of the existing situation, primarily from the structural aspect, and then from the point of view of energy efficiency. The third step consists in the presentation of variant solutions for improving the structural elements of buildings, and then the application of appropriate systems essential for improving the thermal protection.

Structural strengthening and improvement of thermal protection of existing buildings have so far been mostly observed and carried out independently. However, we could see in numerous examples that after sudden seismic events, the investments on the buildings that were not structurally reinforced, and had interventions around the thermal envelope, is lost in this rehabilitation as well. Also, the additional costs occurring in that case, as well as the additional disruption of the normal life activities of the tenants in the building, can be mentioned as a downside of the separate execution of these interventions. On the other hand, if integrated structural and energy upgrading is applied, then the structural integrity of the building can be considered truly safe. This means that even if a certain seismic effect occurs, the building will be able to withstand the event without it affecting the energy reconstruction at all. Practically, in areas with moderate to high seismic risk, it is imperative that any energy reconstruction is carried out only after the building has been brought to a level of appropriate structural stability, in accordance with modern standards. Otherwise, the risk of losing the investment is excessively high, as shown by many examples in the practice.

3. EXISTING MASONRY BUILDINGS CONSIDERED IN THE STUDY

Residential building in the period after World War II introduces a new concept of designing and organizing housing space, breaking ties with the previous tradition and certain characteristics of cultural heritage. Apartments for social housing and newly designed workers' neighborhoods are defined by strict uniformity, a simple repeating form, small number of floors and emphasized horizontal lines of openings on the facades. The buildings are still mostly built in the system of load-bearing brick walls, with reinforced concrete ceilings and wooden roof structure.

The period from the fifties to the mid-sixties is characterized by a large number of built apartments, which, however, did not always meet the needs of the users. The reason for this situation was the lack of design standards and regulations. The first national standard related to seismic design was issued in 1964 [4], after the catastrophic earthquake in Skopje in 1963.

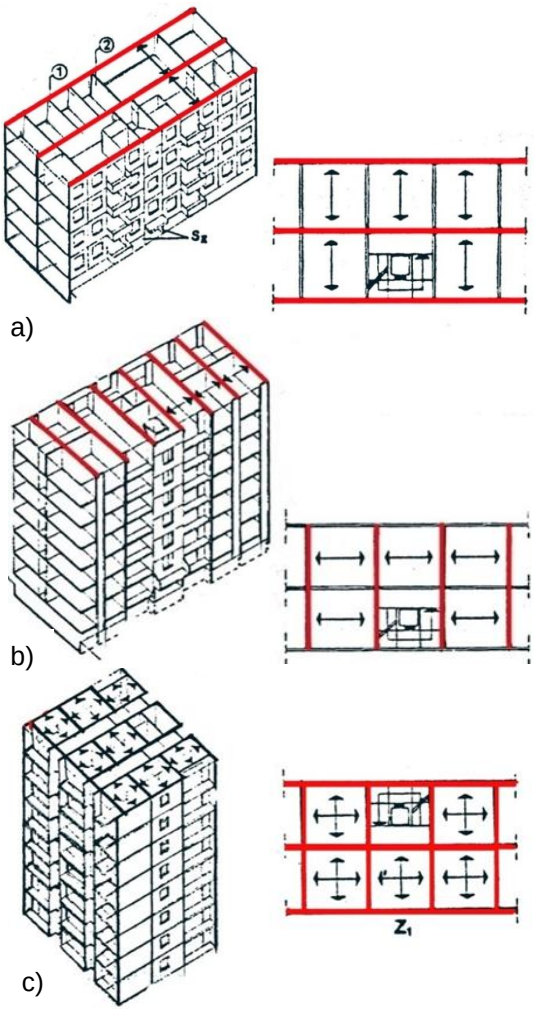


Figure 1. Massive structural system [5]
a) longitudinal, b) transverse, c) crossed

Most of the multi-family residential buildings built before 1964 are generally low, from 3 to 5 stories. Bearing walls in structural systems can be arranged as longitudinal, transverse or placed in both orthogonal directions. In this period, the walls were built as unreinforced masonry (URM), 25 to 38 cm thick. Solid bricks measuring 12x25 cm and compo were used for masonry. These buildings are heavy and massive, due to the relatively large thickness of the masonry walls. The distance between the load-bearing walls is determined by the span of the ceilings and is not greater than 5.0 meters. The seismic behavior of URM walls can be characterized as brittle, since cracks occur when tensile stresses exceed the tensile strength of the wall, as stated in [6]. Floors were in the form of semi-prefabricated composite masonry and stiffened with horizontal concrete beams.

Builders of masonry (URM) buildings often made gross structural errors by designing load-bearing walls only in one direction without adequate connections between the walls and the floor slabs, with insufficient connections with the surrounding walls, large openings, poor quality materials, and the like. The expected longer service life of these buildings and modern building design standards require a higher level of safety.

The disadvantages of existing buildings in terms of energy efficiency are mainly due to the lack of regulations at the time of their construction, as well as the deterioration of materials over time. The first application of the thermal envelope in our region occurred in the early 1970s, as a result of the oil supply crisis [2]. Nowadays, new buildings during the design process must comply with a set of regulations on energy efficiency, and also existing buildings during reconstruction must satisfy minimum energy performance requirements. Within the framework of the *National Typology of Residential Buildings in Serbia* (Table 1) [3], a specific categorization of the existing building stock and its extensive research in terms of energy characteristics have been carried out. Existing residential buildings most often have load bearing facade walls made of bricks without thermal insulation.

Table 1. National typology of residential buildings in Serbia from 1946 to 1960 [3]

	Family housing (up to 4 apparterment)		Multifamily housing (more than 4 apparterment per entrance)			
Type	1	2	3	4	5	6
	Freestanding	In a row	Freestanding	Lamela	In a row	High rise
1946-1960						

The thermogram shows a high intensity of heat loss through the facade walls of the heated part with prominent horizontal reinforced concrete ring beams in comparison to the unheated ground floor part of the building (Fig. 2). On the higher floors, secondary heating from solar radiation can be observed, as well as increased heat loss through the facade joinery. The original joinery is double-glazed wood and in a large number of apartments it has been replaced with new PVC or aluminum.





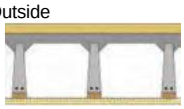
Figure 2. A residential building with load bearing facade brick walls without thermal insulation [3]

The lack of energy standards is also clearly visible when looking at the evolution of thermal transmittance (U-value) of different building elements (walls, windows, roofs and floors) for residential buildings. As can be seen in Table 2, older structures have significantly higher thermal transmittance values than modern ones, leading to higher energy consumption and significantly worse thermal comfort.

It is important to emphasize, an energy upgrade investment will not be effective when applied in a building of questionable structural integrity. First the building must be brought into a state of required load-bearing capacity and safety. This phase is primary and must be a guarantee for the successful implementation of other measures that should achieve the desired quality of housing and the achievement of overall goals.

Parts of buildings where increased heat transfer occurs are called thermal bridges. Their formation is most often the result of the complex structural composition of the building, or its geometric discontinuity, and therefore they can appear at the base of buildings (plinths), on ring beams, reinforced concrete columns, window lintels, or around windows if they are not installed correctly. In existing buildings, the goal is to reduce the effects of thermal bridges to a tolerable level.

Table 2. Elements of the thermal envelope-Present state [3]

Structure	Figure	Description	Thermal transmittance
External Wall 1	Inside Outside 	Plaster 2cm, brick wall 38cm, decorative plaster 3cm	1.26
External Wall 2	Inside  Outside	Plaster 2cm, brick wall 25cm, decorative plaster 3cm	1.67
Floor Construction to Unheated Area (Basement)	Inside 	Parquet 2.2cm glued, cement screed 3cm, ribbed semi prefabric. concrete slab *Avramenko* 30cm	2.05
Floor Construction to Unheated Area (Attic)	Outside  Inside	Sand 2 cm, rammed earth with chaff 5cm, ribbed semi prefabric. concrete slab *Avramenko* 30cm, straw plaster ceiling 5cm	1.06
Windows and Balcony Doors		Wooden, double frame, double sash (narrowbox) with single glazing. Internal canvas roller blind	3.50

4. INTEGRATED SEISMIC AND ENERGY RETROFITTING TECHNOLOGIES

During the process of designing and preparing the renovation work, it is important to consider compatibility already in the design phase, especially in terms of: possible spatial overlap; scope of application; level of disturbance; and the desired level of performance. Certain overlaps may hinder the application of seismic or energy techniques because of the practical limitations they impose on each other. The scope of application is related to the number of building elements on which the intervention is applied, while the level of required interventions is related to the time required for the realization of those works. So, for example, if seismic intervention is required only on a few elements of the building, while the energy intervention is intended to require work on the entire building, the two interventions can be considered less compatible in terms of scope, but probably also in terms of the disturbance level.

Technologies and methods currently topical in the scientific literature, by Gkatzogias, Pohoryles at al. [2], can be classified into four main directions: (1) integrated exoskeleton solutions; (2) integrated interventions on the existing building envelope; (3) replacement of envelope elements by higher performance elements and (4) interventions on horizontal elements, such as roof and floor slabs.

4.1. Integrated exoskeleton solutions

Integrated exoskeletons are external structures that are connected to existing buildings in order to improve their structural stability and safety and reduce energy consumption. Concrete or steel systems are most commonly used. The exoskeleton system can be superimposed on the facades by creating an independent structure on its foundations. It can accommodate new spaces and support possible elevations.

Examples of such external structures range from simple beams combined with shading elements, to diagonal steel trusses or frames that carry different types of panels, such as integrated photovoltaic systems, green facades or shading elements, as shown in Figure 3. Integrated solutions also include the use of thermal insulation integrated with auxiliary reinforced concrete frames or walls.



Figure 3. Application of a steel exoskeleton wall system for integrated seismic and energy retrofitting of buildings [7],[8]

Exoskeleton systems are not always feasible, as in the case of densely built-up urban areas, which lack the space around the exoskeleton facility, which further complicates the excavation of additional foundations [9],[10]. Since forces are usually transferred from the existing building to the exoskeleton by slab-level connections, application of the exoskeleton may not be effective when the horizontal slab is not rigid. An additional limitation for exoskeletons is a significant change in the external appearance of the structure, which may make the intervention inapplicable for certain types of buildings.

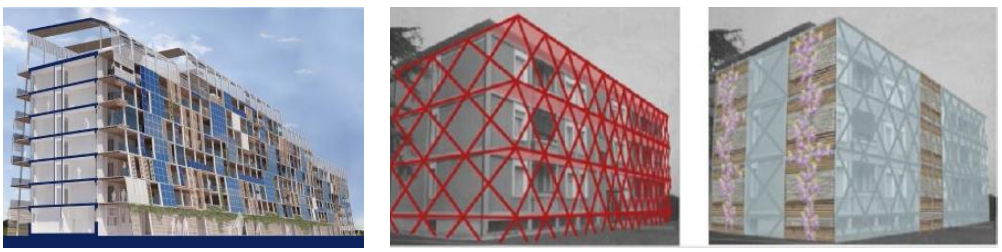


Figure 4. Application of a steel exoskeleton shall system for integrated retrofitting [8],[11]

The steel exoskeleton system which features solar green-buildings on the southern façade, along with thermal insulation using EPS, new energy-efficient windows, and adjustable louvre shading systems for controlling solar radiation can ensure a 70 % reduction in heating, as proposed by Stasi et al. This systems integrates various technologies to create thermal buffer zones, shown in Figure 4, such as balconies or additional space, which help to reduce solar radiation during the summer months, provide solar heating during the winter, and support plug-and-play installations for new HVAC systems [11].

4.2 Integrated interventions on the existing building envelope

Considering the high stiffness of the walls and the high energy transmittance of the vertical envelope of the building, special attention is paid to the development of combined renovation strategies of these elements, to satisfy both seismic and energy aspects. Different variant solutions can be found in the literature, such as: (1) application of composite materials; (2) in situ constructed panels/walls, (3) prefabricated panels (cement-based or wood-based), and (4) the local strengthening of the existing openings integrated with upgrading of the old fenestration. In the case of all envelope strengthening solutions, the increase in shear capacity in the foundation, as well as in the shear forces acting on the existing frame, means that a careful assessment of the foundation and frame elements should be carried out, as these elements may need to be further reinforced.

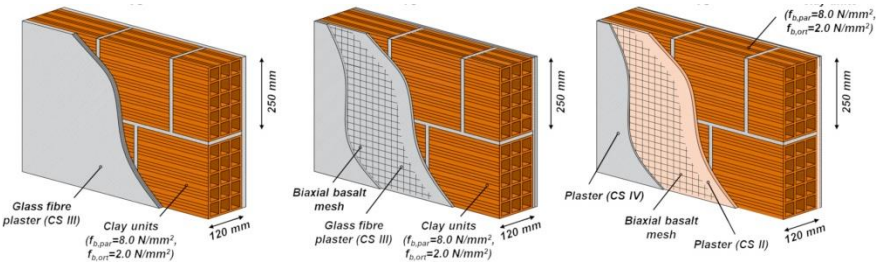
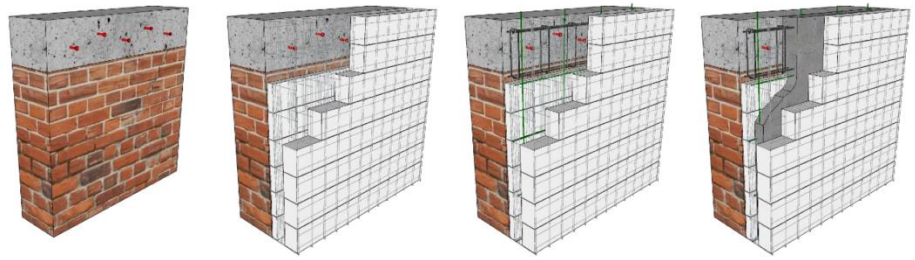


Figure 5. Composites for the combined seismic and energy retrofitting [12]

Until now, methods of strengthening masonry structures with composite materials, shown in Figure 5, have been widely used in practice. As stated in *Technologies for the combined seismic and energy upgrading of existing buildings [7]*, they range from textile-reinforced mortars (TRM), fibre-reinforced polymer sheets, which are bonded using epoxy raisins (FRP) and engineered cementitious composites (ECCs) or steel fibre reinforced mortars (SFRM), using short fibres dispersed in a mortar, to steel meshes for reinforcing thin layers of plaster. These systems can be applied in the form of two- or one-sided jacketing and with the insulating panel either on the outer face or between the TRM and the masonry. Previous research has shown that the exact positioning of the TRM and the insulation material does not play an important role in the in-plane response, as long as proper bonding between the different layers is achieved. Positioning the TRM reinforcement above the insulation layer does not seem to compromise the activation of its fibres. Compared to the symmetrically reinforced specimens, single-sided configurations resulted in only a slight reduction of their efficiency This is a key benefit in a real-world retrofitting scenario, as it allows to perform all the work from the outside of the structure, drastically reducing the cost and the disruption of building occupancy.

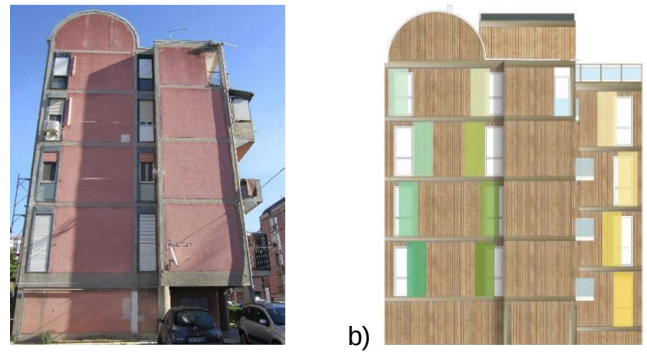
In situ constructed panels/walls represent the system consists of a thin RC wall cast in-situ between pre-assembled layers of insulating material, as shown in Figure 6.The reinforcement of the concrete layers consists of steel bars arranged in the longitudinal and transverse direction with defined spacing. The retrofitting system is connected to the existing structure at each floor level, using steel connectors embedded in the horizontal ribs.



a) b) c) d)

Figure 6. Installation phases of the Insulated Concrete Formwork technology: (a) installing the connectors, (b) placing the insulated formwork, (c)placing the steel reinforcement, and (d) casting the concrete.[10]

Prefabricated panels (cement-based or wood-based) have recently gained traction for their use in integrated seismic and energy strategies (Figure 7). Multiple studies have proposed the use of CLT and OSB panels as an integrated retrofitting strategy for either load-bearing masonry buildings or RC buildings. The advantage of precast panels is that they may be applied faster onsite, reducing the time and cost of the intervention.



a) b)

Figure 7. Proposed external cladding for CLT panel retrofit of case study building: (a) current state; (b) cladding with wooden boards [2]

Strengthening of openings with structural window frames integrated with fenestration replacement is particularly suitable for URM buildings. The seismic behaviour of the existing structure can be improved if the steel frame is adequately linked to the masonry and designed considering the original stiffness of the wall. The auxiliary elements work in parallel with walls and provide a beneficial confining effect to the surrounding masonry, increasing the in-plane shear strength and stiffness of the existing masonry wall [7]. The use of a structural steel window frame has been recently tested for individual masonry wall specimens.

4.3 Replacement of envelope elements with better performing materials

Retrofitting interventions on existing non-structural envelope elements, e.g. for masonry infills, may often not be feasible in practice or not economically viable. Researchers has focused on the development of elements that can provide at the same time adequate seismic resistance and improved energy performance. In terms of the seismic performance,

this can mean (1) an increased stiffness and strength of the new infills, or (2) increased deformability of the frame by reducing interactions between infill and RC frame. For energy performance, approaches can include the use of new and more energy efficient materials.

4.4 Interventions on floor diaphragms and roofs

In the seismic behaviour of a structure, horizontal diaphragms have the task of transferring the horizontal actions to the resistant elements. In masonry buildings particularly, the floor and the roofs are typically made of timber joists and wooden planks or one-way steel beams with large flexural deformability and low in-plane stiffness, for this reason, stiffening interventions are often necessary [7].

For roofs, Pohoryles, Bournas, da Porto et al. [7] proposed a technique for the recovery of historic wooden roofs. The solution is based on the construction of a thin folded shell overlaying the existing roof pitch rafters and planks. Each pitch plane is transformed into a diaphragm composed of pitch joists, by perimeter chords and by web panel overlaying the existing planks.

5. CONCLUSION

The need for seismic and energy reconstruction of existing masonry buildings stems from the desire to protect and preserve the buildings, to extend their life, to improve the level of housing and to ensure safety and security. In the past, several solutions were used in practice, but the integration between these two aspects limited their application and made them more expensive. Starting from the current need for a holistic approach to renovation, this study aimed to highlight the possible advantages of an integrated solution that combines seismic and energy retrofitting in a single intervention. In addition to the possible higher performance that includes a harmonious combination of seismic and energy reconstructions, less time-consuming interventions have been improved, and therefore the costs of subsequent reconstruction have been reduced, even considering the lower investment return period. The paper provides an overview of open questions and possible promising solutions that can be further improved to overcome the shortcomings and obstacles that still prevent their widespread use in practical applications. Various proposals have attempted to fill the research gaps that still exist by adopting several techniques and materials, either more traditional or more innovative. Since this is a truly new research area, existing solutions are continuously improved, new solutions and ideas are provided, thus enriching the current overview and possible available methods.

Experimental research should enable better evaluations of the applied measures, to show both the good and the bad sides of certain interventions that can be implemented at the same time at a low cost. This, combined with some new methods on existing buildings, will show the full potential of this approach.

ACKNOWLEDGMENTS

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Research paper

PUBLIC PERCEPTION OF THE QUALITY OF THE NEW BELGRADE URBAN LANDSCAPE (BELGRADE, SERBIA)

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Abstract

Intensive urbanization often threatens the spatial identity of cities and the value of existing urban landscapes. The development of gray infrastructure is usually not accompanied by the improvement and increase of the city's green spaces, which negatively impacts the aesthetics of urban areas and the perception of the urban landscape by the urban population. Factors such as natural landscape elements, visual harmony, building proportions, and spatial identity have a significant impact on the emotional response of the population and their daily interaction with space.

This paper analyzes the public participation in assessing the quality of New Belgrade's urban landscape, with the goal of determining its recognizability, understanding the emotional response of the inhabitants to urban vistas, and examining citizens' attitudes regarding the improvement of the current situation. A survey among 60 visitors via random sampling was conducted in the Bežanijska Kosa park, where a viewpoint offers a vista of New Belgrade's urban landscape. The results show that a significant number of respondents (40.48%) visit the park because of the urban vista, which is aesthetically acceptable for most respondents, but they recognize the need for improvement. The dominance of gray infrastructure was identified by 71.67% of respondents, who believe it diminishes the quality of the urban landscape, and improvements should focus on increasing the amount of greenery on and around buildings (91.67%). The reconstruction of existing green spaces and their better maintenance were cited as key factors in improving the characteristics of New Belgrade's urban landscape. The results highlight the importance of green spaces in urban environments, with users recognizing their value, which can serve as guidelines and recommendations for managing urban spaces and landscapes. Respondents emphasized the importance of preserving New Belgrade's identity as an urban entity that balances contemporary needs with cultural and natural heritage.

Key words: *urban landscape, New Belgrade, visual quality, public perception, spatial identity*

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1. INTRODUCTION

Urbanization and the rapid development of cities pose challenges in preserving the value of existing urban landscapes, as well as in visually integrating newly constructed buildings into the inherited elements of the landscape. The visual harmony of the landscape can be disrupted by unplanned construction, poorly maintained facades, and the excessive display of advertisements on buildings or their facades, and contribute to visual pollution, directly impacting the mental health of the population by causing stress and anxiety [1]. Not only transformation of urban landscapes but also contemporary city lifestyles contribute to the deterioration of human health and well-being, creating conditions for diseases of society such as stress, depression, insomnia, and others. The World Health Organization [2] has reported an alarming increase in the number of people in the cities suffering from stress and burnout syndrome. Urban greenery has a significant role not only as a part of urban landscapes making them more soft by creating of visual “pauses” within the urban scenery, but also in improving the well-being of residents. Urban greenery enhances the city’s environment and helps reduce stress, offering opportunities for the recovery of cognitive and physiological processes [3-7]. Greenery as part of the urban landscape has the highest value in large cities, where even a simple view through the window can improve one's mood [8]. Therefore it is clear why integrating green spaces into urban areas as a part of landscape identity must be part of sustainable development of contemporary cities. On the other hand, the historical identity of urban areas is equally important, allowing residents to feel and understand their history through space. In the context of urban heritage protection, landscapes should be understood as spaces of everyday life, socio-cultural constructs, and mental and subjective representations of the environment that change over time [9]. As an inseparable part of landscape people should be include in the process of understanding and improving it. So it is crucial to consider public opinion and perspectives regarding to the emotional responses of residents and their everyday interaction with space and urban landscapes. Engaging the public in assessing the impacts of various landscape changes can serve as a starting point for evaluating future changes and making decisions related to the management of urban landscapes, and as a foundation for the development of future city strategies and urban infrastructure regulations [10, 11].

This study focuses on public participation in the evaluation of the value of the urban landscape of New Belgrade (Belgrade, Serbia), aiming to determine its significance for the residents of the area and the city as a whole, to assess its recognizability, and to understand the emotional responses of residents towards urban vistas. It also examines citizens' opinions and attitudes regarding the enhancement of the current urban landscape condition from the perspective of landscape architecture.

2. METHODOLOGY

2.1. Description of the Study Area

The research was conducted in a park on Bežanijska Kosa (Figure 1, Figure 2), which territorially belongs to the municipality of New Belgrade. This municipality is located on the left bank of the Sava River and is the most populous municipality in Belgrade, characterized by a specific identity and visual features.

The urban planning concept of New Belgrade represents an applied example of the Functional City concept developed by Le Corbusier and reflects European modernism [12]. The basic characteristics of the Functional City are defined through 95 points of the Athens Charter (1943), emphasizing functionality and the construction of tall buildings while providing ample space for greenery. Special importance is given to factors such as light and air, natural landscape elements (i.e., various types of green spaces), and the relationships between natural and built landscape elements [12,13,14].

Bežanijska Kosa park (N 44°49.135' E 020°23.631') is located on a hill overlooking the landscape of New Belgrade and parts of blocks 37, 38, 40, and 65 can be perceived from it. The type of view from the park toward the urban landscape was determined based on the General Regulation Plan for the Green Areas System [15], while the types of biotopes in the study area were defined using the GIS Biotope Database (2013). Land use patterns were examined through the Urban Atlas (UA) database.

To define the spatial scope of the view, including the directions and width of the field of vision from the viewpoint in Bežanijska Kosa Park toward the New Belgrade landscape, an analysis of viewpoint photography (Figure 3) was conducted, taking into account the observer's orientation, the camera's field of view width, and recognizable landmarks in the landscape. This process resulted in a triangular depiction that defines the boundaries and direction of the field of view toward New Belgrade.



Figure 1. The location of the park on Bežanijska Kosa, the viewpoint, and the extent of visibility.



Figure 2. The park and the access routes on Bežanijska Kosa.



Figure 3. Viewpoint toward New Belgrade in the park on Bežanijska Kosa, Photo: M. Pešikan

2.2. Primary Data

The research involved the collection of primary data through a survey condacted with 60 visitors of Bežanijska Kosa park, where a viewpoint offers a vista toward the urban landscape of New Belgrade. Respondents were selected using a random sampling method, and the survey included a combination of different types of questions. The use of various question types aimed to explore different dimensions of respondents' attitudes and, in particular, to obtain accurate information [16].

The survey consisted of 15 questions, which can be classified into four groups.

The first group included questions about the socio-demographic characteristics of the respondents (gender, age, occupation, and education).

The second group comprised questions related to the frequency of park visits, reasons for visiting, and the way the area is used.

The third group of questions focused on evaluating the aesthetic quality of the vista — that is, the aesthetic characteristics of the urban landscape of New Belgrade. These questions used a Likert scale ranging from 1 to 5 (1-very poor, 2-poor, 3-acceptable, 4-very good, 5-excellent).

The final group of questions related to users' opinions on improving the quality of the urban landscape, their participation in activities aimed at maintaining this or other green areas, and their views on the need for more green spaces.

The survey was conducted in October 2024 and February 2025, over a total period of 4 days (2 weekdays and 2 weekend days). Data processing was performed using Microsoft Office Excel 2007, and the results are presented in the form of tables and charts.

3. RESULTS AND DISSCUSION

The vista from the park at Bežanijska Kosa toward the urban landscape of New Belgrade belongs to the panoramic type and illustrates the connection between gray and green infrastructure.

The vegetation characterizing the access area of Bežanijska Kosa Park, according to biotope types, falls into the category of urban wastelands, while the spatial scope of the vista is characterized by urban wastelands, dumps, and elements of green infrastructure (Figure 4).

Regarding land use, the study area belongs to the category of continuous urban fabric and industrial facilities (Figure 5).

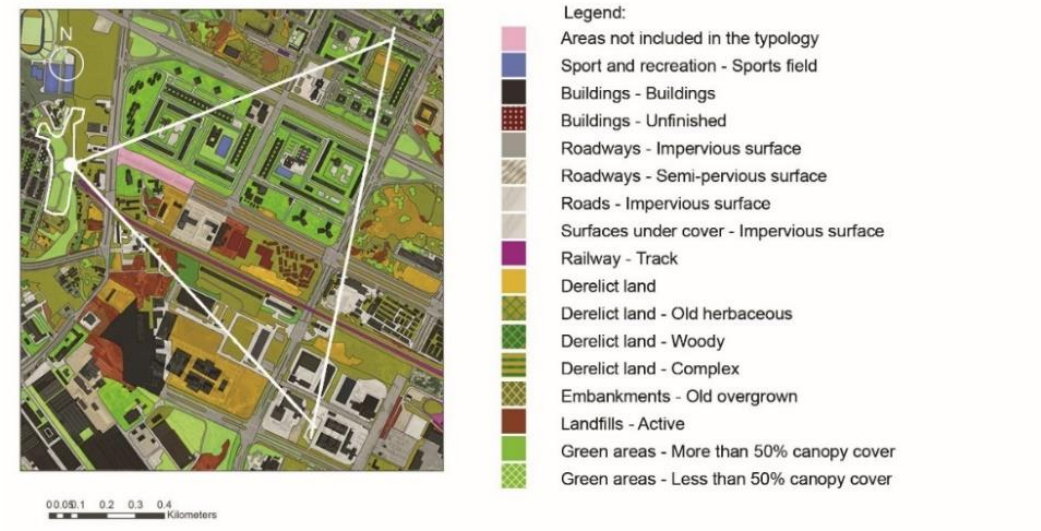


Figure 4. Biotopes of the study area (GIS Biotope Database, 2013)

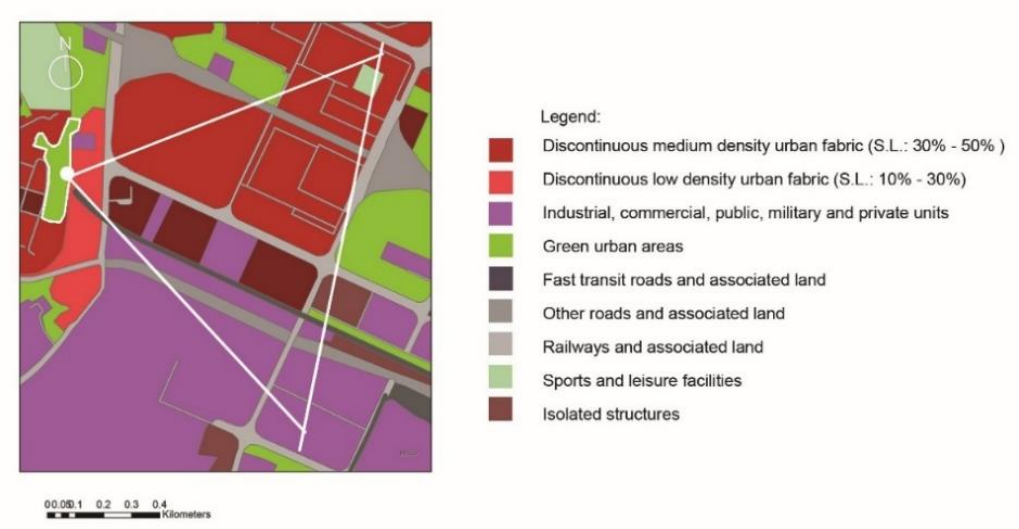


Figure 5. Land use of the study area (Urban Atlas, 2019)

3.1. Socio-Demographic Structure of Visitors

In the conducted research, a total of 60 users of the park at Bežanijska Kosa were surveyed. Of the total number of respondents, 28 were male and 32 were female.

Among the surveyed park visitors, those belonging to the 18–25 and 26–45 age groups were equally represented, together accounting for more than half of the respondents (73.34%).

The largest group of users were employed individuals (26), followed by students (16), while the number of unemployed respondents was the smallest (Table 1).

Regarding education, the majority of respondents had completed secondary education (21), while a similar number had completed higher vocational education (12) or university education (10). The fewest respondents had completed only primary education (7).

Table 1. Socio-demographic characteristics of park visitors at Bežanijska Kosa

Age(y.)	Number	Portion (%)	Occupation	Number	Portion (%)
<18 y.	1	1,66	student	7	11,67
18-25 y.	22	36,67	University student	16	26,67
26-45 y.	22	36,67	employed	26	43,33
46-65 y	8	13,33	unemployed	3	5,00
65+ y.	7	11,67	retired	8	13,33
∑	60	100	∑	60	100

More than half of the surveyed users live in the immediate vicinity of the park (55%), but a significant share of visitors also come to the park intentionally (45%).

Among the total number of users living near the park, the majority can be classified as long-term residents (78.79%), as they have lived in the neighborhood for more than 10 years.

The results show that factors such as residents' attachment to the location, as well as accessibility, are crucial for the visitation and use of a specific green area or urban space.

Proximity and accessibility are often cited in research as key factors influencing the visitation of certain urban green spaces [17-22].

In addition, the results showed a significant share of users who visit the park even though it is not located near their homes, indicating the importance of factors such as significance, attractiveness, and recognizability of the location, which become decisive when choosing a specific green area or urban space to visit.

3.2. Frequency of Visits and Reasons for Visiting

The largest number of respondents visit the park 2–3 times a month (40%), followed by those who come 2–3 times a week (26.67%).

More than half of the respondents (55%) visit both on weekdays and weekends, while the distribution of users who visit exclusively on weekdays or exclusively on weekends is quite similar (Table 2).

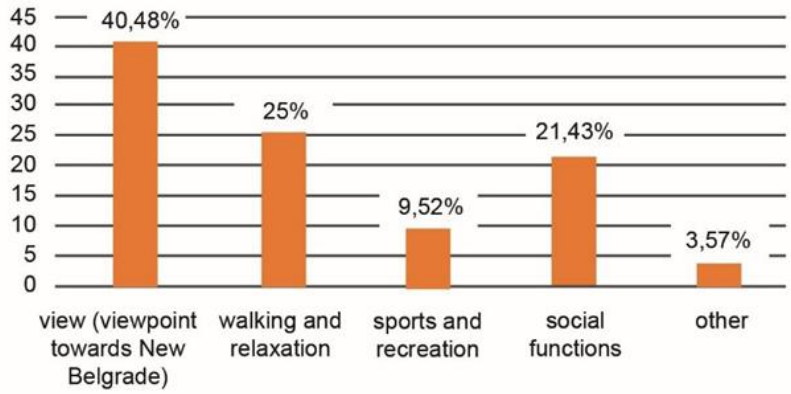
The analysis of the duration of stay in the park shows that the dominant period is 1–3 hours (38%), but a significant share of users (33.33%) stay somewhat shorter, around 1 hour.

Table 2. Temporal dynamics of park visits

Frequency of visits	Number	Portion (%)	Time of arrival	Number	Portion (%)	Duration of stay	Number	Portion (%)
Every day	9	15	Workday	13	21,67	Half an hour	2	3,33
2-3 times a week	16	26,67	Weekend	14	23,33	1 hour	20	33,33
2-3 times a month	24	40	Not specified	33	55	1-3 hours	38	63,34
The first time	11	18,33				Longer than 3 hours		

The main reason visitors come to the park at Bežanijska Kosa is the view — specifically, the vista toward the urban landscape of New Belgrade (40.48%). The obtained results show that the vista toward New Belgrade's urban landscape constitutes a key element of the identity and recognizability of this green space (Graph 1). The motivation for visiting is a factor that determines the reason for choosing a specific area [23]. Walking and relaxation in the green space are cited as the second most common reasons for visiting the park (25%).

Graph 1. Reasons for visiting the park at Bežanijska Kosa



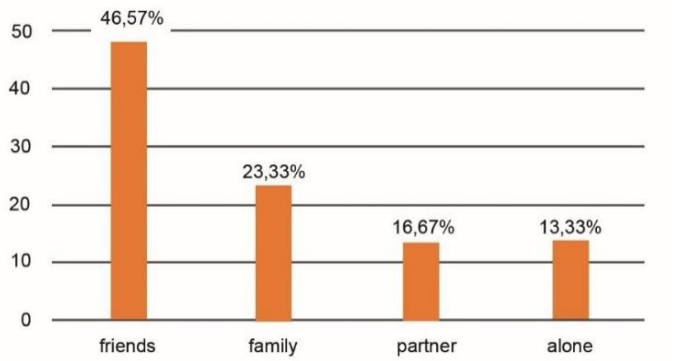
These two activities are frequently mentioned as typical uses of urban green spaces [24,25] and highlight the important psychological function greenery provides in urban environments.

The research results also indicated a pronounced social function of green spaces (21.43% of users visit the park to engage in social activities), a conclusion also supported by the responses to the question about whom users spend time with while in the park (Graph 2).

The characteristics of the area itself influence how the space is used, primarily through the opportunities it provides for performing certain activities [18,26].

In addition to the pronounced ecological, aesthetic, and social functions of the park at Bežanijska Kosa — reflected in spending time there with friends or family — a significant share of users visit the park seeking solitude (13.33%). Considering with whom a user visits and uses an urban space represents one of the fundamental factors influencing its use [27].

Graph 2. Users' responses to the question: "With whom do you most often visit the park?"



3.3. Satisfaction With the Aesthetic Characteristics of the Urban Landscape of New Belgrade

More than half of the respondents rated the aesthetic characteristics of the urban landscape of New Belgrade, observed through the vista from the park at Bežanijska Kosa, as good (35%) or very good (33.33%). These results indicate that there is room for improvement.

When asked about the feelings evoked by the urban landscape of New Belgrade, users predominantly mentioned feelings of peace and tranquility, a sense of calmness, relaxation, and restfulness.

Respondents emphasized the need for a greater presence of greenery within the observed landscape, which they believe would have a positive effect on their emotions.

It is important to note that some users expressed negative feelings such as sadness, melancholy, anxiety, and nostalgia, which they attributed to the dominance of built structures in the landscape, excessive urbanization of New Belgrade, and similar factors.

The results of the evaluation of users' satisfaction with the characteristics of New Belgrade's urban landscape show that users recognize the great potential of the urban landscape, but also that it is not adequately utilized, which reflects on the aesthetic image of the landscape.

Contemporary challenges in the urban development of New Belgrade, such as privatization processes, commercialization of green spaces, and the expansion of the informal economy, lead to changes in the character of the area [28], resulting in problems such as insufficiently regulated urban growth, neglected residential blocks, and abandoned public spaces [29].

The opinions of users in this study confirm the findings of Marić et al. (2010) [29] that, instead of the planned unified urban fabric, the open urban and green spaces in New

Belgrade are under threat, with commercial interests often outweighing the needs of the wider public.

3.4. Improving the Characteristics of the Urban Landscape of New Belgrade

A large portion of users stated that the view toward the urban landscape of New Belgrade is dominated by built structures (71.67%), while 91.67% expressed the opinion that changes in the aesthetic characteristics of the landscape should primarily focus on increasing the presence of greenery.

Among the specific mechanisms proposed to improve the condition, users emphasized the importance of reconstructing existing green spaces around buildings and along roads (20.50%) and better maintenance of the existing green spaces that are part of New Belgrade's landscape (21.12%).

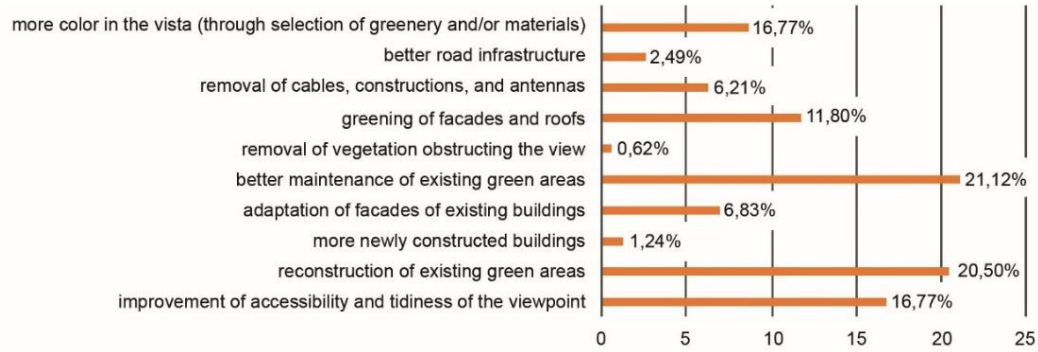
Accessibility and the arrangement of the viewpoint in the park were also highlighted (16.77%), along with greening roofs and facades of existing buildings (11.80%).

Green roofs and green facades are recognized as solutions that can help mitigate the visual dominance of gray infrastructure elements and create a more pleasant urban environment.

Reconstruction and continuous maintenance of green spaces stand out as key activities for preserving and enhancing landscape quality, with a focus on their aesthetic and ecological functions.

Other proposed mechanisms for action were represented with a share of less than 10% (Graph 3).

Graph 3. Users' responses regarding mechanisms for improving the urban landscape of New Belgrade



Maintaining green urban spaces is crucial for preserving the identity of New Belgrade as well as for improving the quality of life of its residents. The General Regulation Plan for the Green Areas System [16] emphasizes the importance of preserving vistas from characteristic positions and viewpoints. This involves not only the physical conservation of space but also the preservation of its cultural and ecological significance. Therefore, urban planning and heritage management must be aligned with the needs for conserving original architectural and urban principles as well as green spaces.

The urban vision for New Belgrade was based on modernist principles that included healthy living in harmony with nature and functional space. Preserving these principles and

adapting them to contemporary conditions can be considered a challenge that requires an integrated approach and participatory urban heritage management [30].

Of the total number of surveyed users, more than half (65%) stated they would participate in activities aimed at improving this or other green spaces in the city. Additionally, 98.33% believe that there should be more well-maintained green areas in the city.

Based on the analyzed results, it can be concluded that users have a positive attitude towards green spaces, understand their necessity, importance, and significance.

Furthermore, it can be concluded that users' ecological awareness is well-developed and encouraging, although efforts should still be made to raise it further, particularly through education on the use and appreciation of such spaces.

4. CONCLUSION

As a result of unregulated urban development, New Belgrade is characterized by significant changes in the structure and character of space, affecting public goods as well as the residents of the area and the city as a whole.

The conducted research demonstrated that public opinion recognizes the importance of preserving and enhancing the aesthetic values of urban landscapes. The study showed that users frequently visit the park at Bežanijska Kosa, with many citing the observation of the vista toward New Belgrade's urban landscape as their primary motivation for visiting. The potential of New Belgrade's urban landscape is significant but not fully utilized, which impacts the overall landscape image — a fact recognized by the respondents.

Considering users' opinions, the aesthetic characteristics of New Belgrade's urban landscape are generally rated as good or very good, but there is evident room for improvement. Surveyed users recognized the importance and value of integrating greenery into the urban landscape and its positive emotional and psychological impact.

Users' opinions emphasize the need to preserve New Belgrade's identity as an urban unit that meets contemporary needs while respecting the principles that safeguard cultural and natural heritage. Therefore, preserving and enhancing the vista toward the urban landscape of New Belgrade is of exceptional importance, as well as reconstructing the viewpoint in the park at Bežanijska Kosa. Citizen participation in planning and decision-making related to public goods is extremely important, as it is based on the individual's motivation and desire to improve the quality of community life, protect the environment, participate in decisions that will affect users' lives, care for social conditions, and achieve satisfaction with the state of their surroundings.

Collecting data about users, their motivations, and ways of using urban green spaces should be a research priority, as many decisions regarding green space management are based on such data. Implementing the results obtained in this way into decision-making processes would contribute to achieving general user satisfaction with new spaces and vistas.

Moreover, strategies, plans, and individual projects related to the planning, design, and construction of urban spaces should aim for a multidisciplinary and integrated approach that considers existing natural and built elements and their relationships.

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Research paper

IMPORTANCE AND TYPES OF LANDSCAPE EDGING ON URBAN GREEN AREAS

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Abstract

Landscape edging (barriers) play a significant role in increasing the aesthetic value and functionality of entire green areas. They provide a way to solve the transition between two different surfaces, creating border and transitional zones between green areas and the surrounding spatial elements i.e. between structural elements within green areas. Different functional zones of the green space can be separated by using landscape edging and design of the barriers follow the stylistic arrangement of the green area. Barriers contribute to defining the spatial organization and composition of the green area and especially the lawn. The choice of material for the landscape edging affects both the decorative and functional aspects of the landscape design. Barriers made of natural materials or artificial origin influence the aesthetic characteristics of the space, directing the design in a rustic or modern direction. The modern trend towards ecological sustainability implies the use of permeable and semi-permeable materials, gives preference to barriers with joints (semi-permeable) and barriers made of loose material (permeable), as well as the use of natural and recycled materials. Plant material can be used to form barriers, involving different categories of plants. This creates a "softer" transition between the spatial elements. Different taxa of shrubs, flowering plants, ornamental grasses or combinations of these plant categories can be used for this purpose. Landscape edging is also a tool for enhancing the aesthetic, functional and ecological performance of the space. In an effort to create aesthetically appealing and sustainable solutions, the design of barriers emphasizes the importance of combining functionality with aesthetics, contributing to the overall aesthetic experience and ecological value of the entire green space, while reducing maintenance costs. Careful consideration of the materials from which the barriers will be made, their form, and their function enables the creation of stylistically different, visually attractive spaces focused on environmental sustainability.

Key words: *landscape edging, landscape design, urban green areas, plant material*

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1. INTRODUCTION

Defining boundaries within urban green spaces, which divide the area into smaller spaces or into zones of different function i.e. use, is essential. According to Wang et al. (2022) [1], such boundaries significantly influence landscape patterns, mechanisms for landscape change, and dynamic processes. In this context, landscape edging — also referred to as kerbs or edge barriers — can be used. Barriers can have a key role in shaping the landscape, from both an aesthetic and functional aspect. Not only do they help in defining the boundaries of urban green spaces, barriers provide for a better space management and protect greenery from mechanical damage. Properly placed kerbs can contribute to maintaining green spaces by preventing the spread of grass or other types of plants beyond designated zones.

Different functional zones within a green area can be separated using edging, which allows for a clear division of space and improves the overall functionality of the area. For example, edging can be used to separate pathways from lawns, lawns from flowerbeds, trees from shrubs, or other zones (such as recreational areas, children's playgrounds, restaurant gardens, and similar spaces). This delineation supports better use of space and improves user experience. From a design standpoint, edging enhances the overall composition by creating clear lines and contrasts between different surface treatments and vegetation types.

Beyond visual and spatial roles, edging can also have ecological functions. When properly designed and implemented, edging contributes to soil protection, reduces erosion, and can facilitate surface water drainage—an especially relevant aspect in urban environments facing challenges with stormwater management and climate change adaptation.

Despite its importance, the topic of landscape edging is still underrepresented in academic and professional literature. This paper aims to summarize practical knowledge and field experience related to edging in the greening of urban spaces. We emphasize the benefits of landscape edging as well as the multifunctionality of edging for plant protection, spatial organization, maintenance efficiency and investment optimization. We present and analyze different types of landscape edging according to a set of criteria we made through our empirical knowledge offering a deeper insight into it. Additionally, our aim is to put special focus on plant-based edging as a sustainable solution, bringing it closer to the wider scientific public and provide key design considerations as well as guidelines for plant selection. We address the following research questions: (1) Which are the main benefits of landscape edging? (2) What types of edging can be used in green spaces, including advantages and disadvantage of each type? (3) Why give priority to using plant-based edging?

2. METHODOLOGY

This paper is based on the theoretical and qualitative research, which includes collecting secondary data in the field of landscape architecture and horticulture to address the exploratory nature of the research questions. In the field of landscape architecture, not only in Serbia but also further afield, there is a lack of scientific data dealing with landscape edging and this topic is mostly based on practical knowledge and experience. Our focus was to collect, summarize and present available knowledge and experience related to landscape edging and offer it through this paper as an additional tool not only to landscape engineers but also to all interested groups. Different types of edging are analysed according to a set of criteria:

- type of material – it can be part of nature (i.e. a living material - plants), natural or artificial origin
- spatial forms – possibility to make linear or organic form in green ares, as well as edges in horizontal or vertical direction
- width and hight limitations – possibility to create edge with a different width or height in a green space (e.g. visual barriers which can be very high and wide) which depends of the landscape design, function of the edge, characteristics of the material and construction stability; no limitations in width but height limited to ground cover; narrow edges which stand verticaly but height limited to the ground level (typically for edges that serve as root barriers) or up to 25cm (low physical barrier)
- place/space of usage – possibility to be used in large semi-natural or natural landscapes (suburban or rural) with a significant ecological function (like shelterbelts or hedges) or in green areas which were or could be created under the higher human influence (e.g. green urban areas, parks, gardens etc.); type of landscape design (project design follows tendency to create modern or rustic/traditional green space)
- ecological benefits – contribution to the improvement of ecological factors such as increase air quality, noise and wind reductions etc., making healthier living conditions or contribution to the environmental protection.

3. BENEFITS OF LANDSCAPE EDGING

Landscape edging plays an important role in pulling the landscape together. Edging forms a clean line between planting areas and opened turf area or groundcovers, different types of planting areas, planting areas and paved areas etc. is not just about creating a visually appealing border; it serves several practical purposes that contribute to the overall health and longevity of green areas. Benefits of landscape edging can be summarized as:

- improvement of aesthetical quality of green areas (promoting tidy, well-managed space);
- defining spaces in green areas (creating sense of order and organization);
- increase the hygiene on green areas;
- effective addition to the green area and increasing its total value;
- weed prevention (ability to prevent unpleasant plants from encroaching into other designated areas);
- preventing dust, soil and mud to be transfer from the lawn to paved surfaces;
- preventing the penetration and spreading of roots from the lawn to other zones of the green areas;
- keeping soil and mulch in place, preventing erosion;
- cut down the green area maintenance costs;
- cut down the lawn maintenance costs (make some management tasks easier, some of them should be less frequently done or can be skipped).

4. RESULTS AND DISSCUSION

There are various types of landscape edging, each offering unique characteristics and gathering to different aesthetic preferences and functional needs. The general division of landscape edgings can be made according to the nature of materials, so primarily we can distinguish 2 groups: edges in which plants are used or those made of other materials. In the following text different types of landscape edging are presented and analysed taking into account the aforementioned criteria.

4.1. Landscape edging using plants

This type of edging involves the use of various categories of plants to form borders around or within green spaces. Vegetative barriers are an important element in landscape design—they help structure the green space, protect plants, and enable both visual and physical separation between different spatial zones. Beyond their functional and aesthetic value, plant-based barriers also provide significant ecological benefits.

According to Podhajska et al. (2020) [2], vegetative barriers can significantly enhance air quality, while Kafafy (2010) [3] emphasized their function as natural noise isolators. Plants within barriers help filter pollutants such as dust and harmful gases. This is particularly relevant when trees are included in the barrier. As noted by Mohd Noor et al. (2013) [4], a single tree can remove approximately 26 pounds of carbon dioxide annually, equivalent to emissions from 11,000 miles driven by a car. Additionally, green spaces can retain between 0.2 and 2 kg of dust particles per square meter annually, depending on the leaf type—directly contributing to healthier living conditions.

Trees and shrubs used in vegetative barriers serve as natural filters. To achieve rapid effects, fast-growing plant species are preferred. Vegetative edging can also be utilized in urban environments for the reduction of noise pollution. Since the 1970s and 1980s, studies have shown that plants can attenuate noise through reflection, refraction, scattering, and absorption of sound [5]. The degree of noise reduction depends on multiple factors, including the biological characteristics of foliage, plant capacity for sound absorption, as well as the type, spatial arrangement, size, and density of vegetation. These are all critical considerations for designers when planning vegetative edges in urban environments.

Urban vegetation provides both quantitative and qualitative benefits. These include financial returns through ecosystem services and qualitative improvements such as environmental sustainability, social wellbeing, and aesthetic enhancement. As Loh (2008) [6] argues, although these benefits are often discussed separately, they are in fact inseparable and must be valued collectively within the built environment.

Vegetative edges can be designed to create dynamic and appealing spatial forms both horizontally and vertically. Horizontally, they often take the shape of geometric lines, arcs, or spirals. Vertically, vegetative edging can be layered to form small or large visual barriers that serve as protection from wind or unwanted views. If they are used within densely built urban environments vegetation in vertically edges not only helps environment but also provides visual contrast and relief [7].

Shelterbelts are used to reduce wind speed and turbulence, enhancing comfort for both users and plants within the space. This type of plant-based barriers are common for large natural or semi-natural landscapes and it is advisable to use species that grow both vertically and laterally. Depending on the climate and habitat conditions various tree species or shrub

taxa can be used in forming shelterbelt, in a one-line or multi-line application, and a combination of trees and shrubs is preferred. Advantages of using this type of landscape edging include ecological, aesthetic and economic benefits. Ecological adventages include the support of biodiversity and variety of plants, contributing to bird, insect and animal habitats. Additionally, shelterbelts discrease or stop erosion processes which are caused by wind or water thereby having an economic significance. Edging landscape by using these type of barriers makes the planning and management of the landscape easier.

One of the modern trends in landscape architecture and horticulture are living walls, which provide vertical greening solutions with both aesthetic and functional benefits [6]. Living walls, formed in various ways and filled with plants, can serve as effective spatial barriers, offering privacy and enclosure in gardens, backyards, or terraces. Species such as ivy (Hedera helix L.), climbing vines, various shrubs, or bamboo (Bambusa vulgaris Nees) can be used to create a natural screen, offering visual protection while enhancing the ecological value of the space [8] (Figure 1).



Figure 1. Landscape edging using different plant categories (a-herbaceous; b- woody; c- woody-herbaceous; d- green wall)

4.1.1. Selection of plants

Using plants in making barriers creates a "softer" transition between different zones in green spaces. In the process of plants selection the attention should be given to following [9]:

- the intended visual and functional effect of the barrier;
- the overall design of the green space, particularly lawn design;
- the purpose of the entire area and the usage patterns of specific zones as well as the whole space;
- environmental conditions, with an emphasis on climate factors;
- site-specific habitat conditions, including microclimatic factors such as light and shade exposure, wind shelter, air circulation, turbulence, and prevailing wind directions;
- soil type and quality.

Both herbaceous and woody species, including deciduous, coniferous, and evergreen plants, can be used in the construction of vegetative barriers. Various shrub taxa may be planted in groupings or shaped as formal hedges. Shrubs characterized by low height or slow growth are suitable for edging along pathways, while taller, fast-growing shrub species are ideal for forming elegant green hedges.

Aromatic woody species such as rosemary (*Rosmarinus officinalis* Linnaeus) and lavender (*Lavandula officinalis* Chaix ex Vill.) are particularly valued for their low maintenance and versatility in various design combinations. Among tree species, ornamental cultivars are

commonly used due to the wide range of decorative foliage and floral characteristics. Tree-based barriers may be formed through individual planting, planting in small groups, or through protective belts. In the category of conifers, species from the Thuja and Cupressus genera are most frequently used due to their dense and structured growth.

Among herbaceous species, a wide array of taxa is used for forming flower beds or ornamental grasses of various heights, typically planted in groupings or linear formations, depending on the size of the surface area. Particularly striking ornamental grasses include: pampas grass (*Cortaderia selloana* (Schult. & Schult.f.) Asch. & Graebn.), blue fescue (*Festuca glauca* L.), golden grass (*Hakonechloa macra* (Makino) Honda), fountain grass (*Pennisetum alopecuroides* ((L.) Spreng), chinese silver grass (*Miscanthus sinensis* Andersson) [9].

Culinary and medicinal herbs are increasingly being applied in landscape architecture [10], and they also have a role in the formation of vegetative barriers in urban green areas. Numerous species can be used, including: *Ocimum basilicum* L. (basil), *Laurus nobilis* L. (bay laurel), *Anethum graveolens* L. (dill), *Petroselinum crispum* var. neapolitanum and *Petroselinum sativum* Hoffm. (parsley), *Thymus vulgaris* L. (thyme), *Allium schoenoprasum* L. (chives), *Mentha piperita* L. (peppermint), and many others.

The inclusion of medicinal plants in barriers contributes to the aesthetic, sanitary, health-related, and nutritional functions of green spaces.

Perennials and rose gardens also have a place in the formation of vegetative barriers. Compared to herbaceous plants, they offer greater longevity, although their maintenance requirements differ.

Although plant-based edges are suitable for various places and every type of design certain limitations in the usage of plants in edging exist and are connected to width and height they can achive. Actually, plants' maximal height is connected to the biology of each species but can vary due to habitat condition, and often, especially in urban areas, it is significantly shorter than in natural or semi-natural landscapes. Plants need time for growing so the maximal effects of the greening and edging, especially using trees and shrubs, are often visible after 10 or more years. Thus, limitations which are common for using woody taxa can be avoided: (1) by using mature individuals of trees which can make the cost significantly higher, (2) woody taxa with initially lower height according to their biology, that is, cultivars of some trees whose heights are usually, at the moment of installation, close enough to their max biological height. Third solution is based on the usage of herbaceous species or perennals which achive the effect of immediately finished green area; however, there are some limitations in height and width. Actually, most of them, have maximal height of 25cm and even if they are used only in one line, for their optimum growth, require that the edge width must be 30-50 cm.

In contemporary discussions surrounding sustainability, diversity, and biodiversity, plant-based barriers are recognized for their broader ecological value. They provide habitat and food sources for birds, insects, and other organisms - especially when shrubs dominate the planting composition.

Using plants as a living material, with their specific morphological, structural, and textural properties, as well as dynamic variability over time, enables the creation of a wide range of spatial and visual options - many of which are not achievable through the use of conventional construction materials.

4.2. Landscape edging using other materials

Further division of this category of landscape edging can be related to the nature of materials so we can distinquish: edging using natural materials or edging using artificial materials. Divison of those two groups are present in the following text.

4.2.1. Natural materials

When constructed from natural materials, landscape barriers provide a rustic, ecologically sustainable appearance that blends harmoniously with the environment. The most commonly used natural materials include natural stone, wood, brick, mulch, sawdust, or bamboo stems/stalks. Natural materials in landscape edges don't bring high ecological benefits as usage of plants, but certain low benefits in the context of enviromental protection exist, as a better choice for the environment compared to the usage of artificial materials.

Stone is one of the most durable and resistant materials for constructing barriers in green spaces. It is typically used to edge paths, plazas, or to delineate boundaries between different planting zones. Stone barriers often separate two distinct vegetation types (for example, an open lawn from a flowerbed, or a lawn from a grouping of woody plants). When it is necessary to prevent surface encroachment by inert materials, stone proves to be a suitable solution. Both natural and processed stone are used, offering a long-lasting and rustic look. Stone is suitable for creating linear or organic forms as well as horizontal or vertical. When using stone barriers, there are no strict width or height limitations and it depends on the landscape design. This material can be used in various type of outdoor spaces and its usage alway is realted to traditional design tendencies. The most commonly used type is river pebbles, which are laid directly on the soil surface [9]. Stones may be laid lengthwise or crosswise, depending on the intended function and aesthetics of the barrier (Figure 2a). Low stone walls of varying height and width—either single-layered or multi-layered—are also used. The complexity of constructing stone walls depends on the stone dimensions, the purpose of the barrier, and the required foundation preparation, labor, and financial investment. Stone landscape edging can be used in large landscapes, as well as in the form of gabions. Gabions are mostly used in large semi-natural or natural landscapes with a primarily anti-erosion function, then aesthetic and low ecological function (as a material of a natural origin).

Wooden edging is popular for its natural appearance and versatility in shape, height, size, thickness, and color. Its use is common for urban green areas like parks, gardens, or other elements of green infrastructure connected to the higher human impact. Treated or impregnated wood is typically used due to its greater resistance to moisture and environmental factors. However, the use of treated wood may have negative effects on nearby insects and plant material. Wood can be used in the form of posts, planks, or logs, especially for rustic-style landscapes. If landscape project has the tendency to follow modern design, wood can be also suitable. In moden design projects wood elements used for edging are different in their form, appearance, shape and impregnated wood is always used. Limitations in width and height are related to the stability of the construction and landscape design. Wood is suitable for creating linear or organic form but certain limitations exist. In more complex landscape designs—especially those requiring curved lines, frequent directional changes, or sharp angles — wood may not be the optimal material choice for constructing barriers (Figure 2b).

Brick can be applied in various landscape architectural styles always with tendency to rustic design. It adds elegance and warmth, while in classical layouts, it can evoke a more

rural aesthetic. Brick edging is generally more stable and longer-lasting than wooden alternatives. When laid directly into the soil, bricks form surface-level barriers that can be easily moved or removed. Used that way, brick is suitable for creating not only linear but also organic forms of edge. Brick can be use in a forms of small walls where the vertical dimension of the edge is added. For improved stability, especially along paths or paved areas, a base foundation is often prepared prior to installation (Figure 2c). Brick doesn't have a usage in large landscape for creating edging. Ecological benefits are low and are limited to be safe for the environment compared to artificial material.

Mulch is a natural material made by shredding tree bark, typically from pine trees (*Pinus* sp.), and is laid directly onto prepared soil at the height of 3-5 cm. It is suitable for creating different horizontal forms with tendancy to make traditional design. Different linear or organic forms can be applied relatively easy with no limitations in width but height is limited to ground cover. Its use significantly enhances the aesthetic qualities of green spaces. Mulch is available in various granulations and colors, depending on the intended use and maintenance strategy, such as replenishment or replacement. It is resistant to wear and serves as an excellent drainage layer. Mulch can be applied to both large and small surfaces in various types of green areas but it doesn't have a purpose in natural or semi-natural landscapes. Its ecological benefits are medium and are connected to the benefits of plants and ground not directly to the improvement of ecological factors. The benefits include: preventing the spread of weeds between zones, retaining soil moisture, and moderating microclimatic extremes in the soil and near-surface layer—areas that are crucial for plant growth. Its use reduces both maintenance operations and costs associated with greenery management (Figure 2d).

Bamboo stalks are less commonly used than stone or brick, but they can serve as eco-friendly, lightweight barriers that preserve the natural character of the landscape. Tall bamboo stalks can be used as screens or dividers, providing both visual and physical separation between functional zones (for instance, seating or retreat areas from the rest of the space, or walking paths from other site features, including artistic or exhibition installations) (Figure 2e). They are suitable for creating linear or organic forms, both horizontal and vertical. Hights are limited to the bilogy of the species, availoability at the market and landscape design. Disadvantages are connected to the stability of the barriers, transparency or frequency of the replacement of stalks due to their decomposition. Compered to other natural elements, bamboo stalks are significaly less lasting with a high price of use. Mosty they are used in projects with tendency to follow modern design and better performace especially in the way of creating visual barriers can be achived by using multi-line application. Although bamboo is a apart of nature, its usage in landscape edging in a form of stalks leads to low ecological impact, the same like using of stone, brick or wood. In some cases live plants of bamboo can be used, when the ecological benefits are high but it demands specific climate and habitat conditions.

Gravel (pebble mix) is also less commomly used compared to stone or brick, probably because of the lack of a vertical form. It is often applied to differentiate zones with distinct planting schemes or as a supplementary material in green spaces, typically laid in front of plantings. Like mulch, gravel can be used to cover bare soil beneath trees and shrubs. Its texture and diameter variety offer an easy creation of various linear or organic forms but always horizontal with no limitations in width. Gravel can be used not only in traditional design projects but also in a modern ones. Its application can have both positive and negative effects

on plants, and it is widely used in landscape beds as a low-maintenance groundcover. In such cases, it is recommended that landscape bed edges be constructed from other materials, often artificial (e.g., rubber, plastic, metal, etc.) (Figure 2f). Due to the lack of a third dimension (height) it doesn't have an application in large landscapes.

All of these materials not only enable efficient spatial functionality but also contribute to urban ecological sustainability. Plant-based and natural barriers can prevent erosion, stabilize soil, and facilitate surface water drainage, supporting stormwater management. Furthermore, their application significantly reduces the need for intensive maintenance, thereby lowering the financial resources required for the upkeep of urban greenery.



Figure 2. Natural materials (a- stone edge; b- wooden edge; c-brick edge; d-mulch edge, e-bamboo stalks edge, f-gravel edge)

4.2.2. Artificial materials

Artificial materials used for edging green spaces can enhance the aesthetics, functionality, and maintenance efficiency of urban greenery. The most commonly used artificial materials include plastic, concrete, metal, rubber, composite materials, and geotextiles. What is common for all of them is the absence of ecological benefits not even at a minimal level for the environment, plants or ground and they do not have a usage in large landscapes, natural or semi-natural.

Plastic edging is lightweight, durable, and easy to install. It typically comes in the form of a flexible roll, bundle or section with a different height and length suitable for placement along the edges of lawns, flowerbeds, or other zones within green spaces. Using plastic elements for edging can lead to limitations in landscape design. Actually, creating edges made of plastic elements with the specific organic forms is more demanding, especially high precise or complex project design which might be impossible due to the lack the variety of elements in terms of length, height or curviture that exist at the market. So the designs are limited to the possibility of fitting the elements available at the market and often changes to previous landscape designs have to be made or a decision needs to be made about picking another type of edging. Plastic edging enable forming only a very narrow edge with the function of separating two zones in the green areas. With a ground level height or above ground, up to 25 cm, plastic edges cannot be used as a visual barrier but can be used as a physical barrier of low impact (to prevent children or small animals to use some zone). Its usage is also related to preventing plant roots from growing from one zone to another. Plastic edges are not recommended to be used in projects with the tendency in rustic design. It is frequently used

in small-scale applications where flexibility and easy of handling are prioritized (Figure 3a). Compared to other artificial materials plastic edges are used most often due to their availability at the market, low price and costs of installation, as well as an easy installation process.

Concrete barriers are more durable and stable than plastic, making them suitable for creating clear and long-lasting boundaries. Edges made of concrete are suitable for making both, linear and organic forms as well as horizontal or vertical one. The limitation in forms, width or height depend on the stability of the construction and landscape design. They are commonly used for edging larger green spaces such as gardens, parks, or courtyards with the tendency to follow modern design. Concrete elements may be cast on-site or prefabricated, and can also be customized in color or pattern using stamped concrete techniques (Figure 3b). Concrete barriers are expensive and sometimes followed by demanding and long-lasting building works but, on the other hands they offer a high variety of possibilites in landscape design.

Metal edging gives a space a modern and clean appearance and is often used for precise line definition in landscape design. These edges are usually made of steel or aluminum, often treated to resist corrosion. Metal edging can be bent into various shapes (mostly linear but can be suitable for organic too) and provides a neat and professional finish to green spaces (Figure 3c). Metal edges are with a ground level height or above ground, up to only 8 cm, and cannot be used as visual or physical barrier to prevent small animals from using a part of green areas. Their main function is to be root barriers, an effective tool in minimizing structural damage from offending roots. Comparing metal edges to plastic edges or other artificial or natural materials, metal edging is more expensive but brings higher aestetic characteristics to green areas and has a long-lasting effect.

Rubber edging is flexible and a more environmentally friendly compare to other artificial materials, particularly when made from recycled materials. It is ideal for edging smaller areas or as a weed barrier, as it helps retain mulch or soil more effectively than harder materials (Figure 3d). Rubber edges are at the second place of usage among edges made of artificial materials due to their availability at the market, price and easy installing at the green area. However it should not be used in traditional landscape design as well as in large natural or semi-natural landscapes. Rubber and plastic edging have similar characteristics related to their usage but perhaps the important difference is in maximal height above the ground. Actually, rubber edges are present at the market with a maximal height of 15cm above the ground and, at the moment, there is significantly less variety at the market compare to plastic elements.

Composite edging combines plastic and wood fibers, offering both durability and sustainability. Composite materials often resemble wood visually but offer a longer lifespan and are resistant to rotting, making them a practical and ecological choice for various landscape designs (Figure 3e). It can be used as narrow borders with a function of root barrier or low physical barrier, in project with tendency to have modern design, with various spatial pattern (linear, organic, mostly horizontal or vertical up to 15cm high). Whenever one has to make a choice between using plastic, rubber or composite edging, the lead should be given to the composite edges. Although the price of these edges at the market is higher compared to those of plastic or rubber due to the production process, they enable the creation of clear, strong enough and nice low edges.

Geotextile mesh is primarily used to prevent weed spread across green spaces, but it can also serve as a subsurface edging solution. These barriers are not visible from the surface, as they are intended for underground soil stabilization and shaping. A major advantage of geotextile use—especially in combination with plant materials—is its water permeability in both directions, which helps maintain soil moisture balance. A subcategory of geotextiles includes herbicidal fabrics, which are also permeable to water. These contain slow-release herbicides, designed to inhibit root growth in targeted zones. According to manufacturer specifications, their herbicidal effect can last up to 10 years, eliminating the need for lawn edge trimming or weeding (Figure 3f). Geotextile meshes are suitable for every type of design but it should be known that creating proper form (linear or organic) demands some skills due to the fact that this material lays under the ground and it is not visible from the surface. If some stronger, clearer and stiffer edge is needed, a better choice is using some other type of barrier.



Figure 3. Artificial materials (a- plastic edge; b- concrete edge; c-metal edge; d-rubber edge, e- composite edge, f- geotextile)

Barriers made of artificial materials excluding concrete have a significant usage to prevent tree roots near sidewalks to penetrate pavement cracks, causing further damage or lifting of the pavement. The cost of this damage exceeds $100 million annually in the United States [11]. Vertical root barriers have proven effective in redirecting root growth to deeper soil layers, thus reducing damage to infrastructure [12, 13, 14]. However, it is important to emphasize that the use of artificial materials for forming edging can have adverse effects on plant material in the immediate area. These effects are due to the creation of specific microenvironmental conditions in the soil zone just below ground level, where the root system develops, and in the air layer just above the ground, where stems or rosettes of herbaceous species grow. Artificial materials can cause greater temperature fluctuations in these zones—higher heating in summer and cooler conditions in winter—which can indirectly harm the plants, initially affecting the roots and later other plant parts.

In this way, artificial edging materials may act similarly to urban heat islands, concentrating thermal stress on vegetation. Over time, this often results in plant dieback along the edges, which can then spread inward toward the center of the planted area. This phenomenon is particularly evident when lawns are edged using artificial materials.

A potential solution lies in combining plant material with natural materials in the construction of green space barriers. This hybrid approach can mitigate thermal stress and preserve ecological balance while maintaining structural definition in the landscape.

6. CONCLUSION

Barriers in green spaces are not merely structural elements but represent a tool for enhancing the aesthetic, functional, and ecological performance of the landscape. Careful consideration of the materials used for constructing these barriers, along with a clear definition of their form and function, allows the creation of stylistically diverse, visually appealing spaces focused on ecological sustainability.

Although each of the materials discussed has its own advantages depending on the specific needs and aesthetic preferences of users, plant-based barriers offer distinct advantages. Using plants in barrier construction creates a “softer” transition between different zones within green spaces and provides visual and psychological relief from the densely built urban environment. Plants can be used in landscape edging of every type of green area, from large natural or semi-natural landscapes to very small green spaces (urban pocket or business parks). Using plants in landscape edging enables the creation of a wide range of spatial and visual options - many of which are not achievable through the use of conventional construction materials. Careful plant selection can be crutial not only in forming desired edges and maximazing the benefits that plants bring, but also might significantly optimize the further maintenance of the entire green area. Certain disadvantage can be found in time needed to achieve maximal effects of the green edges. The formation of plant-based barriers requires the involvement of experts in landscape architecture and horticulture, who possess the necessary knowledge and skills for selecting and managing plant material, ensuring the durability and longevity of the barriers as well as the green space as a whole.

Landscape edging using natural materials leads to rustic, ecologically sustainable appearance that blends harmoniously with the environment. An exception is the usage of bamboo stalks which are connected to the projects with modern tendencies. All edges made of natural material are suitable for creating various forms, organic or linear, while some (mulch or gravel) have a limitation in the creation vertical forms and are limited to ground cover. However, the usage of mulch or gravel has no limitations in border width.

On the other hand, barriers made from artificial materials (except concrete) are generally less demanding to construct and maintain, but in the long term, they may have adverse effects on surrounding plant material. They are known to be without ecological benefits, do not have usage in natural or semi-natural landscapes and are connected to the projects with modern tendencies. Exclusing concrete, all other artificial material in landscape edging do not have usage in creating visual borders, particularly they enable the formation of very narrow edges with the only functions as separations of two zones in the green areas or as root barrier.

Careful consideration of the landscape edging enables the creation of stylistically different, visually attractive spaces focused on environmental sustainability and higer value of the entire green space.

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Review paper

THE GREENING OF URBAN RUINS - AN EFEECTIVE WAY FOR MULTIFUNCTIONAL REVITALIZATION OF ABANDONED URBAN SPACES

Marija Pešikan[1], Jovana Petrović[2], Nadežda Stojanović[3], Mirjana Tešić[4], Nenad Stavretović[5], Aleksandar Lisica[6]

Abstract

Greening urban ruins represents an innovative approach to the revitalization of abandoned built structures. This process merges greenery with ruins or abandoned structures, creating synergy between natural and built elements of the space. The goal of greening ruins is not only ecological but also aesthetic, as it transforms neglected buildings into green "oases" that promote biodiversity and improve microclimatic conditions in urban environments. As a part of urban green infrastructure revitalized ruins can become an effective way in adaptation cities to climate changes, especially in the terms of rainwater regulation and minimize urban heat island. Revitalization contributes to social cohesion, creating spaces that can become gathering places for various community activities. Case studies at both European and global levels provide examples of good practices that offer insights into the benefits and challenges of revitalizing abandoned structures.This paper explores the potential for revitalizing ruins through the application of plant materials, emphasizing the benefits greenery can contribute to the renewal of abandoned urban spaces, as well as analyzing various greening possibilities, including the use of different techniques such as vertical greening systems, rooftop gardens, green walls, and interior greening of buildings. Greening ruins also contributes to preserving cultural identity, through the appropriate use of plant materials, to become integral parts of contemporary urban ecosystems. The potential for revitalization depends on the structural stability of the buildings, the maintenance and care requirements for green areas, potential legal issues, and financial considerations, which highlight the need for careful planning and implementation. Further research in this area can contribute to the understanding and making practices and specific solutions for the future revitalization of urban spaces through greening.

Key words: *urban ruins, greening, abandoned urban spaces*

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1. INTRODUCTION

Intensive urbanization and demographic changes have led to the expansion of urban areas and the construction of a large number of buildings, which negatively affect existing urban green spaces. The negative impact most often results in the reduction in size and fragmentation of urban green spaces, particularly evident in central urban zones. The degradation and fragmentation of green spaces lead to the disruption of biodiversity, the loss of habitats for many plant and animal species, and the endangerment of the entire ecosystem [1]. On the other hand, urban green spaces appear to be a crucial asset that could help cities sustainably mitigate the adverse effects of rapid urbanization and urban sprawl [2]. They play a vital role in cities by reducing urban heat, decreasing air pollution, and providing significant environmental, social, and economic benefits. Unfortunately, especially in compact cities, green spaces are often undervalued in the planning and development process [3] and are seen as obstacles to development [2]. Therefore, even a minimal increase in urban green spaces is important today and often follows modern greening trends such as the construction of multifunctional small green spaces, the use of vertical greening techniques, rooftop gardens, and the revitalization of ruins and abandoned urban buildings.

Urban ruins are the result of past human activity in the urban landscape and usually refer to abandoned buildings and sites, such as remnants of wars, abandoned hospitals, unfinished buildings, disused factories, and shopping centers [4]. An urban ruin is considered an unusable, non-functional human creation when viewed in the context of functional buildings designed for a specific purpose [5]. Ruins can be previously constructed buildings that were poorly maintained or completely neglected and abandoned, and which hold value as part of culture and heritage. Additionally, ruins include buildings whose construction was never completed due to various circumstances [6].

Numerous studies show that increasing attention is being paid to abandoned urban ruins due to their diverse impacts, the emergence of relevant policies, and the real challenges cities face. People are increasingly aware of the need to reuse urban ruins, and their large-scale rehabilitation is becoming an essential component of urban resource recovery, economic development, and the promotion of sustainable urban growth [4].

The greening of abandoned city spaces, especially urban ruins are still not recognized enough and promoted in Serbia. Thus, this paper aims to emphasize the benefits of greening urban ruins and various greening methods, including vertical greening systems, rooftop gardens, green walls, indoor and outdoor greening of buildings. We present and analyze some examples of successful revitalization and reuse of urban ruins that preserve the cultural identity of buildings and places, offering an important response to the contemporary needs of the urban environment. We address the following research questions: (1) Which are the main benefits of greening urban ruins? (2) What kind of techniques can be used in context of urban ruins revitalization? (3) Can greening of urban ruins contribute to the cultural identity preservation of the structures or urban ecosystem development, and to what extent?

2. METHODOLOGY

This paper is based on the theoretical and qualitative research, which includes collecting secondary data in the fields of landscape architecture, urban ecology and reconstruction and revitalization of abandoned buildings, in order to address the exploratory nature of the research questions. The secondary data includes relevant scientific papers and project data related to abandoned urban areas. As we emphasize, there is a lack of scientific and project-based data on urban ruins in Serbia. Therefore, our focus shifted to examples from other countries across Europe and beyond. However, a general lack of information persists globally, as the revitalization of ruins—considered a form of abandoned space—has only recently begun to emerge as a recognized approach. We aimed to identify and select examples of best practices that offer insights into the benefits and challenges of revitalizing abandoned structures. The selection of examples was based on the following criteria:

- Context and location - basic information about the location of the ruined object, the urban environment and the previous function of the built structure.
- Applied greening techniques – roof gardens, green walls, interior greening of buildings etc. and type of plant materials.
- Ecological effects - contribution to biodiversity, regulation of microclimate, stormwater management and reduction of the urban heat island effect.
- Aesthetic and ambient contribution - visual transformation of the space and visitors' experience.
- Social and cultural significance – multifunctional reuse of the space, social cohesion and cultural identity preservation.

Through discussing presented study cases we tried to highlight some guidelines including context of the location, applied greening techniques, outcomes, and observed challenges. At the end we made conclusions that can contribute to better understanding and implementation of practices as well as provided specific solutions for further research and future revitalization of urban spaces through greening.

3. ADVANTAGES OF GREENING URBAN RUINS

Major industrial cities in the United States and Europe have experienced a syndrome of abandoned urban spaces and buildings over the past 50 years, due to the decline of underlying industries [7,8]. Urban redevelopment often failed due to the inability to meet the increasing demands for both economic development and environmental improvement [9]. Trancik (1986) [10] recognized the importance of urban ruins and proposed the Lost Space Theory as a framework for understanding land and buildings left unused and unstructured in the context of urban regeneration and decline [11,12].

The negative effects of urban ruins are mainly as follows:

- high population density and low land consumption per capita make urban ruins destructive to the local tax base and wasteful of scarce land resources;
- negative impact on the overall image of the city;
- severe environmental degradation, which poses health risks and reduces the general well-being and happiness index of residents; and
- threats to public safety and an additional economic burden [13,4].

The deterioration and degradation of materials used to construct these buildings also occur naturally due to various causes (e.g., wear and chemical interactions), especially under the influence of climate change (notably temperature fluctuations). However, abandonment and lack of maintenance significantly accelerate this process.

Among the most commonly used methods of reclaiming abandoned urban spaces is their conversion into multifunctional green areas [14]. The benefits of greening abandoned spaces are numerous, with major positive effects on the building, the environment, and the people—all at once. These benefits depend on the types of plants used and the surface area they occupy.

Recognized environmental benefits include: air purification and improved air quality, retention of airborne particulates, dust, and pollutants, reduction in vertical air flow, moderation of the urban heat island effect, creation of microclimates, rainwater and stormwater retention, and the formation of new urban ecosystems.

Building-related benefits include: improved thermal performance leading to greater energy efficiency, sound insulation and noise reduction, extended roof lifespan, cost savings for commercial property owners, creation of new jobs, and opportunities for urban food production.

Sociological and psychological benefits for residents are also highly significant. Numerous cases demonstrate how transforming abandoned urban spaces into vibrant public areas positively impacts daily life and quality of life [14,15,16,17].

Several empirical studies have examined the positive mental health effects of converting abandoned spaces into green spaces [18,19], revealing reductions in residents' stress levels and increases in physical activity [20].

Hollander (2010) [21] proposed the following benefits of urban regeneration of ruins: improved physical infrastructure, enhanced community safety, better public facilities, increased walkability, and a restored sense of community. This conceptual framework shows that enhanced urban spaces can directly and indirectly improve residents' wellbeing—physically, mentally, and socially.

4. TECHNIQUES AND METHODS FOR GREENING URBAN RUINS

The restoration of ruined buildings most often aims to preserve their cultural and historical identity, leaving the stylistic and temporal characteristics from the period in which the structure was originally built intact. Additionally, many examples of building restoration show frequent changes in the land use of the site, and repurposing of revitalized ruins is almost always involved.

Contemporary greening trends for abandoned spaces and urban ruins involve the application of various techniques and methods that serve as an important strategic response to sustainable urban development and climate change. In addition to greening the structure itself through appropriate techniques (green facades, green walls, green roofs), revitalization also includes the greening of the building’s immediate surroundings, which acts as a mechanism for increasing urban green spaces (Figure 1).

Vertical greening (green facades, green walls, green roofs) is an essential method used in the revitalization of ruins. It consists of systems in which vegetation grows vertically upward or along wall and roof surfaces, with plant growth and development occurring in limited space [22].

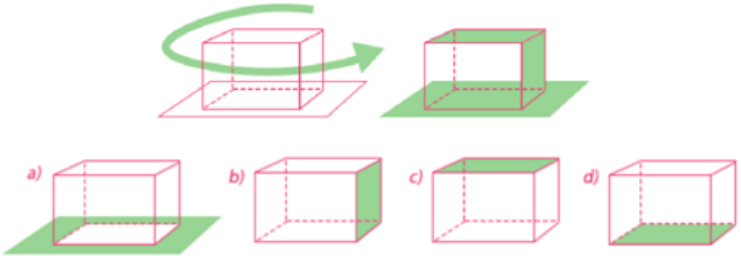


Figure 1: Possibilities for greening urban ruins (a) greening of the surrounding space, (b) wall greening, (c) roof greening, (d) interior greening of the building, Source: authors

Greening the vertical surfaces of buildings involves the use of various categories of plant material and different plant taxa, along with accompanying structural solutions. There are several ways to classify vertical greening systems, but they can essentially be divided into two basic categories: green facades and green walls. Green facades involve the use of climbing plants that gradually cover the wall surface as they grow. Green facades can be: direct, where the vegetation is attached directly to the wall, or indirect, where plants climb along structural support elements.

Green walls, on the other hand, involve more complex structural components that allow for a uniform appearance of greenery, with various plant taxa used in the design. Green walls are further classified into: continuous green walls, which consist of lightweight and permeable panels that allow for individual plantings, and modular green walls, which contain substrate and containers in which plants grow on a vertically constructed surface [23]. Although aesthetic value is often the initial requirement set by investors when selecting plant species for vertical greening systems, priority should be given to the water requirements of the plants. Succulent plants are a good choice due to their drought resistance, though their small height makes them more suitable for small spaces. Agricultural crops and aromatic plants are also commonly used in vertical greening systems, especially in green walls [24,25].

Using green roofs as a greening technique involves creating a limited green space on top of a man-made structure [26]. Green roofs can be classified as extensive or intensive, according to their purpose and characteristics. There is also a semi-intensive category, which represents a combination of the previous two types, where no more than 25% of the surface should be an extensive garden [27]. An extensive green roof has a thin substrate layer with a shallow vegetation layer, typically consisting of succulents, mosses, grass, or a combination of these. Intensive green roofs have a thicker substrate layer that allows better root development and typically supports the growth of woody plant species (trees and shrubs). Maintenance of intensive green roofs is both important and necessary, requiring the implementation of various and often complex measures and operations, carried out according to a defined plan and schedule (Figure 2).

Vertical greening systems on buildings are not part of natural urban ecosystems; they are anthropogenic in nature and purposefully designed to suit the specific type of building on which they are implemented. The clear spatial boundaries of these green surfaces are a key feature that distinguishes them from other urban ecosystems [28]. Buildings where these greening techniques are applied gain additional functions—besides ecological—such as social and aesthetic roles.

It is important to underline that using vertical greenery or roof greening cannot replace the complexity and species diversity of the habitat established on the ground. But certain benefits compared to the "ground-level" ecosystem exist and are as follows [29]:

- they are undisturbed,
- they have no predators,
- they create the conditions for the desired type of vegetation and the animal type whose population is stimulated.

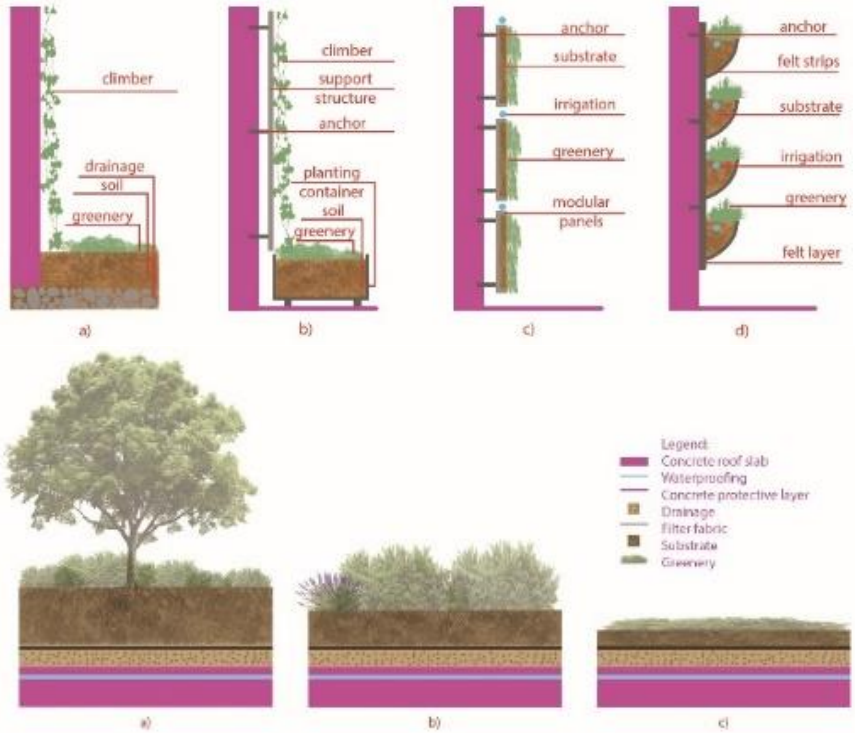


Figure 2: Schematic representation of the categorization of vertical greening systems, green walls, and green roofs (a – direct green facade; b – indirect green facade; c – modular green wall; d – continuous green wall; (a – intensive; b – semi-intensive; c – extensive green roof) [30]

The interior space of a ruin can also be greened. Vertical surfaces within the building (such as load-bearing walls, partition walls, panels, various shelves, etc.), the floor surface, and even the ceiling can become segments of the structure that can be greened using a wide range of techniques and methods. The application of a specific greening technique depends on the building's structure, the investor’s preferences, and the available budget.

The application of different methods and techniques for greening ruined structures can be analyzed in the context of large abandoned complexes (e.g. industrial complexes) or individual buildings and urban quarters. In both cases, the ruined space is almost always distinguished either as a separate point in space with a specific identity or as an independent point, categorized as part of micro-greening initiatives. At the European and global levels, there are notable examples of good practice that illustrate diverse approaches to the revitalization of abandoned urban spaces. Through the application of appropriate greening methods and techniques, these projects have led to the integration of cultural heritage within the framework of the ecological and social needs of contemporary cities.

5. SELECTED EXAMPLES OF MULTIFUNCTIONAL REVITALIZATION OF URBAN RUINS

Among the examples of successful revitalization of abandoned industrial complexes in Europe, one standout project is the former weapons manufacturing and testing facility in Zurich, Switzerland – Maschinenfabrik Oerlikon (MFO), which has been transformed into a public urban space that has significantly enhanced the quality of life for the city's residents. The structure, which symbolizes the former industrial building, is located in the city center and has been greened using vertical greening systems—indirect green facades applied to three double-walled exterior sides of the building. Those double-walled structures of the building were covered with wire mesh where numerous climbing plants were planted. The project includes more than 100 different plant species, mostly ornamental cultivars of climbing plants, such as species from genera Wisteria Nutt., Clematis L. and Parthenocissus Planch. as a key landscape architecture element. The climbing plants are in the direct contact with the ground or, on the upper stairs, they are in the containers fulfilled with substrate of adequate depth. Towards the rear of this spacious hall structure, four wire chalices were placed also with the climbing plants. Shrubs in a form of hedges were used as a technique to direct the visitors and by spreading outside of the building they made a connection between inner and outer side of the building. Social cohesion is encouraged by the following:

- a central spot around an embedded pool of water designed for sitting and enjoying,
- numerus staircases, walkways and cantilevered loggias emerging in the spaces between the double walls,
- a deck on the roof for sunbathing and providing a panoramic vista of the surrounding area and
- the large hall which can be used for a variety of purposes.

The fourth facade is characterized by an open concept, offering a visual connection to the outer section of the building. The building does not have a closed roof; instead, it features a steel grid structure serving two functions: to provide sufficient light, humidity, and ventilation for the plant material located inside the structure, and to act as a supporting framework for the further growth of vegetation, allowing the plants—once they overgrow the side facades - to continue spreading over the fifth facade (roof). The installation of open-frame staircases leading to seating platforms and balconies encourages exploration of the interior from different height levels, introducing additional spatial dynamics to the use of the space (Figure 3a).

The revitalization of urban ruins in Prado Park in Medellín, Colombia (South America) is a representative example of how an old, neglected element of grey infrastructure can be successfully integrated into park design (Figure 3b). It is located in a dense area close to the city center on a sloping parcel. The challenge of height difference of almost 7 meters was overcome using terraces like a technique of landscape design. The applied concept is based on the principles of preserving the existing structure in order to maintain traditional construction practices and the identity of the building, as well as to save materials and reduce construction waste [31]. Only facades of the urban ruin were kept and greening was done using indirect green facade as a technique whereas plants are in the direct contact with the ground. New steel structures were added to support climbers such as blue

skyflowers (*Thunbergia grandiflora* Roxb.) which are gradually taking over the ruin. It is important to underline that the landscape design included the preservation of existing greenery along with the planting of new native plant species. The main advantage of the revitalization of urban ruins in Prado Park is greening of the surrounding space and its transformation in a multifunctional urban green space. All plant categories are used in landscape design with the intension to repair and enhance an urban ecosystem: ornamental grasses such as middle-size fountain grasses (*Pennisetum setaceum* (Forssk.) Chiov.) and taros (*Colocasia esculenta* (L.) Schott) enclose smaller spaces, while trumpet trees (*Handroanthus chrysanthus* (Jacq.) S.O. Grose) and kapok trees (*Pseudobombax septenatum* (Jacq.) Dugand) provide shade in open areas. Ground cover such as pinto peanuts (*Arachis pintoi* Krapov. & W.C. Greg.) as well as different types of shrubs are used to attract insects and birds. Maintenance savings were achieved through the implementation of an efficient stormwater management system, which is used for irrigating the vegetation [31].

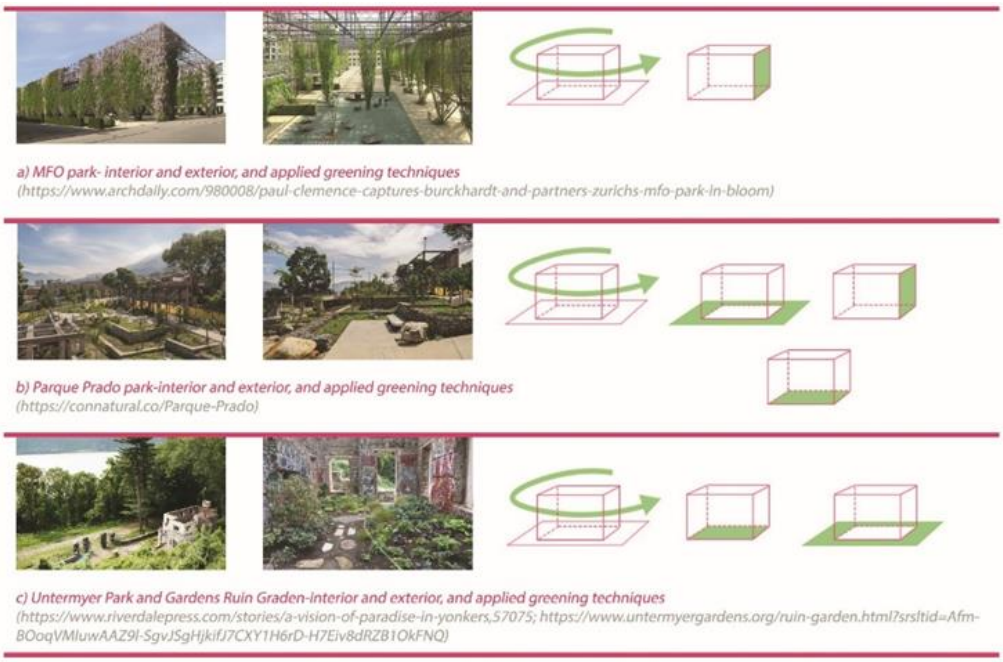


Figure 3: Case studies of urban ruin greening and applied greening techniques

Within the public urban park Untermyer Park and Gardens in Yonkers (New York, USA) lies the Ruin Garden (Figure 3c). The old, ruined Gate House, located at the park's entrance, has been reconstructed and repurposed. The building was restored while preserving its original characteristics, including the graffiti on the walls and the aesthetic of decay. The landscape design included greening of the building's interior and its immediate surroundings. The interior of the ruin lacks a roof and floor slabs, allowing plants to grow under natural sunlight and moisture conditions, covering the entire ground floor of the structure. The greening was achieved using foliage- and flower-decorative plant species, herbaceous and shrubs, including: *Pulmolaria* 'Raspberry Splash', *Helleborus* x *ballardiae* cultivars, *Tiarella* 'Candy Striper', *Heuchera villosa* 'Black Pearl', *Geranium maculatum* 'Espresso', *Hydrangea anomala* subsp. petiolaris 'Miranda', *Polystichum luctuosum*

(Kunze) T. Moore, *Polygonatum odoratum* 'Variegatum', among others [32, 33]. Vertical greenery is presented in a form of direct green fasades which extend along inner walls. Climbers are in the direct contact with the ground and their growth and extension along the wall are spontaneous (without supporting construction). The landscape design of the space around the ruin follows the aesthetics of the interior that evoke a feeling of being in a ruined and abandoned place. The revitalized ruin is created as a place that encourages more private activities and a closer connection with plants and history. The revitalization of this ruin serves as an example of how neglected spaces can be transformed into attractive spot, which in turn support local economic development and attract curious visitors of Untermyer Park and Gardens and wider.

Table1. Overview of significant characteristics of selected examples of greening urban ruins

Urban ruins	MFO Park	Prado Park	Ruin Garden
Location	City center	City center	In the suburb
Applied greening techniques	Indirect green facades; Surrounding greening Plant hedges	Surrounding greening; Interior greening; Indirect green facades Direct green fasades	Surrounding greening; Interior greening; Direct green fasades Sponatenous greening
Used plant category	Climbings; shrubs	Woody species (trees and shrubs); Herbicious species; Climbers; Ground covers	Herbicious species; Climbers
Facilities	Exist, added and made of new materials	Exist, added and made of recycled materials	Inheritable and made of stone
Part of larger complex	No	Part of an urban park	Part of a historical complex
Publicity and opening time	Public and always open	Public and always open	Public with opening hours
Design style	Post-industrial	The ruin aesthetic	The ruin aesthetic
Outcomes	Aesthetical and ambiental benefits; Social coehesion; Ecological site-specific benefits	Wide ecological benefits; Aesthetical and ambiental benefits; Social coehesion; Psychological benefits	Hystorical and cultural benefits; Aesthetical and ambiental benefits
Challenges in terms of greening	Preserve the identity of the object; Avoid a sense of empty space; Provides a counterbalance to the urban surrounding maintenance	Reuse of existing demolish material; usage of recycled materials in landscape design; Avoid a sense of chaotic space; maintenance	Preserve the hystorical and cultural identity; Preserve the aesthetic of ruin

6. DISCUSSION

The analyzed examples highlight the importance of greening urban ruins, as reconstructed and revitalized spaces become multifunctional, environmentally efficient, and possess ambient and aesthetic value. They are accessible for public use and contribute to social cohesion. The presented cases of greening urban ruins, realized over the past two decades, demonstrate various approaches in terms of greening methods, techniques applied, materials used, plant selection, site-specific conditions, and the outcomes and challenges of revitalization (Table 1).

Green facades represent the most commonly used greening technique in urban ruins. Depending on the structure, the degree of decay and stability of the object, as well as the complexity of the design, the choice between direct or indirect green facades is determined. Although green roofs are a highly effective technique offering numerous benefits for both the building and its surroundings, their implementation in the context of urban ruins is either absent or limited (typically applied to only part of the roof). This is largely due to the use of open-roof concepts during the revitalization of ruins, aimed at ensuring optimal conditions for plant growth within the interior—such as sufficient light, humidity, and ventilation.

Ensuring adequate natural lighting and ventilation greatly enhances both the aesthetic and ambient qualities of the space. In addition to interior greening, greening the immediate surroundings of the building—when and where feasible—is of critical importance, as the structure and its context should be viewed as an integrated whole. Greening the broader environment around a ruined structure is particularly relevant in responding to the modern demand for expanding green spaces in urban areas and achieving the full spectrum of benefits that greening abandoned sites can provide—primarily ecological, but also aesthetic, social, psychological, and economic.

The choice of plant material depends on the characteristics of the structure itself, its surroundings, and the desired effect. All plant categories and a wide range of species may be used (e.g., Prado Park), while in other cases the palette is deliberately more limited (e.g., Ruin Garden). Climbers are almost always included, as they play a key role in emphasizing the aesthetic of ruination and in symbolically linking the structure to its past (e.g., ruins overgrown with vines). However, using a large number of plant species and categories does not necessarily result in the desired visual effect; on the contrary, it can lead to a sense of spatial overcrowding and visual chaos. Due to the typically limited space of urban ruins and specific microclimatic conditions in urban cores, it is recommended to use native plant material and limit the number of species. Richness and diversity can be achieved through the use of a larger number of cultivars within a single species.

MFO Park is a good example of this approach, demonstrating that it is possible to create an urban oasis in the city center using only two plant categories and a limited number of species.

The examined cases of greened urban ruins reveal a wide range of positive outcomes: enhancement of aesthetic and ambient values of the site and its surroundings, preservation of historical and cultural heritage, stimulation of social interaction and cohesion, and improvement of ecological conditions within the urban environment. These outcomes largely depend on the size of the site, the extent of greening, and the possibility of greening the immediate or wider surroundings. The greater the level of greening and the larger the greened area around the ruined object are (e.g., Prado Park), the more significant the positive impact on the environment is—and vice versa (e.g., Ruin Garden).

Thus, the outcome of greening urban ruins, in terms of environmental benefits, can range from being site-specific (e.g., MFO Park) to having a wider urban impact (e.g., Prado Park). Accordingly, we can refer to these as site-specific project impacts and outcomes or broader-scale project impacts and outcomes.

The fundamental characteristic of greening urban ruins is the individual and often site-specific approach unique to each building and location. Every structure undergoing greening, as well as the site it occupies, is defined by its own cultural, social, and economic values, along with microclimatic conditions. Therefore, it is difficult to generalize the practices related to greening buildings or adapting cultural heritage to meet contemporary urban needs. Although each structure and site requires an individual approach, certain conceptual similarities can be identified across various examples:

- the existing built structure is viewed as cultural heritage;
- the buildings either lack a roof or have a permeable/grid-like structure to allow light penetration and support the survival and care of plant material;
- multiple greening techniques are typically applied;
- there is a preference for using native plant species;
- the projects aim for ecological and economic sustainability;
- they seek to encourage social interaction among the population.

Greening urban ruins also comes with certain challenges. First and foremost, it is necessary to assess the structural stability of the existing building and the load-bearing capacity of the structure, which requires the involvement of experts to ensure the safe implementation of the project. This assessment defines the possibility of reusing existing materials and the need to reinforce the load-bearing structure. Additionally, since these are typically abandoned and old urban buildings, it is essential to determine property ownership of the parcel and land, and to obtain all necessary permits for the changes proposed by the project. The selection of plant material must be suited to site conditions and local microclimate, and the maintenance requirements of the green areas must also be considered. Contemporary trends favor the use of resilient plant taxa with low water needs, as well as native species, which contribute to self-sustainability. It is also crucial to allocate the project budget efficiently and define priorities during the design and reconstruction phases. To ensure that the overall solution aligns with urban development policy, careful planning and implementation are required.

7. CONCLUSION

Greening urban ruins represents a strategy for revitalizing abandoned urban spaces, which not only contributes to environmental protection and the development of green infrastructure, but also provides social, psychological, economic, and aesthetic benefits. Such projects enhance the characteristics of the structures themselves, improve the microclimatic conditions of the site, promote the development of urban biodiversity, play a role in adapting cities to climate change, and foster social cohesion. As multifunctional spaces, they serve as areas for rest and recreation for urban residents, helping to reduce stress and promote well-being. Through the use of vertical greening techniques, green roofs, interior greening, and greening of surrounding areas, as well as adaptive reuse of ruins, it is possible to create sustainable and multifunctional environments that improve the

quality of urban life. The revitalization of ruins also plays a role in preserving cultural heritage and spatial identity, linking the past with contemporary urban needs. The potential for revitalization depends on factors such as the structural integrity of the building, plant care requirements, investment value, and the resolution of legal issues related to ownership and management—emphasizing the need for careful planning and implementation. Although there is no universal approach to greening ruins and abandoned urban spaces, developing criteria for selecting structures and forming a priority list would be beneficial. The evaluation of site or building suitability for revitalization, the design process, implementation, and long-term maintenance and management require a multidisciplinary approach, involving engineers and experts from various fields.

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Review paper

THERMAL BRIDGES AS INDICATORS OF INSTALLATION DEFICIENCIES IN ETICS FACADES

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Abstract

External Thermal Insulation Composite Systems (ETICS) are widely utilized to increase the energy efficiency of buildings by minimizing heat loss through exterior walls. However, when improperly installed, thermal bridges are formed, significantly decreasing the overall thermal performance of the façade system. This study aims to identify installation defects in ETICS facades by characterizing thermal bridges and their impact on energy performance. The selection of infrared thermography as the primary technique for detecting thermal bridges was based on its ability to reveal surface temperature variations quickly. In-situ thermographic examinations were performed on a case study edifice to discern prevalent installation deficiencies. This inquiry offers a methodical framework for identifying and scrutinizing ETICS installation shortcomings through thermographic imaging, thereby providing valuable insights for enhancing insulation methodologies. The investigation disclosed that thermal bridges predominantly manifested at the junctures of walls and floors, around window apertures, and at points of external element attachment, culminating in increased thermal losses, condensation issues, and risks of mold proliferation. The evaluation of the recognized deficiencies underscored a pressing necessity for elevating installation quality control measures and rigorous compliance with established protocols. The research outcomes underscore a fundamental imperative for amalgamating inspection strategies with preventive measures to bolster the energy efficiency and longevity of ETICS facades. Prospective research endeavors should concentrate on the advancement of detection methodologies.

Key words: *ETICS facades, thermal bridges, infrared thermography, installation deficiencies, energy performance*

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1. INTRODUCTION

Improving the energy efficiency of the external walls of buildings is most often achieved by applying an external thermal insulation system (ETICS) [1]. This system is widely accepted due to its affordable price, easy installation, and effective reduction of heating and cooling needs. The long-term performance of ETICS depends on the materials' thermal properties and the installation quality. Errors can lead to breaks in the insulation layer, reducing its efficiency and creating thermal bridges that impair the energy performance of the building [2].

Thermal bridges allow increased heat transfer through the facade, which leads to more significant heat losses and increases the risk of condensation and possible damage to structures [3]. These problems often occur due to incorrect insulation installation, inadequate installation, or deviations from the prescribed work standards. As a result, the facade system may degrade more quickly and provide lower energy savings than expected.

This paper investigates how installation deficiencies contribute to the formation of thermal bridges in ETICS facades and considers possible solutions to reduce these phenomena. The research combines theoretical analyses of thermal bridges as indicators of installation deficiencies in ETICS facades at the Cultural Center in Pirot, Serbia. Infrared thermography was used as the primary diagnostic method, allowing for the visualization of temperature anomalies and identifying critical areas on the facade.

The research results indicate the importance of proper installation procedures and regular inspections as key factors for the long-term and efficient operation of ETICS facades. Special emphasis is placed on the need for preventive quality controls, both in the design and construction phases, to reduce the adverse effects of thermal bridges.

Although previous research has analyzed the impact of thermal bridges on energy efficiency, few studies systematically link specific construction errors to anomalies detected by thermography. This paper fills this research gap by analyzing real-world examples of irregularities and their thermal consequences.

2. THEORETICAL BACKGROUND

2.1. Mechanisms of heat transfer and thermal bridges

Thermal bridges arise when discontinuities in the insulation layer or structural components establish a conduit for heat transmission, circumventing the designated thermal insulation barrier [4]. The vulnerabilities, characterized by markedly decreased thermal resistance compared to adjacent materials, result in heightened heat transfer and localized temperature fluctuations [5]. The leading causes include direct conduction through high thermal conductivity materials and convective losses at junctions. Depending on the shape, thermal bridges can be linear (e.g., wall-to-slab joints), punctate (e.g., fixing anchors), or surface discontinuities (Figure 1).

In addition to energy losses, thermal bridges can cause condensation on surfaces and the development of mold, which poses a risk to the durability of ETICS facades [2]. If moisture accumulates inside the system, materials can deteriorate over time, threatening both insulation performance and the structural stability of the building [6]. Therefore, the precise installation of the insulation is crucial, especially at the joints where the continuity of the thermal insulation is most vulnerable.

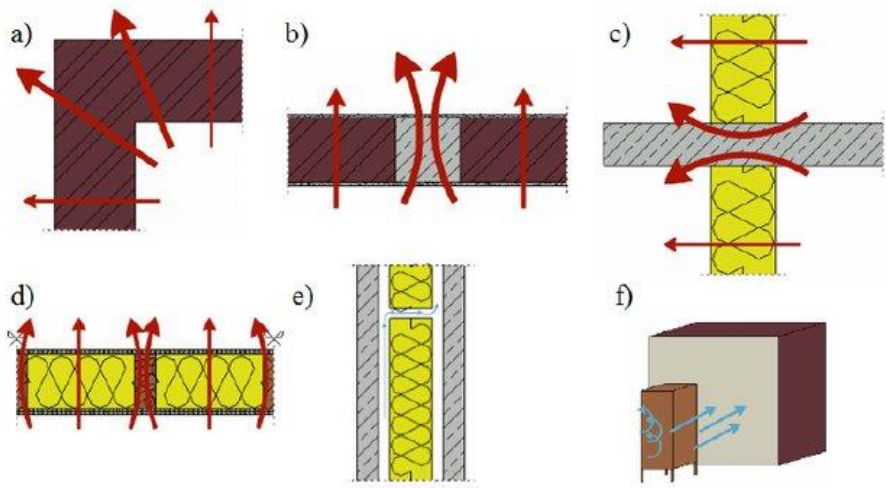


Figure 1. Types of thermal bridges: a) Geometrical, b) Material, c) Structural, d) Periodically repeating, e) Convective, f) Environmental dependent [7]

Various measures are applied to reduce thermal bridges in buildings, where it is crucial to pay attention to the critical points of the construction where heat losses are most pronounced.

One of the practical approaches is careful planning of thermal insulation, where special attention is paid to places where there may be a break in the continuity of the insulation layer [8]. Systems with a continuous layer of thermal insulation, such as ETICS facades, enable the reduction of thermal bridges by preventing breaks in the insulation [9].

Furthermore, architectural solutions play a crucial role as well. Correct positioning of openings can reduce the risk of thermal bridges at the joints of the facade and windows. Also, using quality facade joinery, such as windows with double low-emissivity glass and thermal breaks in the frames, additionally improves the insulating properties of these elements [10], [11].

In recent approaches, modern materials, such as airgel with extremely low thermal conductivity, enable even more effective protection against heat loss. However, their correct placement and the choice of materials are also crucial. The precise installation of the insulation prevents the creation of cracks and inconsistencies that can impair the building's energy efficiency. In addition, appropriate processing of joints and penetrations through the facade can significantly reduce the occurrence of localized heat losses.

Various control methods are applied to ensure the quality of the work performed, including infrared thermography, which enables the detection of problematic points at an early stage of the building's exploitation. In addition, computer simulations and optimization of design solutions help choose the most efficient combinations of materials and construction solutions, contributing to the long-term energy efficiency of buildings [12].

2.2. Common installation deficiencies in ETICS facades

One of the key challenges in achieving the continuity of thermal protection of buildings is the inadequate execution of details, where local thermal bridges most often occur due to insufficiently covered surfaces with insulation, poor joints around openings, and improperly designed structural connections [13]. Such leaks not only impair the building's energy efficiency through increased energy consumption but also contribute to the creation of

conditions suitable for the occurrence of condensation and the development of mold, which further endangers the quality of the indoor environment and the health of users.

Systems of contact facades with mineral wool thermal insulation represent a modern approach to improving the energy characteristics of external walls, both in new and existing buildings. These multi-layer compositions combine several functional requirements: they provide effective thermal and sound insulation, high fire resistance, and good vapor permeability, thus creating a healthier and more energy-efficient environment; whether stone or glass wool, mineral fibers are key in stabilizing the building's thermal regime and increasing acoustic comfort.

The ETICS system can achieve the expected performance only if it is applied according to a carefully defined technological procedure, which includes substrate preparation, correct adhesive application, precise installation and mechanical fastening of thermal insulation boards, and final surface reinforcement (Figure 2). Each of these stages has a decisive influence on the final quality of the system and its long-term reliability.

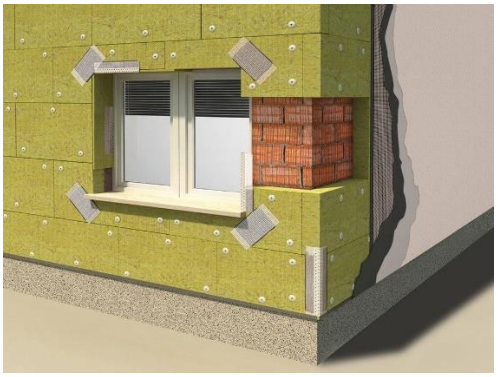


Figure 2. Execution Elements of an ETICS with Mineral Wool [14]

The preparation of the substrate is a key initial step in the installation of the contact facade and includes the removal of all impurities, leveling the surface, and checking the load-bearing capacity of the walls. In cases where the substrate is absorbent, a primer is recommended to improve the adhesion of the adhesives. The glue is applied along the edges and in the central part of the thermal insulation boards, where it is necessary to ensure a minimum contact area of 40%. The installation is carried out horizontally, from the bottom up, whereby the outer side of the higher-density board should face outwards, opposite to the direction of the dominant wind. Special attention should be paid to the correct arrangement of the joints between the plates to avoid creating linear thermal bridges. Cross-stacking the thermal insulation elements is recommended for additional static stability of the system in the corners of the building.

Frequent mistakes in practice are related to improper installation of thermal insulation boards, poor sealing of joints, and pronounced thermal conduction at the places of mechanical fastening [15]. Such failures significantly reduce the insulation effect and contribute to the increase in energy losses [16].

Mechanical fastening with dowels is an essential step in ensuring the stability and durability of the system, especially when using stone wool, which is heavier than other types of insulation. The dowels are installed after the glue has been set, and their number and arrangement depend on the object's height and exposure to the wind. In standard conditions,

installing about six dowels per square meter is recommended, while in the edge zones and the case of multi-story buildings, this number increases. Dowels are inserted into pre-drilled holes and installed by hammering or screwing, depending on the type, with mandatory alignment with the surface of the insulation to prevent the formation of spot thermal bridges. The correct selection of dowels relies on the substrate type and the insulation thickness, and each dowel must penetrate at least five centimeters into the load-bearing wall. Plastic dowels with a metal core and a broad head are recommended for better load distribution for stone wool.

The surface is strengthened by applying a polymer-cement adhesive into which a glass mesh is pressed with an overlap at the joints. This reinforcement significantly contributes to the mechanical resistance of the system and prevents the occurrence of cracks. After the base layer of glue dries, the final decorative plaster—silicone, acrylic, or mineral—previously prepared with a suitable primer, is applied. The correct installation of dowels and mesh ensures not only the functional stability of the system but also its long-term resistance and aesthetic quality.

Doweling has a significant role in contact with facade systems because improper installation can lead to the separation and collapse of parts of the facade. Proper selection of dowels, their exact position, and installation following technical requirements contribute to the safety and durability of the entire system. It is recommended to carry out a pull-off test, which checks the bearing capacity of the substrate and determines the force required to pull out the dowel, thereby confirming its adequacy. At the same time, there must be a mass of glue under each dowel to prevent moisture retention and the appearance of additional thermal bridges.

3. METHODOLOGY

Infrared thermography was used as the primary diagnostic method for detecting irregularities in the performance of the ETICS facade system, as it visually displays temperature differences on the surface, thereby clearly identifying potential thermal bridges and installation errors [17]. Thermographic tests were carried out using a FLIR infrared camera, model B20 PAL, where the emissivity value was set to 0.95, ensuring accuracy in detecting thermal anomalies on the contact facade.

The measurements were carried out during winter since there is a pronounced temperature contrast between the interior and exterior space, enabling a more precise visualization of irregularities. The recordings were made at night under stable external conditions to eliminate the influence of solar radiation and wind on the temperature readings. The process previously included stable heating of the interior space of the building to achieve a sufficient temperature difference between the interior and the outer shell of the building.

The contact facade of the House of Culture in Pirot, immediately after the recent rehabilitation, was analyzed. The inspection is focused on the characteristic points of joints, such as the joints of wall and mezzanine constructions, window frames, and places of mechanical fastening, since in these zones, the most common are the leaks that lead to the formation of thermal bridges [18]. Temperature differences greater than 2°C concerning neighboring zones were considered a threshold for identifying a performance error. In addition to quantitative readings, a qualitative analysis of thermographic patterns was also

applied, and temperature irregularities associated with specific failures in assembly were observed.

The results were systematically compared with the reference guidelines for correctly installing the ETICS system to identify frequent errors such as incorrect installation of the thermal insulation layer, discontinuities in thermal protection, and inadequate fastening technique. In this context, infrared thermography has proven to be a handy tool for diagnostics and quality control of performed works, offering a reliable basis for preventing errors and improving the system's energy efficiency.

4. RESULTS AND DISCUSSION

4.1 identified deficiencies and their impact

Thermal bridges are most often identified at the points of joints and penetrations through the facade system, where there is a significant increase in heat losses and an increase in the building's heating needs. Thermographic analysis indicated the presence of pronounced thermal anomalies in the area of the fastening points and along the perimeter of the window openings, which means inadequate covering with thermal insulation and omissions in execution. The observed deficiencies contribute to increased heat loss and the risk of condensation, especially in the winter [19].

Additional analysis of the available photo-documentation and technical reports indicated several irregularities that led to the partial collapse of the facade of the House of Culture in Pirot carried out in the ETICS system. Among the key causes, inadequate preparation of the substrate was singled out, whereby basic mechanical operations, such as rough treatment ("scratching" or "etching"), necessary to ensure adequate adhesion, were not carried out. Of particular concern is that the thermal insulation system was applied directly over the wall and painted with an acrylic mural without prior treatment, which seriously impaired the stability and adhesion of the layers of the system.

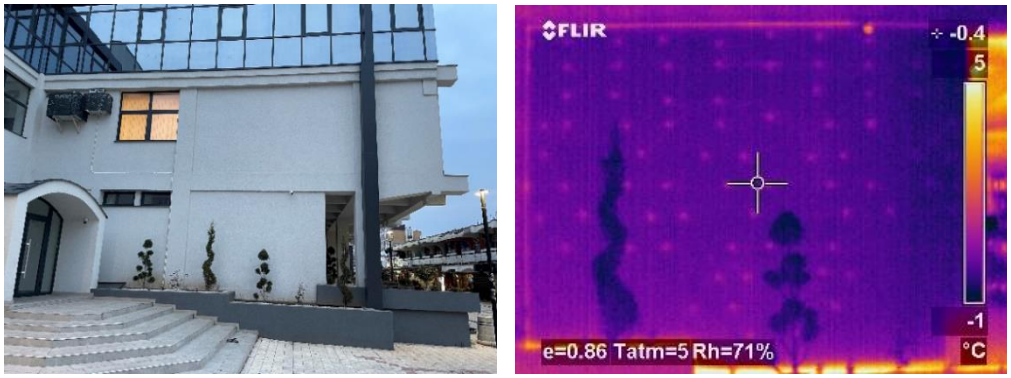


Figure 3. Part of the South-East Façade and Its Thermographic Image

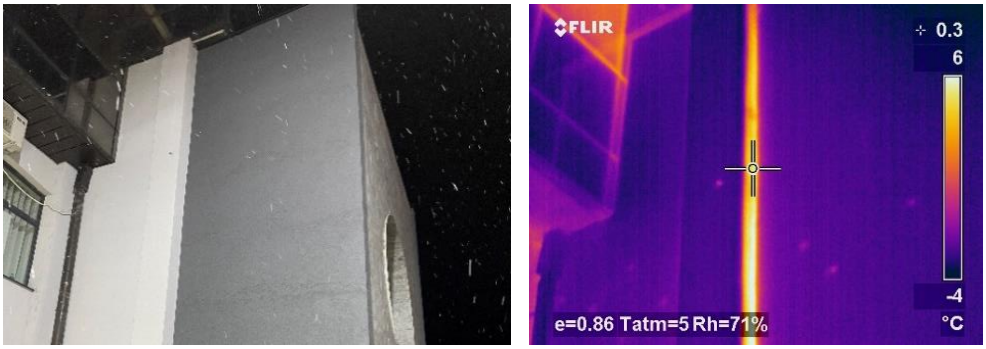


Figure 4. Part of the North-West Façade and Its Thermographic Image

The photo-documentation additionally indicated the improper application of the glue on the thermal insulation boards made of mineral wool, which resulted in uneven adhesion and weakening of the adhesive properties of the facade system (Figure 3). Inadequate installation of panels in the corner area of the building was observed without applying the so-called "binding" (alternate overlapping), which resulted in the structural weakening of the facade covering in critical places (Figure 4). Improper processing of edges and corners, as well as incorrectly placed reinforcing mesh, additionally contributed to the reduction of mechanical resistance and overall stability of the system.

One of the most serious omissions is reflected in the complete absence of doweling, which is the essential structural element for the mechanical fastening of thermal insulation boards. Thermographic images clearly showed the lack of dowels on specific facade segments, jeopardizing the system's resistance to external influences and long-term stability. According to the basic technical standards, installing dowels is a mandatory measure to achieve durability and reliability of the ETICS system, and their absence is considered a gross failure in the execution of works (Figure 5).



Figure 5. Part of the North-West Façade and Its Thermographic Image

The absence of technical and certification documentation made it even more challenging to analyze the state of the facade system. The attached documentation did not contain data on the installed components or confirmation of their mutual compatibility, which indicates the possibility of using non-compliant materials. Such practice is contrary to European standards, which require the application of system solutions with certified components from one manufacturer.

The identified irregularities point to systemic deficiencies in the preparation of the substrate, the installation of thermal insulation boards, and the general quality of the work performed, which resulted in the partial collapse of the facade. Based on the findings, it is recommended that the critical parts of the facade be reconstructed with strict adherence to project documentation.

The research results indicate that the prevention of the appearance of thermal bridges in ETICS facades depends on precisely defined installation methods and planned thermographic inspections. Previous research confirms that the combination of infrared thermography and field measurements represents a key diagnostic method for detecting construction errors and assessing their impact on the energy performance of the building [20], [21]. The findings indicate the need for stricter quality control measures during construction and post-construction inspections to minimize the effects of thermal bridges. Advanced anchoring techniques and improved joint sealing practices are recommended [13].

5. CONCLUSION

This study points to the key role of proper installation in reducing thermal bridging in ETICS facade systems. Effective control and timely detection of irregularities through precise detection methods must be integral to every project to ensure greater energy efficiency and a longer service life of the building's outer envelope. Thermal bridges are visible indicators of performance failures, which significantly impair the thermal characteristics of the building. Improving energy efficiency requires immediate repair of existing defects and prevention of long-term deterioration of the facade system. The systematic introduction of thermographic tests following the guidelines for proper installation should become a standard procedure in the execution and quality control phase.

Infrared thermography has proven to be an extremely effective diagnostic tool for detecting problems arising during the performance of the ETICS system. Defects invisible to the eye, such as poorly applied glue or insufficient thermal protection, become visible thanks to thermographic images. These analyses enable the timely detection of irregularities and thus become irreplaceable in the quality control of performed works. Identifying fundamental installation problems using thermography creates conditions for developing long-term solutions that reduce energy losses and improve the thermal characteristics of the facade.

Although surface irregularities were quickly detected by thermography, more precise information on heat losses was obtained by in situ measurements. Numerical simulations that followed the field tests further confirmed the observations and enabled the prediction of energy performance in the long term. Based on the results of this research, the systematic application of the thermographic method as part of regular inspections of ETICS facades is recommended. Future directions of research should be focused on the improvement of detection methods and the adoption of advanced performance techniques. Additionally,

efforts should be directed toward developing higher-quality thermal insulation materials that are less prone to forming thermal bridges.

ACKNOWLEDGMENT

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Review paper

THE SIGNIFICANCE OF THE INTEGRATING CONCEPTS IN SPATIAL PLANNING: INSIGHTS FROM BULGARIA

Diana Ivanova[1]

Abstract

Based on the theoretical and practical spatial planning experience this paper aims to draw the attention of the professional spatial planning community and legislative authorities to the importance of legal regulation of an integrating strategic, program and planning document - a concept to ensure the integrated development and implementation of strategic and planning documents at municipal level. The research is built on the spatial planning practice in Bulgaria, but it uses a holistic approach and lays on well-established principles in the field. Thus the basic elaborated statements could be applicable to spatial planning in general because they outline a possible algorithm for integrated decisions which contribute to the balanced and harmonious planning, management and functional-spatial development of the territories. Some of the main findings of the study are the notions formed about the links and interactions between the different types of legally regulated strategic, planning and programming documents; the place and role of the necessary integrating concept for functional and spatial development and the possible structure and content of such kind of document.

Keywords: *functional-spatial planning and development, integrating concepts, structural models*

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1. INTRODUCTION

The main instrument of spatial development of territories is spatial planning. In spatial planning practice in Bulgaria, it is often observed that the mandatory regulated strategic, program and planning documents are developed in isolation and without a unified vision for the functional and spatial development of the municipal territory, on the basis of which the policies of the local government in the spatial planning sphere can be determined. One of the reasons for the identified problem is the lack of a legal and regulatory framework to ensure the interrelation and hierarchical subordination between the goals, priorities and policies set out in the strategic planning and programming documents, reflected in the operational planning developments and implemented through specific projects – investment, social, management, financial, etc. This is the main argument that justifies the need for an integrating document to link spatial planning processes [1].

Based on the analyses held on, researches and practical experience [1, 2, 3], some key problems in spatial planning practices in Bulgaria are identified that are relevant to the explored topic as:

- Incoherence of spatial planning developments – strategic and planning documents – due to the lack of a connecting conceptual basis that would regulate integrated priorities and provisions.
- Lack of understanding of the interrelationships between spatial planning and the protection of the natural and anthropogenic environment and of the possibilities for the harmonious reconciliation and functioning of these systems.
- Incoherence and lack of integration between the specialized researches on the individual functional-spatial and socio-economic strands and spatial planning – isolated projects (investment, social, financial, protection, management, etc.) and independent functional-spatial plans are developed without taking into account the cultural-historical, socio-economic and functional-spatial regional and territorial connectivity and interactions between processes.

The **research aim** of the study is to propose an algorithm for elaboration of an integrating concept for functional and spatial development of a municipality (ICFSDM).

From the aim thus formulated the following **research questions** follow:

- What is the potential of the newly proposed ICFSDM for legal regulation and where does it fit into the existing structure of the planning system?
- What could be the structure and content of the ICFSDM to make it a workable strategic, programmatic and planning document?

In the development of the study, the proven in theory and practice **analyze-synthesize methods** are used, which in this case include:

- **analysis of:** the legal and regulatory basis in spatial planning; the links between the different types of strategic and planning documents; the theory and practice of spatial planning in Bulgaria for the creation of spatial planning developments;
- **synthesis of:** principles, approaches, potentials and mechanisms, taking into account the need for integration of spatial planning processes and developments; structural models to illustrate the proposed ideas; guidelines and proposals for optimizing spatial planning practices.

2. INTERLINKING OF SPATIAL PLANNING DEVELOPMENTS

In order to better understand ideas, put forward, it is necessary to briefly present the structure of the spatial planning system in Bulgaria and to clarify the interconnections between the main processes and documents in the field [4, 5].

The author's notion of the connections between the different types of legally regulated strategic, planning and programming documents and the place and role of the necessary, but unregulated, integrating concept for functional and spatial development of a municipality (ICFSDM) is schematically shown in *Figure 1*.

The functional purpose of the general spatial plan of a municipality – so called **Master plan of a municipality (MPM)** – is to serve as a management tool of the local government in the sphere of spatial planning policy targeted at creating of spatial and functional-management conditions for development and complex planning of different types of territories, taking into account the existing natural and anthropogenic elements and specific socio-economic conditions.

MPM details the guidelines for territorial development of the municipalities, set out in the **Integrated territorial development strategy (ITDS)** of the relevant planning region.

MPM provides the planning basis for the implementation of the goals for socio-economic and functional-spatial development of the municipality.

The provisions of MPM are mandatory for the subsequent detailed spatial planning. **Detailed urban plans (DUP)** have direct investment application and are a necessary planning basis for issuing visas for research and design and for the elaboration, proceeding and implementation of specific investment projects.

Protection plans (PP) and **Management plans (MP)** should be developed and implemented in conjunction with the provisions of the **Plans for integrated development of the municipalities (PIDM)** and the spatial development plans for the territorial scope to which they apply. Such plans are developed for certain types of territories as such for:

- protection of cultural heritage;
- environmental protection;
- nature protection;
- preservation of natural habitats and wild flora and fauna;
- water protection;
- protection of cultural and natural landscapes;
- sanitary and hygienic protection;
- protection against disasters and accidents;
- etc.

In terms of spatial planning and strategic programming, PP/MP include, depending on the specificities of the particular territory, protection regimes, long-term and short-term programs for conservation, protection and management activities and for implementation of the plan.

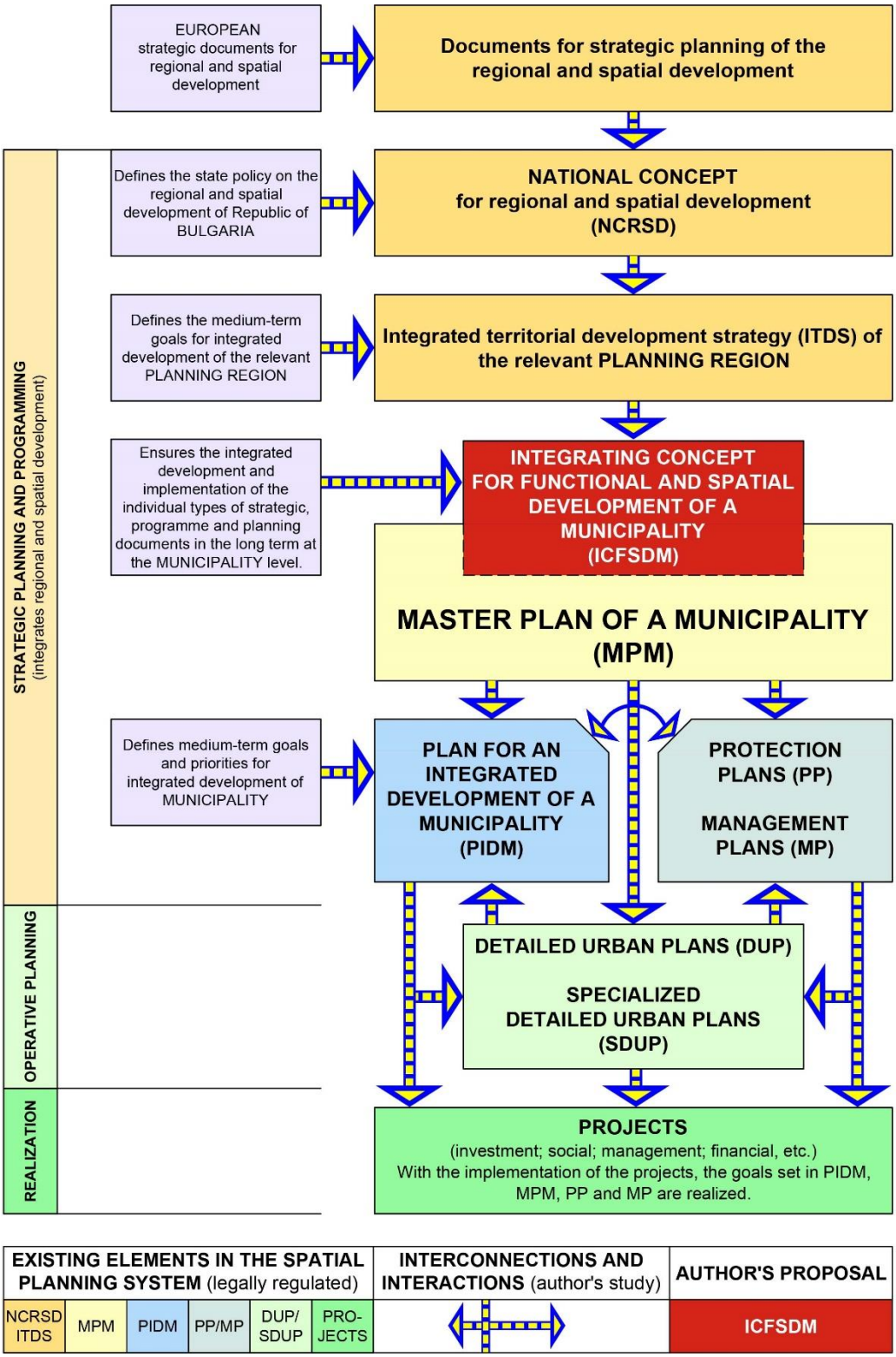


Figure 1. Linkage between strategic and planning documents, source: author's scheme based on [1, 2, 3, 4, 5, 6]

The functional purpose of PIDM is:

- to define priorities, means and stages for achieving the goals, set out in ITDS and for implementation of the development solutions envisaged in MPM;
- to ensure an integrated approach and a comprehensive effect of the implementation of the main planning and strategic documents related to the management and functional-spatial development of the municipality and to the protection and evolution of the territories and society.

PIDM is developed in hierarchical subordination with the goals and priorities contained in the higher level strategic planning documents for regional and spatial development, without repeating them, but by specifying them according to the specificity of the municipality. Such strategic documents of a higher hierarchical level are:

- **National concept for regional and spatial development (NCRSD);**
- **Integrated territorial development strategy (ITDS)** of the relevant planning region.

PIDM defines medium-term goals and priorities for sustainable development of the municipality and connections with other municipalities in accordance with the ITDS of the planning region at level NUTS 2 and with the MPM.

PIDM provides spatial, temporal and factual coordination and integration of different policies and planning resources to achieve the defined goals for lasting improvement of the economic, demographic, social, spatial-functional, infrastructural and environmental conditions of the municipal territory.

In this way, at the normative level, the MPM, the PIDM and the PP/MP are the main link between the Regional Development Act (RDA), the Spatial Development Act (SDA) and the special laws such as the Cultural Heritage Act (CHA), the Act on Waters (AW), the Protected Areas Act (PAA), the Biological Diversity Act (BDA), etc.

From the brief analysis presented, the conclusion naturally follows that there is **a need for legal regulation of an integrating strategic, program and planning document - a concept to ensure the integrated development and implementation of strategic and planning documents at the municipal level**.

It is appropriate to call it an **Integrating concept for functional and spatial development of a municipality (ICFSDM)**.

The **author's proposal** is to regulate legally the ICFSDM as a mandatory element into the existing planning system in Bulgaria in interconnections shown in *Figure 1* and with structure and content shown in *Figure 2*.

3. INTEGRATING CONCEPT FOR FUNCTIONAL AND SPATIAL DEVELOPMENT OF A MUNICIPALITY (ICFSDM)

One possibility is to regulate the ICFSDM as a stand-alone document in the RDA and the SDA, ensuring its integrating character and the mandatory hierarchical subordination of subsequent spatial planning projects. It is more appropriate for the concept to be a mandatory part of the MPMs, given their long-term nature and their focus on the functional-spatial and socio-economic development of the territories, and this should be enshrined in the legal and regulatory framework for spatial planning. This would make it easier for the municipalities in terms of the number of programming documents they have to produce. Another argument for the inclusion of the ICFSDM as a mandatory part of the general spatial plans is the already regulated subordination of the planning documents and the place and importance of the

MPMs in this hierarchy, as well as the monitoring and control system through environmental assessments, conformity assessments and impact assessments of the plan in the process of its elaboration and subsequent implementation.

Figure 2 presents a structural model outlining the guidelines for the development of the proposed for legal and regulatory regulation integrating concept for functional and spatial development of a municipality (ICFSDM), which will ensure the integrated development and implementation of the different types of strategic, programmatic and planning documents.

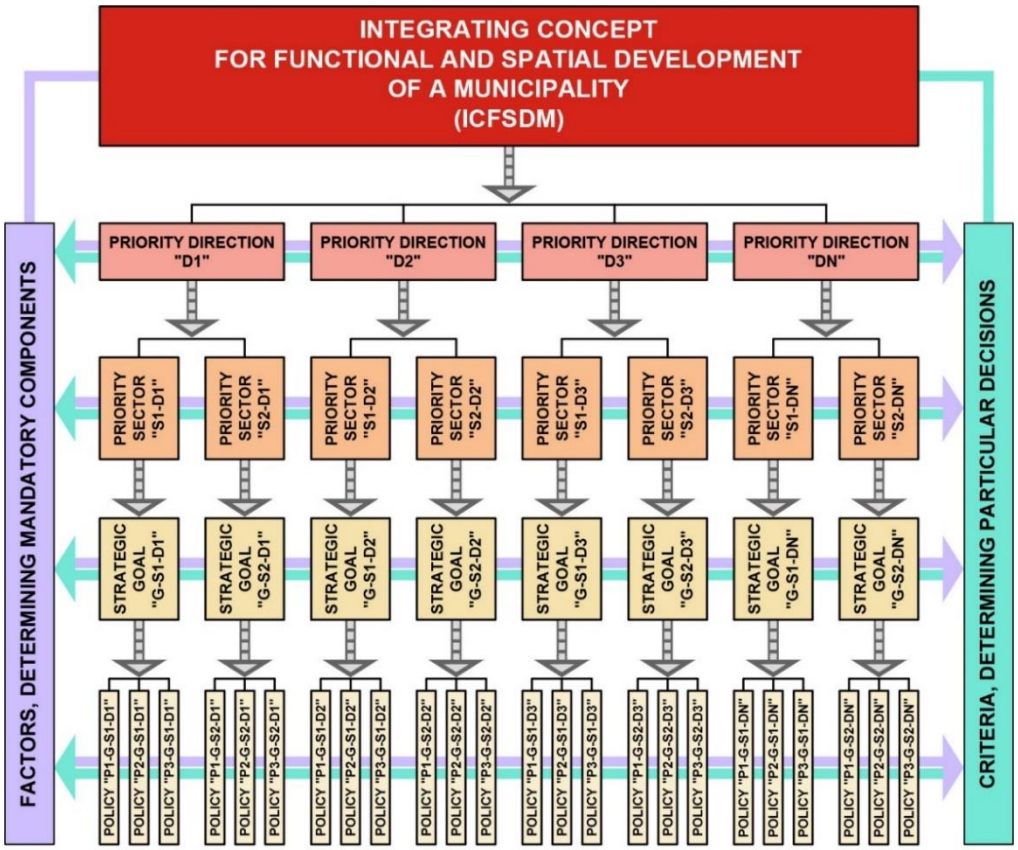


Figure 2. Structural model of ICFSDM, source: author's scheme based on [1, 2, 7, 8]

The structural model of an integrating concept for functional and spatial development of a municipality (ICFSDM) *Figure 2* includes defining of:

- **Priority directions** for functional-spatial development of the municipality.
- **Priority sectors** for each of the identified priority directions.
- **Strategic goals** by directions and/or sectors.
- **Policies** to achieve the strategic goals.

As a matter of principle, there are permanent factors defining mandatory components for each level of spatial planning and management of territories and criteria linked to them, requiring specific spatial planning decisions. Such factors and criteria are cultural heritage, ecology, national security, etc.

The spatial-functional expression of each of the priority directions so defined by ICFSDM has its specificity and interaction with the other directions, which forms the functional-spatial characteristic of the respective municipality. The MPM concepts also define the priority

sectors for each of the priority directions, the strategic goals by direction and/or sector and the policies to achieve the strategic goals. MPM establishes the spatial planning conditions for the implementation of the policies defined by ICFSDM. PIDM specifies the particular actions, timeframes and means for realization of the policies determined by ICFSDM and spatially assured by MPM.

Figure 3 demonstrates the possibility of practical application of the theoretical considerations presented. The example shows the graphic part of the concept of the Master plan of Yakimovo – one of the small municipalities in Bulgaria - where the principles and algorithm for developing the proposed for legal regulation ICFSDM are laid down.

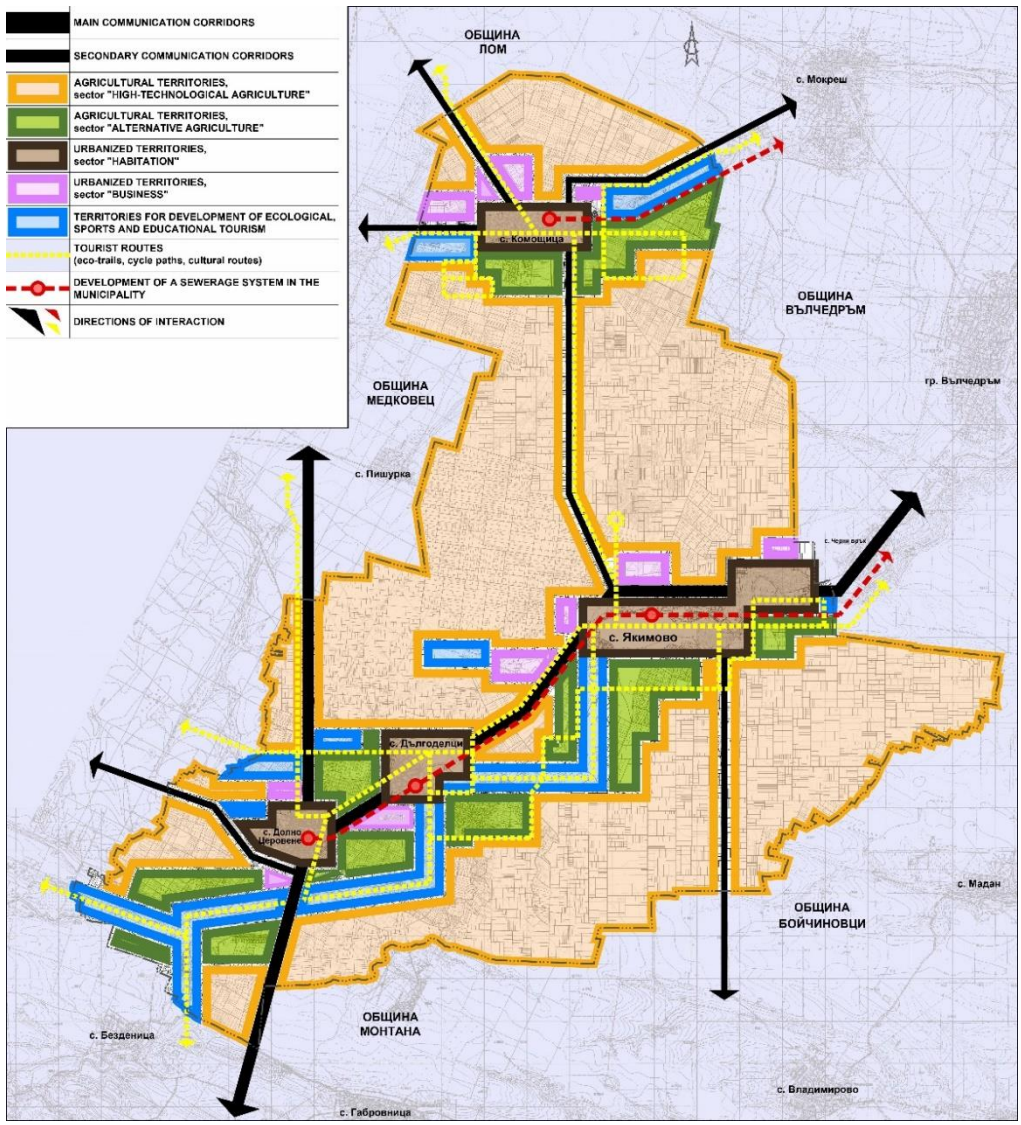


Figure 3. Concept of the MPM of Yakimovo for a functional-spatial development of the municipality, source: MPM Yakimovo [8] and personal archive

Although it is not regulated as a mandatory element, a concept has been developed to the MPM that corresponds to the presented structural model, filling it with specific content depending on the specifics of the municipality. The concept for the functional and spatial

development of the municipality of Yakimovo forms five priority directions: agriculture, urban areas, tourism, transport and technical infrastructure, ecology, cultural and historical heritage. The set priority sectors, strategic goals and policies for each priority direction can be seen in detail in the MPM documentation [8]. In line with the concept, the MPM itself has been developed.

4. CONCLUSION

Using the holistic approach this paper provides clear answers to the defined research questions by:

- defining some gaps in spatial planning theory and practice and in legislative framework in the sphere of spatial development in Bulgaria;
- exploring the potential of the integrating concepts and proving the need to incorporate them into spatial planning;
- proposing a new document, called "Integrating concept for functional and spatial development of the municipality"(ICFSDM), which to be legally regulated and to be included in the existing spatial planning system in Bulgaria;
- presenting author's notion of interconnections between the individual strategic and spatial planning documents and exploring the appropriate place of ICFSDM into the existing structure of the planning system in Bulgaria;
- outlining the structure and content of the ICFSDM, giving the main guidelines for its elaboration;
- demonstrating an example of practical application of the theoretical ideas.

The presented ideas are derived from the spatial planning practice, they are formulated as theoretical propositions and the aim is after their legal and normative regulation to be applied as structural models back in practice. The study proposes an algorithm to develop ICFSDM, thus the goal of the study is achieved.

The author hopes that the ideas presented will contribute to a better understanding of the interrelationships in spatial planning processes and to the establishment of an effective working algorithm in the development and implementation of spatial planning documents.

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Research paper

SUBURBIA: UNIFORMITY AND DIVERSITY IN RESIDENTIAL DEVELOPMENTS

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Abstract

Suburbs represent an integral component of metropolitan development, reflecting diverse urban planning, social, and cultural approaches to housing. They are typically characterized by residential communities marked by uniformity, mass production, and spatial monotony. However, the development of suburban areas reveals significant functional, morphological, and geographical variations, contingent upon regional and cultural contexts. This paper examines the typological characteristics of selected case studies through a comparative analysis of geographical context, functional zoning, and the socio-economic structure of the population. The research focuses on architectural and urban homogeneity, spatial organization patterns, and housing-related aspects. The primary objective is to identify and classify recurring spatial patterns, similarities, and differences in suburban models across North America, Europe, Australia, and Asia, grouping them according to specific typological features of housing.

Key words: *suburbia, urban development, cookie-cutter housing, settlement typology, tract housing, architectural homogeneity, mass housing, comparative analysis*

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1. INTRODUCTION

Suburbia represents one of the most significant phenomena of urban development in the 20th century. It emerged as a multifaceted response to urban growth—initially as a consequence of industrialization, and later as a solution to the immense housing demand that followed the Second World War. The development of suburbs introduced new architectural and urban models, which gradually acquired distinctive characteristics and began to diverge in terms of location, morphology, and housing typologies. A defining feature of suburbia is low-density urban landscapes that typically surround the dense, high-rise urban centres in large cities [1]. Suburbia refers to residential areas located on the periphery of cities, characterized by lower population density compared to central urban districts. These areas often comprise single-family homes, private gardens, and localized commercial zones, offering a hybrid of urban and rural lifestyles [2].

In their spatial manifestations, suburbs serve as a middle ground between the density of cities and the isolation of rural areas, providing residents with a sense of community alongside access to urban amenities [3]. In addition to low building density, suburbs are typically characterized by rigid parceling systems, enclosed residential typologies, and uniform street morphology. Due to these characteristics, suburbs have often become synonymous with architectural and urban monotony. Nevertheless, the suburban form is shaped by various factors, including the desire for home ownership, decentralization of population, and the pursuit of community building [2].

Given the increasing necessity to redefine suburban models, this research aims to examine the extent to which architectural and urban diversity is present in contemporary residential communities. By analyzing suburban patterns across diverse geographical and cultural contexts, suburbs can be categorized into two primary groups: the first includes suburbs that exhibit similar forms of spatial organization [4], while the second consists of suburban areas with varied morphological and functional characteristics [5]. In this context, suburbs are most commonly perceived as homogeneous spaces dominated by uniform family housing; however, typological characteristics can be explored from multiple perspectives and classified according to a wide range of criteria, such as socio-economic composition, distance from city centers, and transportation connectivity.

This study proposes a classification of suburbs based on their typological features, with an emphasis on geographic location, functional organization, and socio-economic structure. The primary objective is to identify and group recurring patterns of spatial organization through a comparative analysis of suburban models across selected case studies, focusing on their typological housing characteristics.

2. RESEARCH METHODOLOGY

The methodology employed in this research is grounded in a comparative analysis and synthesis of a broad range of case studies concerning the spatial form of suburbia. The study is based on a comparative examination of dominant geographic contexts—North America, Europe, Australia, and Asia—with the inclusion of a representative example from Africa. The research draws upon urban planning documentation, case study analysis, and theoretical literature, approached through a comparative lens that considers historical context, spatial patterns, housing typologies, and the visual identity of suburban settlements. In addition to

comparative methods, the study also incorporates generalization, concretization, and specialization as methodological tools. The central research question is whether suburbs predominantly represent homogeneous architectural and urban entities, or whether, depending on the selected criteria, diverse typologies may emerge. The purpose of defining typologies is to identify specific suburban types and provide detailed insight into the built form, location, demographic characteristics, and/or historical background of suburban areas. Based on both inductive and deductive reasoning, nine case studies were selected as typological representatives of defined suburban groupings. The primary criteria for selection included geographic context, followed by functional-spatial characteristics and the socio-economic composition of the population. Through the analysis of these selected case studies, the research explores architectural and urban principles, as well as the social and historical factors that have influenced suburban development.

3. DEVELOPMENT OF SUBURBS

The genesis of suburban areas can be traced back to ancient Rome, when the patrician class began constructing villas outside the city walls, driven by the desire to escape the crowded urban centers. However, modern suburban concepts began to emerge only in the 19th century, in the United States and Great Britain [6]. The expansion of industry and tram transport, rapid urban growth, population increase, and the deterioration of sanitary and housing conditions in urban cores led affluent populations to migrate toward city outskirts [7]. This shift was motivated by the urban bourgeoisie's aspiration to live closer to nature and away from pollution and urban problems [8], a rationale that would continue to justify the growing trend of peripheral development [9].

The earliest suburban models in modern society emerged in 19th-century Britain with the housing concept known as the "Garden City," developed by Ebenezer Howard. His vision proposed a decentralized network of small urban units combining housing, work, and recreation, surrounded by green belts [10]. The first realized model was Letchworth Garden City, constructed in 1903, followed by Welwyn, established as a London suburb in 1920. Howard's idea offered a "golden mean" between rural and urban living and had a profound influence on suburban planning worldwide. His comprehensive concept emphasized that garden cities should not expand horizontally but rather multiply like living cells, whereby surplus populations would establish a new center at a sufficient distance from the original, again surrounded by green space [11]. Furthermore, a network of six to seven such garden cities was envisioned to spatially orbit around a central garden city, together forming a polycentric "social city" of approximately 250,000 residents. This spatial multiplication was conceived as limitless—each completed social city would spark the formation of the next, much like a web-like structure [12]. A defining characteristic of Letchworth was that it slowly attracted more residents through low taxes, low rents, and generous space provisions, primarily appealing to skilled middle-class workers [13].

In the United States, the emergence of the modern suburban form—as a standardized urban model with a functionally optimized residential structure—is most closely associated with Levittown. This suburb became synonymous with mass-produced housing models repeated hundreds of times, with little regard for individual needs. In that sense, Levittown represents the first large-scale, mass-produced residential development, constructed between 1947 and 1951. It arose in response to the post-war housing shortage in the United

States and served as a prototype for post-war planned communities [14]. Levittown offered affordable homeownership opportunities for veterans and their families, playing a crucial role in the emergence of the middle class and the growth of post-war consumer culture. As such, it became a symbol of the “American Dream,” enabling thousands of families to attain homeownership [15].

In other European countries, suburban development evolved more slowly and under different urban, demographic, and social frameworks. The post-war period marked a significant phase of transformation, characterized by planned urban development and the emergence of various forms of multi-family housing integrated into city structures. One of the most notable urban planning projects was the development of Vällingby, a suburb of Stockholm, conceived as part of Sweden’s vision in the 1950s to decentralize the capital. During this period, districts outside Stockholm were rapidly transformed into suburban zones [16]. In Asia, suburbanization occurred later—around the mid-1960s—but at a much larger scale, driven by the need to accommodate massive populations and high urban densities. In contrast to American models, Asian suburbs vary significantly depending on the country, local context, and socio-economic conditions.

4. TYPOLOGICAL CLASSIFICATION OF SUBURBS

Suburbanization, as a model of urban planning, represents an inevitable process within the expansion of large cities. Its essential role in shaping global urbanism is indisputable, as it significantly contributes to the formation of contemporary urban spaces. The purpose of typological classification is to identify specific types of suburban development and provide additional details about their built form. This topic has been explored through numerous studies and various approaches to analyzing different suburban forms [17].

Although suburbs are most commonly perceived as homogeneous spaces of standardized single-family housing, their internal structures and developmental models reveal significant typological diversity. Suburban typology can be examined from various perspectives and classified according to different criteria, including socio-economic composition, physical distance from the city center, and infrastructural connectivity to the urban core. This research addresses suburban typology through classification based on geographical context, functional-programmatic organization, and socio-economic structure.

4.1. Classification Based on Geographical Context

The first criterion for suburban classification is geographical context, referring to a comparative analysis of suburban areas in America, Europe, and Asia. Based on an in-depth case study analysis, the first category comprises **American suburbs,** which represent the most dominant suburban type globally. This group is characterized by planned construction on a large scale, low building density, and predominantly single-family housing known as tract housing or cookie-cutter typology. These suburbs often lack well-developed public spaces, or are defined by zoning policies that strictly separate residential from public and commercial zones. Such spatial arrangements lead to a heavy dependence on private automobiles, as public transportation infrastructure is often underdeveloped. This results in ecological challenges and contributes to suburban sprawl. Socially, these environments tend to foster segregation and socio-spatial stratification.

A characteristic example of the American suburban model is Levittown, the first modern, mass-produced residential community built on Long Island, New York. The Levitt and Sons, Inc. company developed a town that became a national symbol of the post-WWII suburban boom. With over 17,000 identical, low-cost houses constructed, Levittown exemplified a pre-planned suburban development equipped with supporting infrastructure such as shopping centers, playgrounds, swimming pools, and schools. This made Levittown a prototype for suburban residential planning across the United States [18].





Figures 1,2. American suburbia, Levittown, New York, source: (1) https://richardnilsen.com/wpcontent/uploads/2024/09/24-broadacre-hell.jpg (2)https://www.reddit.com/r/Suburbanhell/comments/ual7mw/this_is_levittown_the_first_americanstyle_suburb/?rdt=53539

European models represent planned suburban developments that combine single-family and multi-family housing types with commercial and public spaces. This typology typically includes higher population density, greater vertical development, and more advanced transportation alternatives, particularly well-developed public transit systems. These suburban areas often feature integrated functions and a richer public realm. However, in some cases, there is insufficient connectivity between suburban districts and central urban zones. A key characteristic of European suburbs is the preservation of cultural identity, including local architectural styles and vernacular traditions, which results in greater spatial heterogeneity. Nonetheless, social segregation—including ethnic segregation—is a persistent issue in many European suburbs [19].

A representative example of a European suburban model is Vauban, a neighborhood located on the outskirts of Freiburg, Germany. Built as a sustainable model district on the site of a former French military base, Vauban was developed in 2000 under the influence of the citizens' group Forum Vauban, which advocated for an ecologically responsible urban project. This collaboration between residents and the city government resulted in a masterplan based on the concept of a car-free environment. The community participated in the selection of residents, prioritizing families with children, elderly individuals, and existing Freiburg residents. While Vauban emphasizes residential development and ecological design, it lacks extensive public infrastructure. A section of the district was later developed to accommodate student housing for the University of Freiburg [20].



Figure 3. Aerial view of Vauban neighbourhood in Freiburg, Germany, source: https://www.strongtowns.org/journal/2019/9/18/this-neighborhood-in-germany-shows-us-why-american-planned-communities-are-so-abysmal

Asian suburbs, while facing similar demands for large-scale housing solutions as other regions, tend to follow rapid and massive suburbanization patterns that accommodate high population densities. Unlike American models, Asian suburbs are highly heterogeneous, exhibiting a wide range of features depending on the national and local context. They are characterized by very high residential densities and the integration of residential, commercial, administrative, and industrial functions within the same districts [21]. Vertical expansion is a prominent feature, with high-rise apartment towers serving mixed-use purposes—residential, commercial, and public. In Southeast Asia, particularly in Indonesia and Thailand, a notable phenomenon is "desakota", referring to regions where rural and urban characteristics coexist, blending agricultural activities with urban functions [22].

A notable example of a planned Asian suburb is Tama New Town, one of Japan's largest housing developments. Initiated in 1965, it emerged as a response to the rapid population influx into Tokyo and the increasing cost of urban land, prompting many to move to more affordable peripheral areas. Located 20 km from Tokyo, Tama New Town is distinguished by a hierarchically organized infrastructure and a diverse range of housing typologies, including both collective and single-family units. Although designed within the framework of functionalist modernism, this suburb demonstrates a strong ability to adapt to cultural housing norms, with a clear focus on social cohesion and accessibility to urban amenities [23].



Figure 4. Aerial view of Tama New Town neighbourhood in Tokyo, Japan, source: https://www.ur-net.go.jp/overseas/achievements/tama.html

4.2. Classification of Suburbs Based on Functional Division

The second criterion by which suburbs can be classified is their functional division, which includes residential, mixed-use, industrial, and commercial (business) models. This typological grouping is based on selected case studies from North America, Canada, and Europe.

Residential suburbs represent the most widespread type, characterized by exclusive residential use. The dominant housing model is individual single-family housing. According to these typological characteristics, Mississauga serves as a typical example of a North American suburban city, formed by tract housing developments comprising large numbers of similar or identical family homes. The city exemplifies planned urban development with an emphasis on uniform residential neighborhoods, spacious front and backyards, and low residential density. Housing typologies include mainly single-family detached homes, as well as townhouses and semi-detached houses. Public spaces are underdeveloped, and residents are heavily reliant on private automobile transportation.





Figures 5, 6. Aerial view of Mississauga, Ontario, Canada, source:(5) https://www.gmaps.com, (6)https://www.reddit.com/r/Suburbanhell/comments/iqsnse/dystopian_suburbia_in_mississauga_ontario_canada/?rdt=56130

Mixed-use suburbs include residential areas, commercial zones, public services, schools, parks, and even employment centers. These areas are planned to reduce dependency on travel to the city center. A representative example of a well-developed European mixed-use suburb is Vällingby, located on the outskirts of Stockholm. It is characterized by a diversity of housing typologies—both single-family and multi-family dwellings-as well as planned pedestrian and cycling infrastructure, and the creation of public spaces. The suburb was developed as a new concept urban district, known as the ABC city-Arbete-Bostad–Centrum (Work–Housing–Center). The ABC concept aimed to transform each suburban area into a self-contained mini-city that provided all the essential components for living and working-integrating employment, housing, and central urban functions within a single unit [24].



Figure 7. Aerial view of Vallingby, Stockholm, Sweden, source: https://vaxer.stockholm/omraden/hasselby-vallingby-stadsdelsomrade/vallingby/

Industrial suburbs are typically developed near industrial zones to provide housing for workers. A classical example of this suburban type is Irvine, located in southern Orange County, Los Angeles. Initially developed in the 1960s as a company town by the Irvine Company, it was intended to house company employees. Over time, Irvine grew into a city that became home to numerous corporations and universities. The city's urban plan is highly organized, with clearly defined residential and public zones. The development and appearance of the neighborhood are strictly regulated—in some areas, even roof styles, house colors, and landscaping are subject to guidelines. The community includes bike paths, parks, and green belts that connect to ecological reserves. Older neighborhoods such as Northwood, developed independently in the early 1970s, are less regulated and exhibit more diversity in design. Architecturally, homes are mostly typified and designed in the California style. Since the 1960s, properties have been modified and expanded, leading to greater visual variation in the present-day neighborhood.





Figures 8, 9. Aerial view of Irvine, Los Angeles, USA, source: (8) www.gmaps.com (9) https://www.ocregister.com/2023/01/12/irvine-may-change-how-city-officials-are-elected/

Business suburbs represent hybrid business-residential models, developed with a primary focus on corporate and administrative complexes, while also incorporating housing and other facilities within the development [25]. A prominent example of a predominantly commercial suburb with residential elements is La Défense in Paris. Planning for this district began in the late 1950s as part of a broader modernization strategy for the city. Although primarily designed as a business district, La Défense also includes residential areas, mostly situated on its periphery. Housing is spatially separated from the business zone, leading to

only partial functional integration. While La Défense is a successful example of concentrated business activity in a contemporary urban context, it also highlights the limitations of mono-functional planning. The lack of residential and cultural amenities, weak local community integration, and the fragmentation of the urban fabric result in a district that functions more as a business island than as an integral part of the city's urban structure.



Figure 10. View of La Defence, Paris, France, source: https://www.lexpress.fr/societe/justice/le-quartier-de-la-defense-boucle-apres-un-appel-evoquant-un-individu-arme_2129628.html?cmp_redirect=true

4.3. Classification of Suburbs Based on Socioeconomic Structure

The third criterion for suburban classification pertains to socioeconomic structure. This categorization is derived from selected case studies in Australia, Asia, and Africa. Suburbs may be grouped into three main categories: middle-class suburbs, luxury suburbs, and social housing suburbs.

Middle-class suburbs represent the most prevalent suburban model. A typical example is Craigieburn, a rapidly growing suburb of Melbourne, which addresses the challenges of suburban expansion. The area is characterized by uniform housing design and scale, with dwellings situated on smaller plots, enabling efficient land use and greater housing affordability for many families. Architecturally, the houses exhibit homogeneous features, although recent years have seen a trend toward greater design diversity. Public facilities are strategically zoned and well-integrated with residential areas. The population is composed predominantly of middle-income residents employed in service and administrative sectors, with a strong reliance on private vehicular transport.

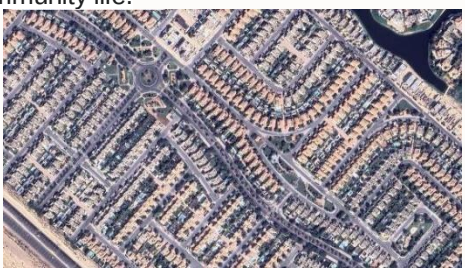




Figures 11, 12: Aerial view of Craigieburn, Melbourn, Australia, source: (11) https://www.gmaps.com (12) https://www.pomsinoz.com/articles.html/where-to-live-in-australia/victoria/craigieburn-melbourne-suburbs-r178/)

Luxury suburbs are urban models that do not differ structurally from middle-class or social housing neighborhoods in terms of organization, but are distinguished by their

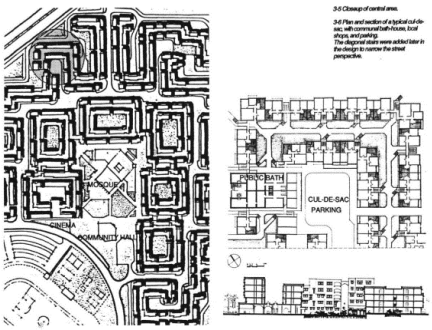
residential typologies. These suburbs consist of single-family housing, often in the form of luxurious villas, and include exclusive amenities such as golf courses, private security, and gated communities with restricted access. An illustrative case is Jumeirah Park in Dubai, a master-planned residential zone covering over 380 hectares and comprising more than 3,000 luxury villas. The villas are designed as freestanding units on individual plots. In an effort to break the architectural monotony, three stylistic variants were introduced: *Heritage style:* Inspired by traditional Arab architectural forms; *Regional style:* A blend of Arab and Islamic elements, featuring flat roofs and terraces to extend outdoor living space; *Legacy style:* Reflecting European influences, with pitched roofs, decorative arches, and classical façades [26]. Unlike earlier phases of suburban development, Jumeirah Park incorporates numerous public and recreational facilities aimed at diversifying the residential model and enhancing community life.





Figures 13,14. Aerial view of Jumeirah Park, Dubai, UAE, source: (13) https://www.gmaps.com (14) https://www.propertyfinder.ae/blog/jumeirah-park/

Social housing suburbs are typically developed as part of state-sponsored housing programs, often characterized by lower construction standards and high levels of socioeconomic segregation. A representative case is the Dar Lamane housing community in the suburban periphery of Casablanca, Morocco. This project, initiated in the 1980s, was designed to provide housing for low-income residents of nomadic and rural origin. It represents a hybrid suburban model, situated in an industrial zone, and structured to include not only residential units but also public urban spaces such as markets, mosques, and communal buildings, thus creating a central node accessible to the entire community. While the area is automobile-oriented, pedestrian and vehicular zones are clearly delineated, ensuring a degree of spatial order [27].





Figures 15,16. The view of Dar Laman, Casablanca, Marocoo, source: https://www.archdaily.com/977864/the-city-outskirts-suburbia-and-low-cost-housing/622105093e4b31b04d00004a-the-city-outskirts-suburbia-and-low-cost-housing-photo

5. DISCUSSION

Based on the conducted research and the analysis of selected case studies, several key conclusions can be drawn: suburbs do not represent homogeneous architectural and urban entities. The typological classification was established according to geographic origin, socioeconomic structure, and functional differentiation. Following these typological criteria, the following characteristics can be identified: The most significant differences among suburban models are observed based on geographic location. According to this criterion: *American suburbs* are characterized by predominantly residential typologies, consisting mainly of single-family homes with private gardens, and are heavily reliant on the automobile as the primary mode of mobility. These environments are defined by low population densities and a limited presence of public spaces. *European suburbs* are typically planned settlements that incorporate a mix of multi-family and single-family housing, exhibit greater urban compactness, and possess a more developed public transportation network. *Asian suburbs* demonstrate a high level of architectural and urban rationality, marked by high-density developments, residential towers, and a mixed-use organization where residential, commercial, and public functions are often integrated within the same building or urban block. The greatest similarities across suburban models are found in terms of socioeconomic categorization, including luxury suburbs, middle-class suburbs, and social housing developments. Additionally, commonalities can also be identified among suburbs grouped according to functional criteria. The *residential suburb* remains the most prevalent suburban typology, typically characterized by a limited range of functions. However, in recent years, a shift has occurred, with an increasing incorporation of public and commercial facilities within these areas. This evolution reflects a transition toward a *mixed-use model*, which integrates various forms of housing, along with public and commercial functions*. Industrial suburbs*, originally developed in proximity to production facilities, may range from being primarily residential to mixed-use environments. *Business suburbs,* on the other hand, represent growth areas of large urban centers, predominantly shaped by corporate and administrative functions, often with limited residential components.

6. CONCLUSION

Suburbanization, as a model of urban planning, represents an inevitable process accompanying the expansion of large cities. Suburbs emerge as a response to increasing housing demands, forming residential zones located outside urban cores, yet not fully integrated within rural areas. This form of settlement thus embodies a hybrid residential model situated between the “urban” and the “rural.”

As a modern form of housing, the suburb first appeared during the Industrial Revolution in the mid-19th century in the United States and the United Kingdom, as a retreat for the upper social classes from overcrowded, inhumane, and unsanitary working-class dwellings. However, suburbs experienced full-scale expansion during the mid-20th century, driven by the sharp rise in housing needs following World War II. This phase was pivotal for the development of suburban areas in America, Europe, and Asia alike. Based on the analysis of numerous case studies across different continents, the following conclusions can be drawn: suburbs can be classified according to various typological characteristics. In this research, the classification was conducted based on geographic affiliation, socio-economic

structure, and functional division. The most notable differences among suburban models emerge in relation to geographic context. American suburbs are predominantly residential, characterized by single-family houses with private gardens, automobile dependence, limited public spaces, and low population densities. European suburbs are typically planned settlements that incorporate elements of collective housing, greater urban compactness, and a more developed public transport system, while also integrating mixed-use functions and varied housing types. Asian suburbs display high architectural rationality and dense residential patterns. The dominant residential form includes high-rise apartment towers, with mixed-use development that integrates residential, commercial, and public functions—even within a single structure. Despite geographic differences, similarities among suburban models are observed in relation to socio-economic factors. These include luxury suburbs, middle-class developments, and social housing estates. In terms of functional classification, residential suburbs remain the most dominant, typically composed of single-family dwellings. However, in recent years, there has been a shift toward including public and commercial amenities within these areas. This evolution reflects a transition toward mixed-use suburban forms, which combine various housing types with public and business facilities. Industrial suburbs, often developed near manufacturing complexes, may take the form of primarily residential or mixed-use neighborhoods. Business suburbs represent expansion zones of major cities, marked by a dominance of commercial activity and a lack of adequate residential infrastructure. Suburbs, as a form of housing, may manifest as various architectural and urban models, each developed to meet the residential needs of local populations.

Depending on their geographic context, suburbs reveal both advantages and drawbacks in terms of urban planning. Identifying the spatial and organizational challenges, as well as issues of quality, remains a key task for future urban and architectural solutions, with the ultimate goal of enhancing the quality of life and adapting suburbs to contemporary living requirements. In this context, future research should focus on design-based challenges, with an emphasis on development strategies that support sustainable mobility and the introduction of new housing typologies—designed to respond to emerging family structures and evolving lifestyles.

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Research paper

ANALYSIS OF FLOOD ZONES IN SECTION OF THE WEST MORAVA RIVER BASIN ALONG THE E-761 HIGHWAY (KM 26 – KM 42)

Borko Radivojević[1], Ilija Ilić[2], Dragan Radivojević[3], Aleksandra Ilić[4]

Abstract

Analysis of floods in the part of the West Morava river basin, particularly in the area of the E-761 highway under construction, aims to assess the impact of floods on infrastructure and the environment, as well as to evaluate the influence of the highway structure on the flood waters flow, with the goal of identifying risk reduction etc. mitigation measures. Using hydrological (HEC-HM v.4.11) and hydraulic models (HEC-RAS v.6.0), meteorological parameters (precipitation), hydrological (discharge), and hydraulic (water levels and flood wave propagation) data were analyzed. By incorporating geographic data (GIS) and terrain topography information, a detailed assessment of flood risks in the areas influenced by the highway was conducted. The results of the analysis highlight critical sections of the basin where there is an increased risk of flooding, which could threaten the construction and functionality of the E-761 highway. This analysis provides important information for infrastructure planning and design, ensuring that the E-761 highway is resilient to floods and that negative environmental impacts are minimized. The case study focuses on the Riljačka River, a tributary within the West Morava basin, which intersects the E-761 highway corridor.

Key words: *Flood, the West Morava river, E-761 highway, hydrological analysis, hydraulic analysis, flood risk, infrastructure*

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1. INTRODUCTION

During April, and particularly in June 2023, Central and Eastern Europe were affected by a series of severe weather events. The magnitude of precipitation, the total volume of rainfall, and the duration of these events meet the criteria for classification as hydrometeorological natural disasters.

Serbia was also affected by this wave of natural disasters. Short-duration but extremely intense rainfall events triggered flash floods in torrential watercourses, leading to their swelling, splashing and flooding of agricultural as well as urban areas. These events caused substantial damage to infrastructure, buildings, and land.

Nearly all torrential watercourses within the entire basin area experienced significantly higher discharges than the hydraulic conductivity of their channels, resulting in overbank flow and the occurrence of flooding.

2. STUDY AREA AND INPUT DATA

In this study, hydrodynamic analysis of flood conditions was conducted for the Riljačka River at highway chainage km 37+000 during the high-water period. The Riljačka River is torrential stream that collects runoff from the Gledić Mountains and flows toward the villages of Drenova and Selište. As with all torrential watercourses, the discharge exhibits significant variability throughout the year, with the channel often carrying low flows or remaining dry for extended periods.

During rainy seasons, the discharge increases rapidly, and there are frequent instances of coinciding flood peaks on both the Riljačka River and the West Morava River (Figure 1).

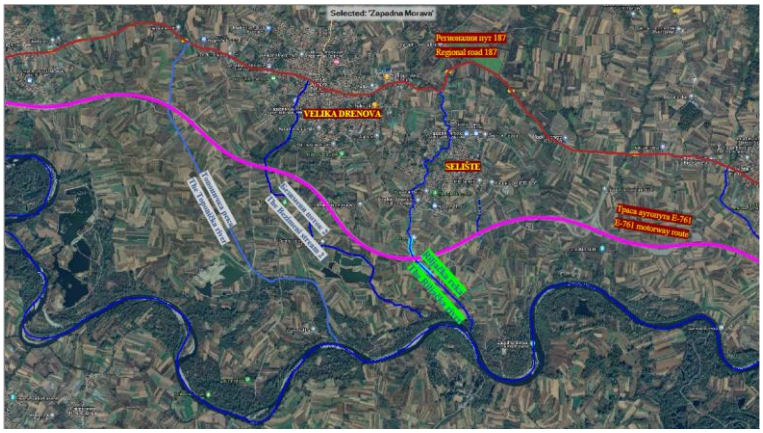


Figure 1. Overview of the E-761 highway section in the West Morava Valley with the axes of the Riljačka River, Bezimeni Stream 2, and Toponička River on the satellite image

2.1. Geodetic data (DEM)

Visualization of the terrain relief is commonly used nowadays for scientific, professional, and commercial applications. The Digital Elevation Model (DEM) is numerical and mathematical representation of the ground surface, most often in the form of a regular grid, in which a unique spatial elevation value is assigned to each pixel. DEM approximates the Earth's surface shape with a limited precision. The accuracy of terrain surface

approximation depends on the distribution and density of the collected data by different types of geodetic survey [1].

For the purpose of conducting the hydraulic analysis, a publicly available DEM over Europe (EU-DEM) was used in combination with traditional surveying data (Figure 2) [2].

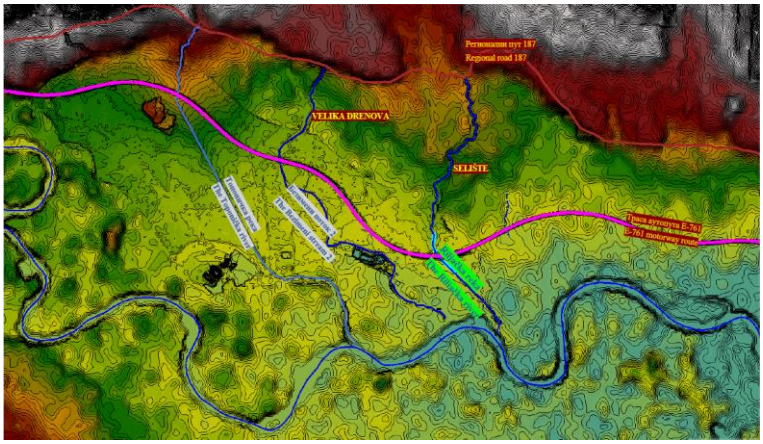


Figure 2. Overview of the E-761 highway section in the West Morava Valley with the axes of the Riljačka River, Bezimeni Stream 2, and Toponička River on the DEM

2.2. Hydrological data processing

The mathematical simulation of rainfall-runoff processes is contingent upon the specific hydrological problem under consideration. For computational flood estimation in small river basins, the model structure necessitates three fundamental components [3]: basin model, meteorological model and control specifications. The selection of process representations, spatial discretization, and temporal resolution is inherently problem-dependent, requiring careful consideration of basin scale, data availability, and desired accuracy in flood peak prediction. In this study, the Riljačka River basin was modeled using the software HEC-HMS v.4.11.

Terrain pre-processing is the first step in HEC-HMS modelling, converts raw DEM data (here, the EU-DEM DSM) into gridded and vector datasets for drainage network extraction and sub-basin delineation. The EU-DEM represents the first reflective surface (e.g., terrain, vegetation) across Europe at 25m resolution. The following steps were applied [4]:

- *Sink filling* modifies the DEM to remove depressions.
- *Drainage preprocessing* generates both flow direction and flow accumulation rasters from the elevation data.
- During *flow direction processing* (Figure 3), the model analyses the DEM to determine the steepest descent pathway for each grid cell.
- The *Flow Accumulation algorithm* (Figure 4) calculates the contributing drainage area for each cell by summing all upstream cells that drain to it.
- Using the derived flow direction data, the model extracts stream segments as connected flow paths between network nodes (Figure 5).
- The drainage area discretization establishes a hierarchical sub-basin structure where each stream reach receives runoff from its delineated contributing area (Figure 5).

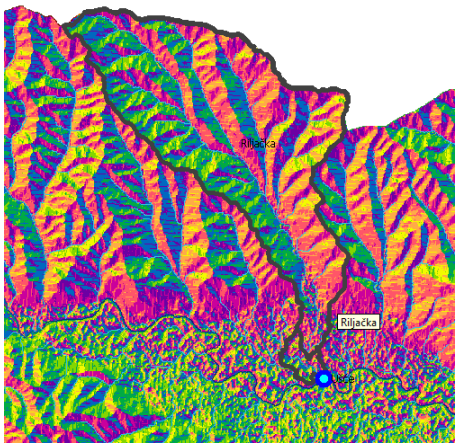


Figure 3. Flow direction



Figure 4. Flow Accumulation

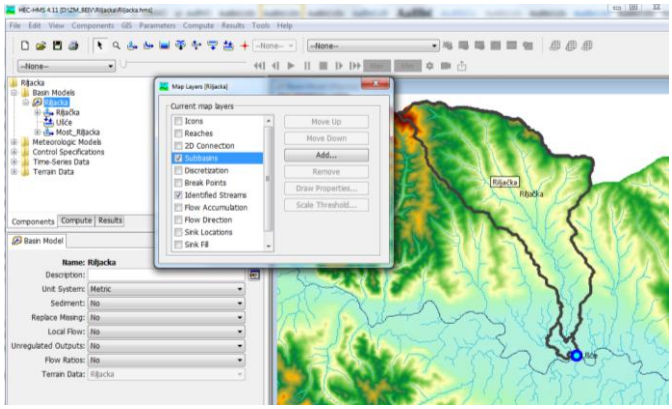


Figure 5. Stream identification and Elements delineation in HEC-HMS model

The second step involves **flood flow estimation**, which is highly dependent on data availability, basin size, and data quality. In contemporary hydrological practice, a combined approach is frequently employed, integrating:

- The Synthetic Unit Hydrograph (SUH) method for runoff hydrograph estimation;
- The SCS-CN (Soil Conservation Service Curve Number) method for effective rainfall separation.

Key emphasis is placed on establishing relationships between basin geomorphological characteristics (e.g., slope, drainage density, shape) and SUH parameters, including: effective rainfall duration (t_k), lag time (t_p), time of concentration (T_c), time to peak of hydrograph (T_p), recession time (T_r), time base (T_b) and peak discharge of unit hydrograph (q_{max}) [5]. Lag time (t_p) is usually defined as the time from the centroid of rainfall to the hydrograph peak. According to research results in Kolubara River basin in Serbia, the following formula is defined by Janković [6]:

$$t_p = 0.75\left(\frac{LL_c}{\sqrt{s}}\right)^{0.37} \quad (1)$$

Where the parameters refer to: the main stream distance from the divide to outlet (L), the main stream distance from the outlet to the basin centroid (Lc) and weighted channel slope (s).

In HEC-HMS, the synthetic unit hydrograph is derived from rainfall data. For ungauged basins, the dimensionless triangular unit hydrograph remains the most widely adopted approach due to its simplicity and reliance on empirical relationships.

The third step involves **model calibration**, which, due to the absence of local streamflow data, was conducted using regionalized hydrological parameters. Specifically, calibration was performed based on:

- The spatial distribution of specific runoff across the basin;
- Unit hydrograph characteristics (e.g., peak discharge, time parameters);
- Extreme flood probabilities (1% and 2% annual exceedance events).

These parameters were derived from regional studies of the Western Morava River basin [7], ensuring physically consistent estimates despite the lack of local gauging data.

Table 1 shows the characteristics of the Riljačka River basin, hydrologic soil group (*HsG*), ratio of time to peak to recession time (*k*), lag time (t_p) and the theoretical discharge values $Q_{1\%}$, $Q_{2\%}$, $Q_{5\%}$, and $Q_{10\%}$ and its specific runoff ($q_{1\%}$, $q_{2\%}$, $q_{5\%}$, and $q_{10\%}$).

Table 1. Characteristics of hydrological ungauged basin of the Riljačka River and theoretical discharge values and specific runoff at two profiles

Parameter	A	L	Lc	s	HsG	CN	k	tp
	km^2	km	km	%				h
Riljačka - Confluence	77.26	26.07	14.24	0.75	B	86.5	1.52	7.06
	$Q_{1\%}$	$q_{1\%}$	$Q_{2\%}$	$q_{2\%}$	$Q_{5\%}$	$q_{5\%}$	$Q_{10\%}$	$q_{10\%}$
	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$
Theoretical values	101.36	1.31	87.54	1.13	69.79	0.90	56.52	0.73
Parameter	A	L	Lc	s	HC	CN	k	tp
	km^2	km	km	%				h
Riljačka – Bridge Profile	75.48	24.10	12.54	0.82	B	86.38	1.51	6.44
	$Q_{1\%}$	$q_{1\%}$	$Q_{2\%}$	$q_{2\%}$	$Q_{5\%}$	$q_{5\%}$	$Q_{10\%}$	$q_{10\%}$
	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$
Theoretical values	107.57	1.42	92.90	1.23	73.89	0.98	60.10	0.80

Based on the calibrated model and the available rainfall data for the period April–June 2023, the daily peak values of flood waves were calculated. On April 4th, the peak was Qa=17.8 m³/s, while on June 12th, the value was Qj=19.9 m³/s.

3. METHODOLOGY

3.1. HEC-RAS Model

HEC-RAS enables the modeling of unsteady flow regimes across an entire network of open channels. Unsteady flow is characterized by variability of hydraulic parameters (flow, water level, speed) in space and time [8, 9, 10, 11]. Basic equations for linear, unsteady flow in open channels are Saint Venant equations:

- Mass conservation equation (equation of continuity):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \quad (2)$$

- Equation of conservation of momentum - dynamic equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\cdot A\frac{\partial Z}{\partial x}+g\cdot A\cdot I_e=0 \quad (3)$$

Where: Q – flow, A- surface area of the flow profile, I_e – friction slope.

The Saint Venant equations are partial differential equations of the hyperbolic type, which cannot be solved in the general case. By introduction of approximations these equations could be used for the calculation of water levels in open channels under unsteady conditions.

To solve them, it is necessary to set initial and boundary conditions. The initial conditions are the values of the variables along the channel at the initial moment of time (t_0). They are obtained by hydraulic calculation of steady flow for the initial flow value $Q(t_0)$.

Boundary conditions are posed:

- External – defined at the profiles at the upstream and downstream end of the calculation reach. At the upstream end, a hydrograph or graph of water levels can be specified, and at the downstream end a hydrograph, level graph or flow curve.
- Internal ones are given at profiles where there is an estuary, a dam, side overflow etc.

3.1.1. 1D Hydraulic model

Hydraulic flow calculations for the Riljačka River, based on computed discharge values during the flood events of April and June 2024, were performed using the HEC-RAS 6.0 software.

Hydraulic analysis of the Riljačka River flow were carried out along the section extending from nest in the West Morava River upstream to Regional Road 187, over a length of approximately 3.5 km.

The following characteristic discharge values were adopted: for the flood peak on April 4, Qa=17.8 m³/s; for June 12, Qj=19.9 m³/s; as well as the 50-year return period discharge ($Q_{2\%}$= 87.7 m³/s) and the 100-year return period discharge ($Q_{1\%}$=101 m³/s).

Due to vegetation growth within the stream channel, a Manning's roughness coefficient of n=0.08 $m^{-1/3}s$ was adopted. For overbank flow across agricultural areas, a value of n=0.12 $m^{-1/3}s$ was used.

Boundary conditions were posed at both ends of the modeled river reach as follows: at the downstream end "normal depth" boundary condition was applied with an energy slope of 0.01%, since the Riljačka River was effectively discharging into the West Morava without backwater effects. At the upstream end, "critical depth" condition was assigned, along with "mixed flow regime" specification to allow for a possible transition between flow regimes within the computational reach.

Two geometric scenarios were analyzed and compared.

- Flow of large floodwaters within the Riljačka River riverbed without a temporary crossing

- Flow of large floodwaters within the Riljačka River channel with installed temporary crossing with culvert designed of four pipes of inner diameter of 800 mm, immediately upstream of the highway route.

3.1.2. 2D Hydraulic model

2D model was developed, and unsteady flow analysis were performed to verify the flow regime during the large flood waves event appearance with return periods of 50 and 100 years. The 2D model was generated based on the Digital Elevation Model (DEM) for the area extending from km 27+500 to km 42+000.

To simulate the runoff, simulated 30-hour hydrographs were generated for the Riljačka River=basin. All hydrographs have peaks equal to the maximum discharges calculated in HEC-HMS.

These simulated hydrographs (Figure 6) are very useful for obtaining the response of the basin, as well as for determining the flow paths and locations of runoff accumulation, and for assessing the impact of the E-761 highway on the water regime.

Two digital terrain models were used, and thus two scenarios were created:

- Before the construction of the highway E-761
- During the construction of the highway E-761

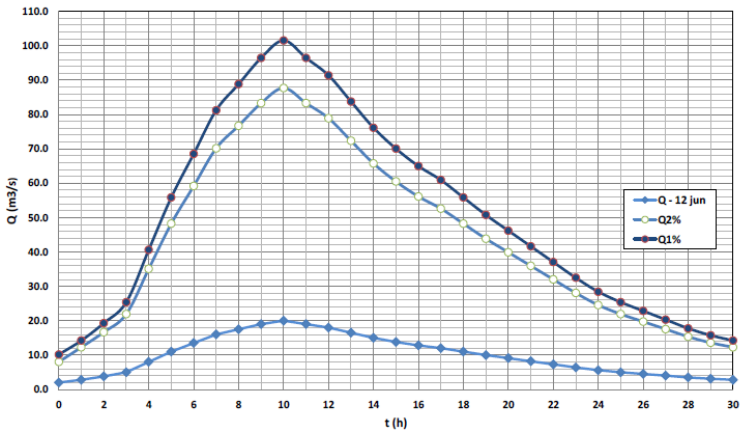


Figure 6. Hydrographs of the flood waves on the Riljačka River

4. RESULTS AND DISCUSSION

4.1 Results of 1D calculations

For the flood peak Qj= 19.9 m³/s in Scenario 1 (without a temporary crossing), water would overflow the riverbed downstream of the crossing location, as well as over a shorter section immediately upstream of the temporary crossing location.

In the case of Scenario 2, water also overflows the natural riverbed, but the impact of the temporary crossing is minimal and not significant, as the crossing would be completely submerged. Under real field conditions, the soil embankment would quickly wash away and disintegrate.

Flood peak discharges $Q_{2\%}$ = 87.7 m³/s and $Q_{1\%}$ = 101 m³/s, for both scenarios would result in extensive water overflow across both riverbanks along the entire section downstream of Regional Road 187.

The computed longitudinal profiles are shown in Figures 7 and 8.

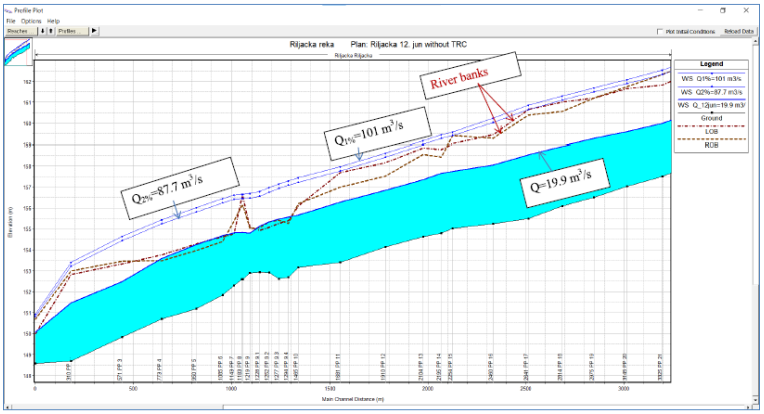


Figure 7. Longitudinal profile of the Riljačka River without the temporary crossing (Scenario 1) – Qj=19.9 m³/s, $Q_{2\%}$=87.7 m³/s, $Q_{1\%}$=101 m³/s

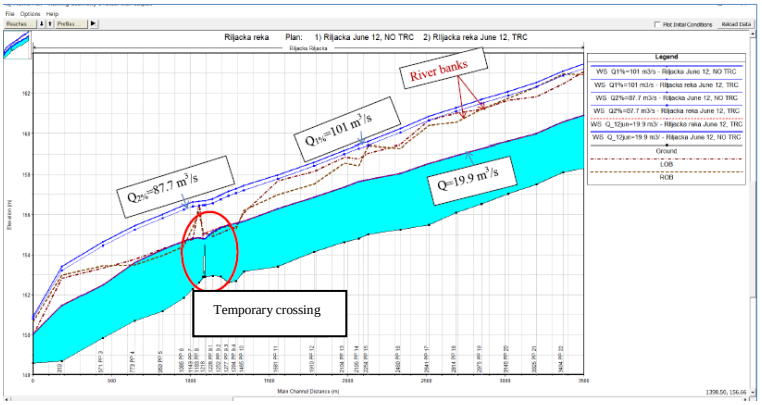


Figure 8. Longitudinal profile of the Riljačka River with the temporary crossing (Scenario 2) – Qj=19.9 m³/s, $Q_{2\%}$=87.7 m³/s, $Q_{1\%}$=101 m³/s



Figure 9. Comparative Analysis of Scenario 1 – Existing Riverbed Conditions and Scenario 2 – Temporary Crossing Installed for the peak flood wave on the Riljačka River (Qj=19.9 m³/s).



Figure 10.Extent of flooded area without and with the temporary crossing installed, Qj=19.9 m³/s.

Figures 9 and 10 show the extent of the flooded area for April 4, 2023, and June 12, 2023, corresponding to the flood peak discharge of Qj = 19.9 m³/s. The flooded area in Scenario 1-flow within the river channel without a temporary crossing-is shown in blue, while the flooded area in Scenario 2-with temporary crossing placed within the channel-is shown in red in the lower layer.

4.2 Results of 2D calculations

Figure 11 shows the flooded area resulting from the arrival of a 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) for Scenario 1, representing the terrain conditions prior to highway construction. Due to the flat terrain in the West Morava valley, there is a clear possibility of water overflow from the Riljačka River into the basin areas of the Bezimeni Stream 2 and the Toponička River. The highway alignment intersects the Riljačka River floodplain, making it very difficult to fully preserve the pre-construction hydraulic regime.

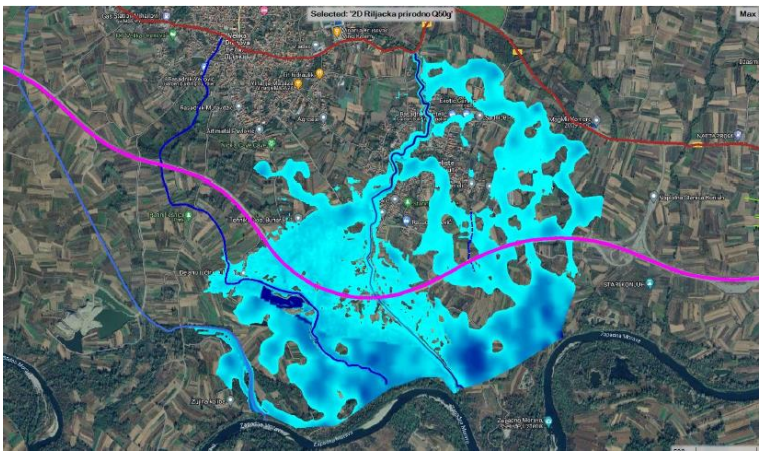


Figure 11. Flooded area resulting from the 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) under pre-construction conditions of the E-761 highway

Figure 12 shows the flooded area resulting from the arrival of a 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) for Scenario 2, representing the terrain conditions after

highway construction. In Scenario 2 as well, water overflows into the basin areas of the Bezimeni Stream 2 and the Toponička River. A noticeable change in the shape of the floodplain is observed compared to the pre-construction state, as part of the area on the southern side of the highway is effectively protected, while on the northern side the floodplain extends westward.

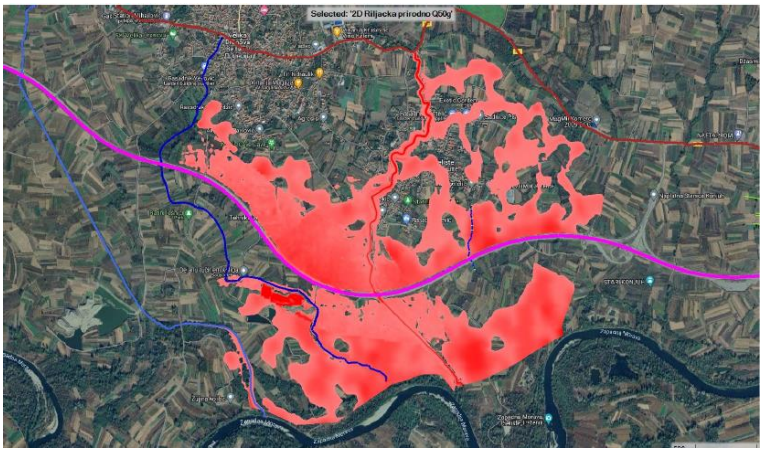


Figure 12. Flooded area resulting from the 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) under post-construction conditions of the E-761 highway.

Figure 13 shows the flooded area resulting from the arrival of a 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) for Scenario 1, representing the terrain conditions prior to highway construction. Due to the flat terrain in the West Morava Valley, there is a clear possibility of water overflow from the Riljačka River into the basin areas of the Bezimeni Stream 2 and the Toponička River. The highway alignment intersects the Riljačka River floodplain, making it very difficult to fully preserve the pre-construction hydraulic regime. The shape and extent of the floodplain are very similar to those for the 50-year flood.

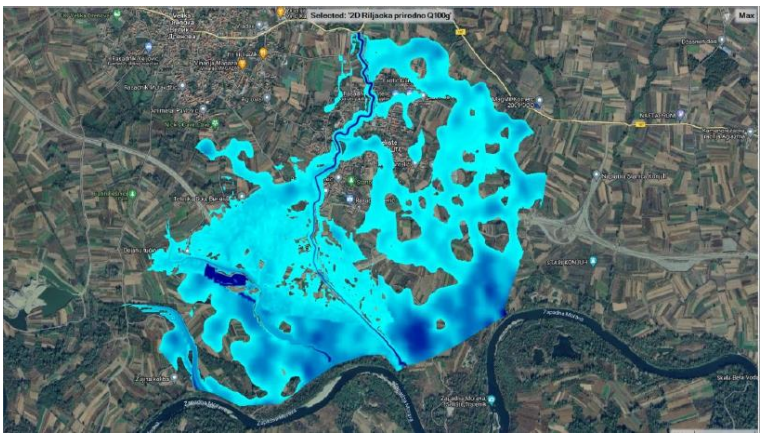


Figure 13. Flooded area resulting from the 100-year flood wave of the Riljačka River ($Q_{1\%}$ = 101 m³/s) under pre-construction conditions of the E-761 highway.

Figure 14 shows the flooded area resulting from the arrival of a 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) for Scenario 2, representing the terrain conditions with the built highway E-761. In Scenario 2 as well, water overflows into the basin areas of the Bezimeni Stream 2 and the Toponička River. A noticeable change in the shape of the

floodplain is observed compared to the pre-construction period, as part of the area on the southern side of the highway remains effectively protected, while on the northern side the floodplain extends westward. The shape and extent of the floodplain are very similar to those for the 50-year flood.

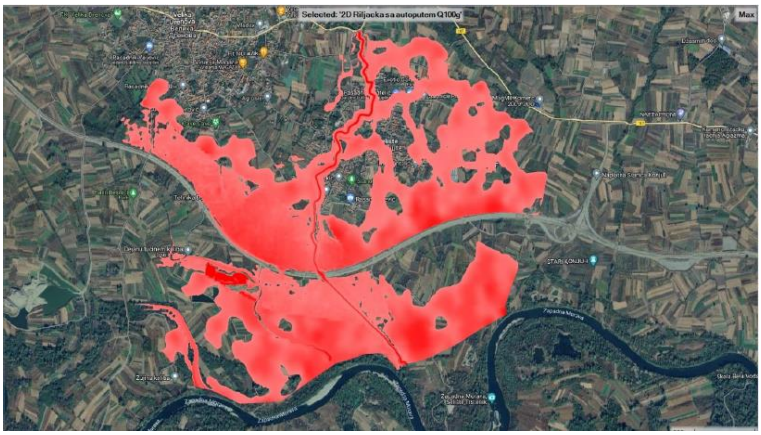


Figure 14. Flooded area resulting from the 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) under post-construction conditions of the E-761 highway.

5. CONCLUSION

The magnitudes of the extreme flow events of the Riljačka River were estimated based on created digital terrain model and data analysis from the nearest rainfall stations.

An analysis in the HEC-HMS software determined that on April 4th and June 12th, large flow waves occurred, resulting in water overflowing beyond the main riverbed of the Riljačka River.

From the calculated data, it can be concluded that the lowest part of the Riljačka River channel, downstream of the E-761 highway route, has a very small impact on runoff formation, meaning that the dominant influence comes from the wave collecting in parts of the basin area upstream of the E-761 highway. Additionally, and importantly, the maximum flow values at the bridge profile remain unchanged, indicating a very limited impact of the highway on the hydrological regime.

For the isolated events that occurred on April 4th and June 12th, for Scenario 1, under natural conditions before the highway construction, there is a minor overflow of the watercourse in the highway alignment zone. For Scenario 2, due to the installation of a temporary crossing with the culvert 4x800 mm, a slight backwaters is created over a length of approximately fifty meters upstream of the installed crossing.

During major 50-year and 100-year flood events, significant overflow occurs from the riverbed of the Riljačka River. Such events are not uncommon on the Riljačka River; on the contrary, they can be considered frequent. This is further exacerbated by the condition of the watercourse, which is overgrown with vegetation and contains large amounts of deposited waste material in certain sections, often leading to flooding of nearby settlements.

For the calculation of flood zones during major flow events, a 2D unsteady flow model was applied using generated 30-hour flood wave hydrographs.

It was observed that, due to the terrain configuration, flood flows of the Riljačka River-particularly in areas located within the floodplain of the West Morava River-result in overflow from the Riljačka River basin into the basins of the Bezimeni Stream 2 and the Toponička River.

Following the partial construction of the E-761 highway, changes in the hydrological regime have occurred. On the northern side of the E-761, the highway interrupts the natural north-south surface flow, causing water to accumulate on the western side of the bridge over the Riljačka River, while changes on the eastern side are significantly less pronounced. On the southern side of the highway, certain areas have become considerably less susceptible to flooding due to the construction of the highway.

Due to the terrain configuration along which the E-761 alignment runs-specifically, along the edge of the 100-year floodplain of the West Morava River-the natural hydrological regime has inevitably been altered, resulting in changes to the shape of the floodplains of both the Riljačka River and other torrential watercourses.

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Research paper

TIMBER VERNACULAR HERITAGE IN DANGER - FROM THE BORDERLINE OF BULGARIA AND SERBIA

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Abstract

The built heritage of the rural areas of the Balkans is characterized by decades of neglect, which developed as a consequence of the abandonment of rural areas, strong urbanization of cities, emigration of residents, and low birth rates. Most of the built heritage fund consists of residential and auxiliary buildings dating from the 19th and 20th centuries, in timber construction with infill made of wicker, mud, and straw. These buildings were built with one or two above-ground floors, with or without verandas, using traditional building principles and natural materials. Today, most buildings are abandoned, their roofs partially or completely collapsed, and parts of the structure and façade damaged. Further deterioration of these buildings increases the risk of complete collapse, jeopardising the record of the development of vernacular architecture in these areas. This paper examines the vernacular timber heritage of the border zone between Bulgaria and Serbia in the rural area of the Stara Planina ('Old Mountain') National Park region. The research is based on a comparative analysis of houses from Bulgaria, in the villages of Stakevtsi and Chuprene, and from Serbia, in the villages of Senokos and Boljev Dol, considering several indicators according to which they can be evaluated as significant examples of vernacular built heritage. Selected examples at risk of decay will be compared from the perspective of the functional plan layout, methods of construction, façade design and decoration.

Key words: Built heritage, Vernacular architecture, Endangered timber heritage, Bulgaria, Serbia

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1. INTRODUCTION

Since the mid-20th century, rural areas of the Balkans have faced numerous challenges. These challenges, initially caused by the rapid industrialisation of urban areas and a decline in agricultural activities [1], has led to an ongoing pattern of rural-to-urban migration. Unlike many developed European countries currently experiencing a trend of rural resettlement, many such regions in the Balkans remain marginalised [2].

The depopulation of villages results in an erosion of their ambience, ecological integrity and built heritage, and has particularly affected villages in mountainous and border rural areas due to high outward immigration and low birth rates [3]. Bulgarian census data indicate that areas most vulnerable to this process lie in the northwestern part of the country along the border with Serbia [4], whilst Serbia's most underdeveloped rural areas are found in its southeastern region [5]. The Bulgaria-Serbia border region includes part of the Old Mountain National Park, where preserved 19th-20th century vernacular architecture, built with local materials and traditional techniques [6] now faces abandonment and decay – posing a serious threat of permanent loss to the identity of the Balkan Mountain region and its authentic architecture.

This research reports the presents results from the project "Vernacular housing compounds along the borderline of Bulgaria and Serbia in the Western Balkan mountain - documenting endangered wooden buildings and related oral stories“ (part of Oxford Brooks University’s Endangered Wooden Architecture Programme). Our team used conventional hand-measuring building surveys in combination combined with 3d scanning, drones, and photographic recordings. Construction details were hand sketched on site with plans, sections, elevations and 3D animations created using CAD. Interviews with residents discussed house occupancy, building rituals, and construction traditions. Houses were selected for surveying based on minimal alteration, specific typologies, notable architectural details and access granted by the owner. The selection criteria for recorded houses were based on the minimal transformation of the building forms, particular house typologies, interesting architectural details and access granted by the owners.

This paper examines heritage at risk by comparing timber vernacular architecture in villages on both sides of the Bulgaria- Serbian border, north and south of the western Balkan Mountain. The primary research, conducted in the villages of Chuprene and Stakevtsi in Bulgaria, and Boljev Dol, Kamenica and Senokos in Serbia, analyses house location, layout, construction, facade design and decoration. Place names are transliterated from Cyrillic to Latin as per standard conventions of each country.

Approximately 20 houses were observed in each location, but only a limited number of housing compounds were studied in greater depth. Surveyed buildings include: Chuprene – 3 houses and 2 barns; Stakevtsi – 4 houses and 1 barn; Boljev Dol – 2 barns; Kamenica – 1 barn and 2 mills; Senokos – 3 houses and 1 barn.

2. HISTORICAL DEVELOPMENT OF VERNACULAR ARCHITECTURE IN THE BALKAN MOUNTAIN REGION

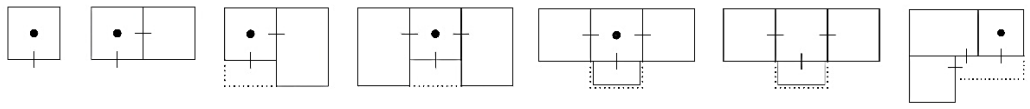
Earlly 19th-century sources describe local vernacular architecture as timber-framed with wattle and daub and thatched roofs. While semi-dug-in “*uzem*” houses were once common,

they had vanished by the century's end, leaving above-ground "*nazem*" houses as more common [7,8].

By the late 19th century (1880s–1890s), above-ground timber-framed houses were common across the Balkan Mountain region. Primarily single- but occasionally two-storey structures, the houses were referred to as "*izha/iža*" or "*kyshta*" [7], with early examples typically consisting of one or two rooms (Fig. 1a); a layout representing the simplest and oldest form of the local house typology. The main room, known also as "*izha/iža*" is where the hearth was located and served multiple functions: cooking, eating, daytime activities and sleeping. The earliest form of the hearth was located centrally in this room, with only a hole in the roof to vent the smoke; later hearths were constructed with a chimney and relocated towards the corners of the bedroom [8,9]. The roof of the house was always constructed as a four-sided hipped roof [6] and a second room, initially a store or pantry, became a bedroom ("*soba*") over time as families grew (Fig. 1b).

By the early 20th century single-room houses were no longer popular [8]. One- or two-storey houses with more complex plans gradually emerged; some, located in sloped areas, incorporated underground rooms for economic purposes like barns or cellars. These rooms occupied only a part of the building, and in all of the cases observed were never built beneath the room with the hearth. Porches/verandas ("*odvodi/trem*") were added along the long or short side of the house, usually on the sunlit facade where also the main entrance is located (Fig. 1c). In some two-story houses a projecting veranda, known in Serbia as a "*doksat*" [10] (Fig. 1e), would be integrated below the main roof and supported by wooden columns on its open sides [11].

As families became larger and wealthier the layouts of their homes evolved according to their needs; bedrooms became deeper at the expense of the porch, which gradually shortened, moved to a corner or was incorporated into the volume of the house (Fig. 1d). The need for additional rooms often resulted in dividing the *soba* or the "*izha/iža"*, whilst in Serbia, houses with an L-shaped plan emerged as the latest stage in the development of housing in the Balkan Mountain region (Fig. 1f) [10].



a) b) c) d) e) f)

Figure 1. Development of the houses- from the left a) one-room ("izha/iža") house; b) two-rooms house; c) house with porch; d) house with more rooms and integrated porch; e) two-story house with "doksat"; f) L shape house (sources: [10], [12], [13])

The spaces around the houses contained many structures related to the daily life and livelihood of the residents. This included two-storey barns with animals kept at ground level and hay stored above [12], separate structures known as "*preshiv*" used for storing grain and other crops, and additional structures designed to shelter different animals.

Buildings were constructed by local, often self-taught craftsmen, with communal participation by all villagers. Materials were locally sourced and easily obtainable and selected on the basis of experience accumulated empirically over a long span.

In the second half of the 20th century, villages – especially in the Bulgarian part of the region – experienced significant growth and change [13]. Contemporary urban planning and development introduced a new type of two-story residential building which, along with public

buildings like schools, cultural centers and post offices, later became abandoned. Shifts in local population demographics saw older houses modernised, often to resemble townhouses, while many more were demolished or reconstructed [11].

3. CASE STUDY OF VILLAGES IN BALKAN MOUNTAIN REGION

The location of the region and villages selected as case studies for the research is shown in Figure 2. The villages were analysed from three perspectives: 1) general features related to geography, demography, and economy; 2) location, siting, plan layout and form of the houses; and 3) construction, facade design and decoration of the houses.

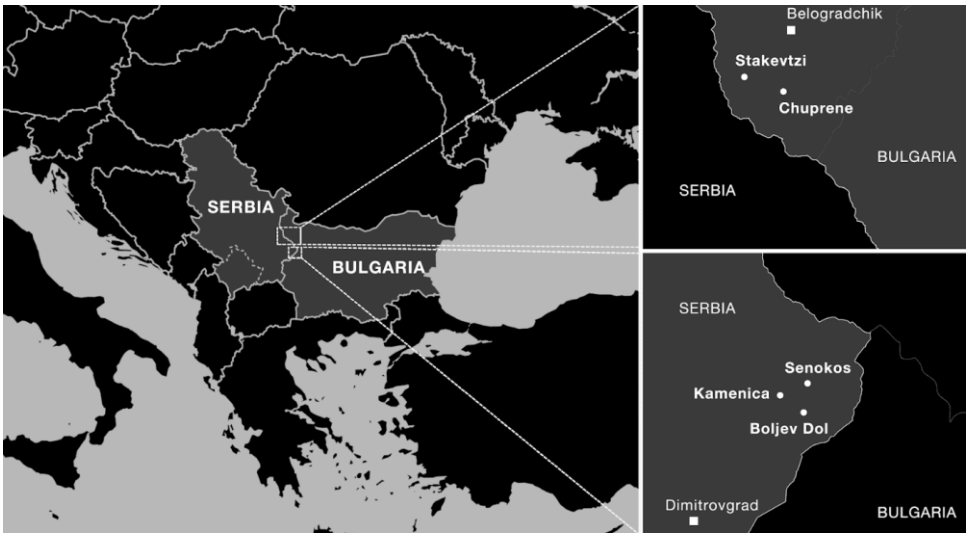


Figure 2. Map of subject area, source: S. Brooks using Google map

3.1. GENERAL FEATURES OF THE VILLAGES

The villages studied in both regions share numerous characteristics typical of this border region, reflecting common cultural traditions and crafts shaped by centuries of life in a rugged yet resource-rich environment.

On the Bulgarian side, the villages are situated on the northern mountain slopes, while the Serbian villages lie on the southern slopes. Although both Chuprene and Stakevtsi are part of the Vidin district, Stakevtsi falls within Belogradchik municipality whilst Chuprene serves as a municipal centre within the same district. Both villages are situated in a river valley.

The villages of Boljev Dol, Kamenica, and Senokos are situated in the Pirot District and are part of the Dimitrovgrad municipality. These three compact villages are among the 37 located in the Balkan Mountain region of Serbia. Boljev Dol is a typical mountain village, Kamenica is situated in a river valley and Senokos is a river-mountain village.

In Serbia each of the surveyed villages cover similar land areas, while Stakevtsi is nearly twice their size, and Chuprene around four times larger. This discrepancy can in part be attributed to the faster rate of depopulation of Boljev Dol, Kamenica, and Senokos (Fig. 3) and the status of Chuprene as a municipality center.

Villages developed near favorable conditions - along the courses of local rivers, in valleys surrounded by protective mountains and dense forests, with agriculture, livestock breeding and forestry [12] historically forming the backbone of local economies. The physical structure of all examined villages formed spontaneously along irregular street networks shaped by the mountainous terrain and natural features.

Villages were subdivided into local neighborhoods "*mahali*", (traditionally formed by extended families and known by family names) or after geographical features, many of which have been preserved to this day. Public spaces centered around gathering points - wells, fountains, churches, votive stones and pubs, with some evolving into squares.

Since the mid-20th century, the villages on both sides of the border have experienced major depopulation, as younger generations migrate to larger towns and cities, leaving behind an aging rural population. With scarce new development and widespread neglect of older structures, the villages face shared challenges – limited financial support, job opportunities and public services. Chuprene, as a municipal center, has managed to retain more residents, sustaining a slightly younger and more active community.

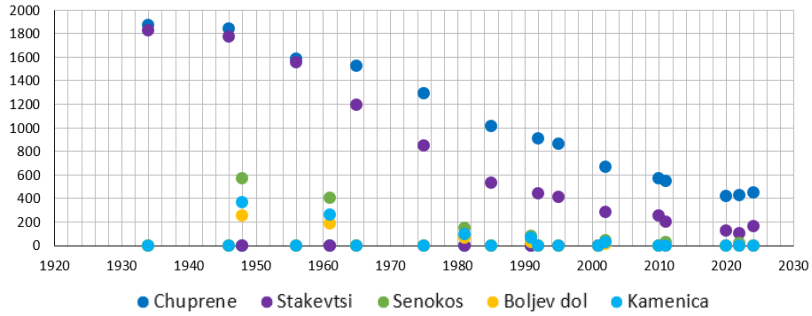


Figure 3. The distribution of people in villages-from 1940s to 2020s, sources [14-17]

3.2. POSITION, PLAN LAYOUT AND FORM OF THE HOUSES

In all the villages, available sunlight and the topography of the terrain play a significant role in determining the orientation and layout of both the houses and their positioning on site.

The most important factor is maximising southern exposure, which is why the principal, and usually longer, façade of the house (where the porch and most windows are located) tended to be oriented to the south. In some cases, depending on the slope and layout of the terrain, the orientation shifts slightly to the east or west, but north-facing aspects are routinely avoided as they offers less light and a greater exposure to cold winds and heat loss [10]. There are also some differences in house position and orientation in relation to access and main roads; in this case, houses often face the street with their longer, principal façades, reflecting their more public character or importance.

In contrast, houses situated along smaller paths or local roads often face inward toward their own sites with a shorter façade oriented toward the street – an arrangement which may reflect a more private and inward-facing way of life.

Most houses in Boljev Dol face roads with their short sides; in Senokos, as the buildings are situated mainly on the eastern and southern slopes, access to the main road is obtained both from the house's shorter or longer façade. In Kamenica, Stakevtsi and Chuprene, there are preserved houses along the main road with their principal façades facing the main road to reflect their prominent positioning. Both Stakevtsi and Chuprene also exhibit houses which face the street with their shorter side, in these instances a layout dictated by the terrain.

Topography further shapes house siting; depending on the terrain configuration, there are noticeable variations in how buildings relate to slopes. Some houses are aligned with their longer side parallel to the slope, following its natural contour, while others are perpendicular to the slope to take advantage of the semi-underground space formed on the downhill side.

With regard to the floor plans of the observed examples, most houses have a relatively simple layout consisting of two or three bedrooms surrounding the room with the hearth. The most common houses in the villages on both sides of the border are usually compact rectangular structures, with a single above-ground floor with or without a porch (Fig. 4a) [8,18]. Nevertheless, many houses, particularly on the Serbian side, have T- or L-shaped floor plans, reflecting adaptations to the terrain, functional needs or later extensions, with almost all having an underground level. In all surveyed villages, there are also examples of houses with two above-ground floors, some of which also feature an underground level located beneath a portion of the house.

In Boljev Dol there is a preserved one-room house representing the earliest stage of development in this region, while in Senokos and Kamenica, as well as in Chuprene and Stakevtsi, there are a few examples of small two-room houses (Fig. 4b). These houses always adhere to a rectangular compact plan with a small entrance porch and workshop or cellar in the basement.

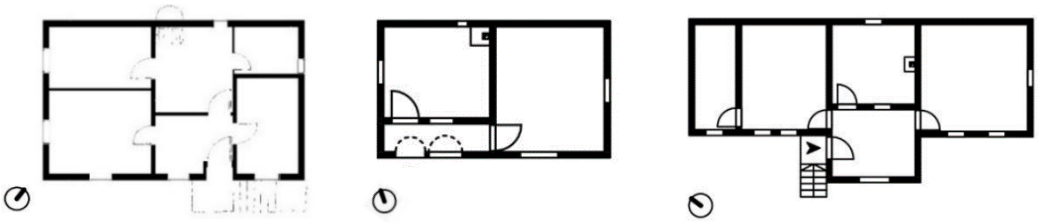


Figure 4. Ground-floor plans of the houses with single above-ground level: a) rectangular house with semi underground level in Stakevtsi b) two-room house in Senokos; c) T-shape house in Senokos, sources: A. Karapandzheva and B. Rančev

The T-shaped plan observed in these villages emerged as a consequence of introducing a closed entrance part - porch in the middle of the original rectangular plan [18]. Most houses with this plan geometry are a single storey building with an entrance positioned laterally on the protruding part of the T-shape. In this case the internal corridor provides access to the main room, a storage room and usually two bedrooms (Fig. 4c).

In summary, the orientation and layout of the houses results from a combination of factors: the size of the household, its economic means, and the materials at their disposal, in turn dictated by available sunlight, natural terrain, and necessary access, all combining to influence the form and structure of the built environment.

3.3. CONSTRUCTION, FAÇADE DESIGN AND DETAILS OF HOUSES

The rural vernacular architecture of the Western Balkan Mountain region represents a unique blend of environmental adaptation, local craftsmanship, and authentic socio-cultural expression (Fig. 5). Construction techniques reflect locally sourced materials, primarily stone, timber and clay, and buildings typically comprise a stone foundation and a timber-frame superstructure. The foundation and basement levels were built with locally sourced stone,

often constructed using dry masonry techniques or with clay mortar, relying on the weight and arrangement of the stones to ensure stability and durability.



Figure 5. Examples of houses: first row- Bulgarian villages, second row- Serbian villages, sources: authors

Upper walls of the houses were usually built using a timber frame infilled with wattle and daub, straw-reinforced clay plaster, cob, or occasionally adobe bricks [10], and finished with a final layer of lime-washed clay plaster resulting in the characteristic white façades of residential buildings (Fig. 6). Wooden structural elements in the timber frame are joined using traditional carpentry techniques with precisely crafted joinery connections and a minimal application of additional binding elements, a method which ensures durability, structural flexibility, and ease of replacement for individual components [19].



aS aB bS bB cS cB dS dB

Figure 6. Comparation of construction, details and finishes: S- Serbian villages, B- Bulgarian villages, sources: authors

Roofs are generally hipped or multi-pitched, made from wooden elements, and designed to shed heavy snow and rain efficiently. Stone roofing is a notable and expressive element of the architecture in the area of Senokos, resulting from the availability of specific local stone that can be easily split into slabs (Fig. 7). Originally, roofs were covered with stone tiles approximately 3-5 cm thick, laid in overlapping rows to cover the joints between lower layers [10]. The ridge and roof crest are also covered with stone and secured with clay mortar, but in some cases covered with clay roof tiles. Meanwhile, in the area of Stakevtsi, clay tile cover prevails, reflecting a different local material; a difference also reflected in the underlying design of the roof structure.

Stone coverings also have a characteristic roof and eaves design of horizontal beams supporting wooden rafters to achieve a gentler roof pitch. By contrast, clay tiled roofs typically lack such horizontal members, resulting in a different frame configuration.

Although wood plays a vital structural and decorative role, in residential settings it remains mostly concealed beneath plaster, contributing subtly to the architectural character. Conversely, in barns and granaries wood is a dominant visual element, with the timber-frame structure faced in planks to create a rhythmic visual pattern on the façade. When plaster is used for ancillary buildings such as barns and livestock shelters, (particularly in the Serbian villages) the earthy texture and color of the clay is retained without whitewash alongside the exposed timber framing resulting in a more rustic appearance [20]. Meanwhile, in Bulgarian

villages, these structures are typically faced sparsely positioned wooden planks to allow for greater natural air circulation.

Typically, wood is adorned with simple carvings, especially on columns, the ends of rafters and beams; occasionally, doors and windows are more elaborately carved. Another decorative element commonly found on house façades is on the columns supporting the arches of the porch, which are often decorated with specific carvings [20].



aS aB bS bB cS cB

Figure 7. Comparation of roof construction, roof covering and façade design from left to right: S- Serbian villages, B- Bulgarian villages, sources: authors

4. COMPARATIVE ANALYSIS - RESULTS AND DISCUSSION

Table 1 summarises the comparative analysis of the Bulgarian and Serbian villages studied, covering general features, siting, plan layout, house forms, construction and decoration. Residents numbers are based on current census data. The number of floors includes the basement. While villages on both sides share notable similarities regarding house position, layout and form, differences appear in construction and façade detailing.

Table 1. Comparative analysis of villages in Bulgaria and Serbia

Attributes		Bulgaria		Serbia		
		Stakevtsi	**Chuprene**	**Boljev D.**	**Kamenica**	**Senokos**
General	residents no.	105	427	1	8	19
	listed houses	2	4	0	0	0
	major economy-past/present	agriculture, livestock, forestry/ none	agriculture, livestock, forestry/ livestock	livestock / none	livestock / none	livestock / farming, cow herding
	church/state	yes/active	yes/active	yes/active	yes/ruined	yes/active
	school/state	yes/empty	yes/active	yes/empty	yes/ruined	yes/ruined
	library/state	yes/active	yes/active	no	no	no
	interventions	yes	yes	yes	yes	yes
Position, layout, form	access to road (mostly)	both	both	from the short side	from the long side	both
	position related to slope	long & short side follows the slope	long & short side follows the slope	long & short side follows the slope	long & short side follows the slope	long & short side follows the slope
	main façade orientation	S, SE, SW	S, SE, SW	S, SE, SW	S, SE, SW	S, SE, SW
	house plan geometry	□, square, T shape	□, square, T shape	□, T & L shape	□, T shape, L shape	□, T shape, L shape
	no. of floors	1-3	1-3	1-3	1-3	1-3

	min. rooms	2-3	2	1	2	2
Construction	type	stone foundation & timber frame	stone foundation & timber frame	stone foundation & timber frame	stone foundations & timber frame	stone foundations & timber frame
	wall infill	wattle and daub, SR clay plast. or bricks	wattle and daub, SR clay plaster or bricks	SR clay plaster	SR clay plaster,	wattle, SR clay plaster or bricks
	façade finishing	LW clay plaster, clay plaster	LW clay plaster, clay plaster & wood	LW clay plaster, clay plast., & wood	LW clay plaster, clay plaster & wood	LW clay plaster, clay plaster & wood
	roof form	hipped or multi-pitched	hipped or multi-pitched	hipped or multi-pitched	hipped or multi-pitched	hipped or multi-pitched
	roof rafters order	fan-like manner	fan-like manner	fan-like manner	parallel	parallel
	roof covering	clay tile	clay tile	clay tile	stone slabs or clay tile	stone slabs or clay tile
	window sashes no.	double & triple	double & triple	double & triple	double & triple	double & triple
	flooring type	earthen	earthen	earthen	earthen	earthen, stone tile
	ceiling type	LW clay plaster/ wooden planks	LW clay plaster/ wooden planks	LW clay plaster	LW clay plaster	LW clay plaster
Decoration	degree	scarce	scarce	scarce	scarce	scarce
	roof elements	carved rafters	carved rafters	carved fascia board & rafters	carved fascia board & rafters	carved fascia board & rafters
	façade features	coloring, arches, columns' carving	coloring, arches, columns' carving	coloring, arches, columns' carving	coloring, arches, columns' carving	coloring, arches, columns' carving
	windows & doors	decorative framing	decorative framing	decorative framing & carving	decorative framing & carving	decorative framing & carving
Legend: LW-lime-washed; □ rectangular plan; SR- straw-reinforced; S-south; SE-south-east; SW- south-west						

A broader discussion of similarities and differences can be found in Table 2.

Table 2. The similarities and differences overview

Aspects	Similarities	Differences
Demography & economy today	The population has significantly declined in the last decades, resulting in no economy today in villages with few residents.	Serbian villages undergo a faster rate of depopulation. Due to a larger population, today Bulgarian villages are more economically developed.

New construction & interventions	A significant number of buildings have new interventions due to the need for repair or the absence of responsibility for preserving the heritage. Interventions include concrete reinforced construction, new roof covering, and converted porch to a closed entrance part.	New construction is more prevalent in Bulgarian villages as a result from more people living there compared to the Serbian villages.
Plan layout and form of the houses	Most houses have a room with the hearth & 2-3 bedrooms. Plans are usually rectangular or T-shaped, with 1/2 above ground floors. Some houses are designed for siblings: so-called 'twin' houses.	In Serbia, some houses have a prominent L-shape floor plan. In Chuprene a square floor plan was uncommon.
Main construction system and joints	All houses on both sides of the border feature ground and semi-underground floors with stone base masonry of local stone. The upper floors-first and second levels-are typically built with a wooden box-frame structure filled with wattle and daub.	In the Bulgarian villages all walls on the ground floor are made by stone masonry, while in Serbian villages there were examples with just two or three of the ground floor walls constructed by stone and the front façade made of timber box frame & wattle and daub.
Roof construction and covering	On both sides there were roofs covered with clay roof tiles. The roof structures beneath these coverings were similar in form and construction, including similar types of joints.	The predominant roof covering in the Serbian villages was stone tiles, with clay tiles in Bulgaria. The difference in material necessitated a different eaves design. In Bulgaria, the rafters often take a fan-like form in contrast to the Serbian cases.
Floors and ceilings	Ceilings were with wooden boards, covered with clay and whitewashed. All floors were made of rammed earth.	In Bulgarian villages there were examples of ceilings with visible wooden boards. In the Serbian villages, the porch floors were often finished with large stone tiles.
Façade design	The facades are colored and lime washed.	In Serbia there were more houses with arches, while in the Bulgarian cases they were less.
Decorative elements	Decoration is generally scarce in the researched area. Both sides exhibit geometric carvings on the main column supporting the porch and on the rafters. Windows and doors have decorative framing.	In Serbian villages carving can be found on windows and doors and on the fascia board of the roof.

5. CONCLUSION

Similarities and differences between the Bulgarian and Serbian villages are described in Table 2. In terms of demographics and economy, both regions are in a state of decline and depopulation, processes that are more apparent in the Serbian villages. Somewhat younger families employed in agriculture, cattle breeding or tourism are present on both sides.

Influenced by European construction methods and designs, the mid-20th century saw Balkan vernacular house construction practices dating to the Ottoman era supplanted by 'modern' reconstructions. Such houses are more evident in the Bulgarian villages, with many residents of the Serbian villages continuing to live in the houses in which they were born.

In terms of siting, plan layout and construction there are many similarities in both regions; both exhibit examples of twin houses, whilst Serbian villages feature more L-shaped houses.

There are subtle differences in the ground floor surface – built entirely from stone in Bulgaria and partially in Serbia. The roof coverings differ due to available materials – heavy stone slabs with a different supporting timber structure is predominant in Serbia, whilst in Bulgaria a fan-type timber roof structure supports a lighter roof covering of clay tiles.

Interiors are largely similar, with rammed earth floors, lime-washed walls and ceilings with wooden boards. Hearth and fireplace designs show many variations on both sides, and while Serbian houses employed simple decorative arch structures, this feature was less frequently observed in the Bulgarian villages. Carved timber decorations are similar across villages and often employed on posts, beams, capitals, porch balustrades, eaves and fascias. Principal carpenters were responsible for creating these details to a particular variation of their liking which could be used as a sign of recognition.

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Research paper

METHODOLOGY DESIGN OF RESIDENTIAL BUILDING BY THE ARCHITECTURAL STUDIO BJARKE INGELS GROUP, CASE STUDY: THE MOUNTAIN AND VM HOUSES

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Abstract

Multi-family housing represents one of the key aspects of contemporary architecture, and the studio BIG (Bjarke Ingels Group) is recognized for creating unconventional and attractive, as well as functional and practical solutions for buildings of this purpose. Using two examples of multi-family housing projects, The Mountain and VM Houses, located in Copenhagen, the methodology of their design is explained through the application of various types of analyses, including contextual, conceptual, and analysis of project formation. The aim of this paper is to provide a systematic overview of the development process of selected projects, from the initial idea to their realization. The research findings show that different approaches to designing buildings with the same purpose and on the same location can lead to distinct but equally high-quality solutions. It has been determined that the use of a single typological unit can result in a very complex form, while the use of different types of housing units can result in a simpler form. This paper highlights the importance and complexity of the designing process of multi-family housing, contributes to the understanding of the design methodology of the studio BIG, and opens possibilities for further application of similar analyses in the study of contemporary architectural projects.

Key words: *Studio BIG, Methodology of Architectural Design, Multi-family Housing, Function of Space, Architectural Form*

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1. INTRODUCTION

Architectural design is a complex process that many architectural theorists have attempted to explain and define. The design process was methodologically divided into several phases by different authors. Markus and Maver divided the process into analysis, synthesis, appraisal, and decision [1]; the British architectural association RIBA divided it into assimilation, general study, development, and communication [2, 3], while Lojanica identified preparation, idea incubation, concept formulation, concept verification and solution development as phases of process of architectural design [4]. Most recent framework has simplified the process into three stages: contextual analysis, conceptualization, and project formation [5]. Contemporary architectural practice encompasses a diverse array of methodological approaches, rendering the design process significantly more complex than a linear sequence of steps. Nevertheless, a comprehensive understanding of this process requires its decomposition into distinct phases and its examination through multiple aspects [6].

The design of multi-family housing faces many challenges in contemporary architecture, and the studio BIG finds original and innovative solutions [7]. As examples of multi-family architecture, The Mountain and VM Houses [8, 9] (Figure 1) were selected as case studies, to demonstrate that, despite being located in the same area and sharing programmatic similarities, they embody two distinctly different formal and conceptual approaches, yet both represent equally successful architectural designs.



Figure 1. VM Houses and The Mountain, source: [9]

The architecture of studio BIG follows new principles and introduces new ways of thinking into architecture. Moving beyond the traditional concept of “form follows function” coined by Louis Sullivan [10], studio BIG emphasizes “form follows fiction” [11] as a central design strategy that integrates multiple aspects simultaneously and fosters a comprehensive design perspective. Contrasting the modernist ideal of “less is more” [10], studio BIG promotes the principle “Yes is more” [12], which welcomes complexity, diversity, and contradictions to generate creative and innovative architectural outcomes [13].

2. METHODOLOGY

According to the most recent contemporary approach [5], the design methodology of selected projects by the architectural studio BIG has been analyzed through several key aspects, including contextual analysis, conceptual analysis and analysis of project formation, simultaneously for each project. In the following text, the results of the conducted

comparative analyses for VM Houses and The Mountain will be presented, through which the methodology design of the studio BIG is demonstrated.

2.1. Contextual Analysis

With regard to the broader context (Figure 2), the case study buildings are located in Ørestad, a newly developed urban district situated on the southern edge of Copenhagen, Denmark. This urban district represents a mixed-use area that integrates residential, commercial, cultural, and educational facilities within walking distance [9].

VM Houses and The Mountain are located in easternmost edge of Ørestad which places them in direct proximity to the border of another district to the east characterized predominantly by low-rise single-family houses, typically one or two stories high. This neighboring residential area is separated from the site by a canal, a strip of greenery, and a street. To the west of the site, there is a zone of multi-family residential buildings ranging from five to eleven stories in height. These are also separated from the subject buildings by a street and a canal, above which is a railway. The distance from the subject buildings to the nearest neighboring structures on both the eastern and western sides is approximately 40 to 50 meters. A dead-end extension of Ørestad Boulevard functions as a spatial boundary that separates the two projects, situating The Mountain on its northern side and VM Houses on its southern side. To the south of VM Houses, the mixed-used buildings are situated, spatially separated from the building site by a small urban park, while to the north of The Mountain lies Ørestad Streethal (Figure 2). The described immediate context had a considerable impact on the buildings' height, storey count and architectural form.

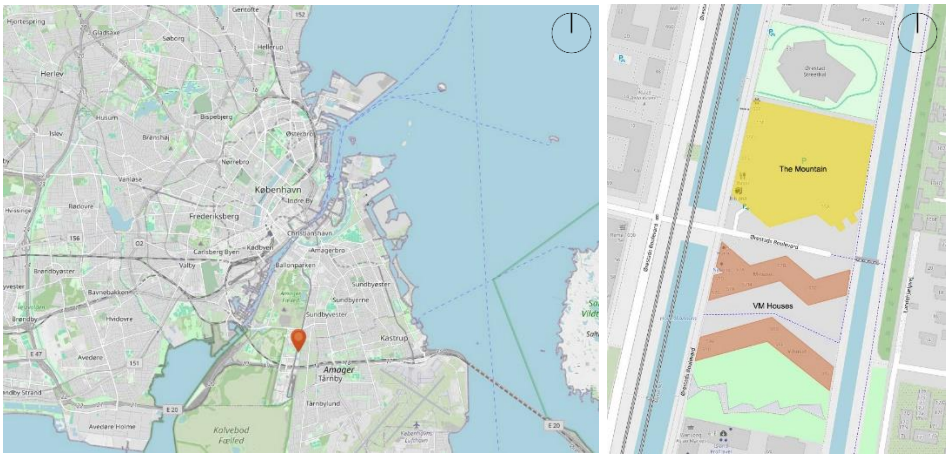


Figure 2. The broader and the immediate context, source: OpenStreetMap, author

The climatic conditions at the location of both buildings are the same as in the rest of Copenhagen. The city has a temperate maritime climate, characterized by mild winters and moderately warm summers [14]. Precipitation is frequent throughout the year, and the number of sunny days is relatively low [14], which creates a demand for increased access to natural daylight in residential buildings.

The cultural and social context encompasses an easygoing lifestyle, high living standards, social cohesion, and a strong sense of community, all characteristic of the Danish environment. In architecture, these values are reflected through the prioritization of comfort, sustainability, and quality of life [15].

2.2. Conceptual Analysis

The concept behind almost every studio BIG's project is based on a narrative approach embracing the principle of "form follows fiction" [11]. Their architectural process is driven by storytelling, frequently initiated through a "what if" question: what would happen if this idea were realized [12]. The initial idea in their projects is developed through multiple iterations and is integrated into the context. As a result, their projects often present spatially compelling structures that stand out due to their consistency with the original concept.

In the case of VM Houses, the concept is formed around the question: What if residential buildings were shaped like the Latin letters: "V" and "M". Instead of simply placing two parallel residential structures, the design adopted the distinctive shapes of these letters (Figure 3) in the floor plan, as this configuration allowed for improved daylight access, better ventilation, enhanced views, increased floor area, and a more dynamic layout. For The Mountain, also known as Mountain Dwellings, the concept was conceived through a question: What if the characteristically flat city of Copenhagen were to gain a mountain of its own. According to that idea the building was designed to resemble a sloped mountain form (Figure 3), with the structure gradually rising in height, featuring a parking facility occupying the lower, inclined base of the building and residential units terraced above it.

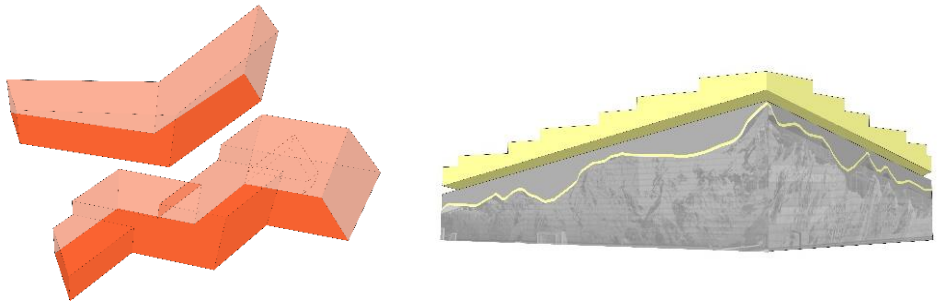


Figure 3. Concept for VM Houses (left) and The Mountain (right), source: author

"The idea is that rather than choosing between opposites, you can try to incorporate opposite extremes," explained Bjarke Ingels, describing the central concept behind studio BIG's "yes is more" philosophy [12, 16]. This conceptual approach applied in case study projects concerns the arrangement of residential units in relation to the complexity of the facade. In the case of VM Houses, a greater number of diverse residential unit types were placed to span two or three floors, resulting in a simpler overall form and uniform facade (Figure 4). Conversely, The Mountain employed a typology where each residential unit is similarly organized as a single-floor unit, but resulting in a dynamic and expressive facade (Figure 4).

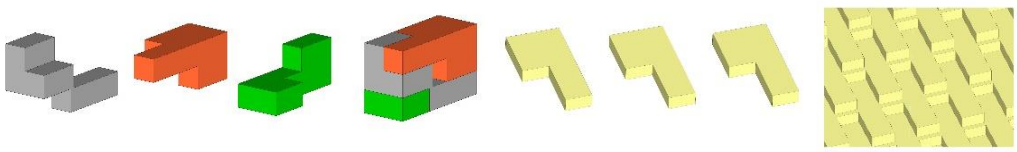


Figure 4. Concept: arrangement of residential units - VM Houses (left) and The Mountain (right), source: author

2.3. Analysis of Project Formation

Project formation is a complex process that involves a series of decisions related to form creation, spatial and functional organization, contextual response and refining architectural details. Bjarke Ingels claims about his works that “even though it’s carefully crafted, premeditated, discussed and designed and tested, when you see it, it has to feel effortless” [17]. This statement highlights the complexity behind Studio BIG’s design methodology, while also emphasizing their aspiration to create architecture that appears natural, fluid, and easy. This effortlessness is firstly noticed in the building’s form and then in other aspects such as materiality, function, and user experience, creating a harmonious and intuitive architectural design.

The following section presents an analysis of methodological and architectural design considerations, beginning with an explanation of the form and its development (Figure 5) as the most distinctive aspect of the architecture of these two buildings.

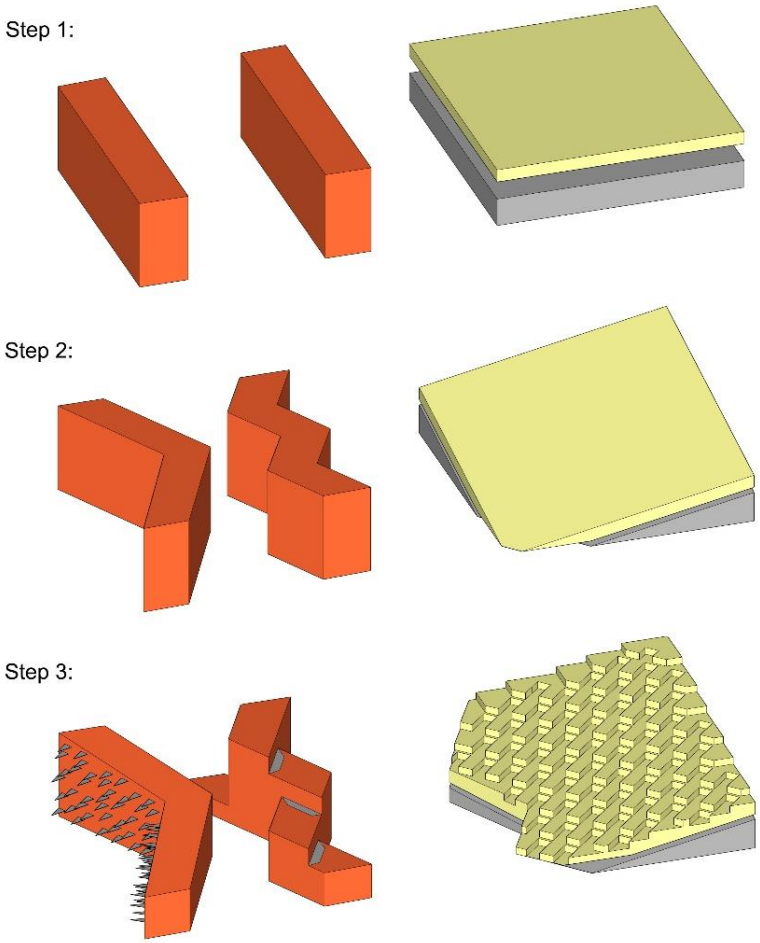


Figure 5. Form creation of VM Houses (left) and The Mountain (right), source: author

The first step in defining the form of both buildings involves establishing their overall volumes and determining their respective functions. For the VM Houses, this consists of two parallel, rectangular prisms that extend east to west, representing the residential buildings (Figure 5). In the case of the Mountain, the initial concept proposed allocating

approximately two-thirds of the overall volume to parking space below, with the remaining one-third designated for housing units above (Figure 5).

The second step in the form development involved the conceptualization of the buildings' defining characteristic shapes. In this step of creating the form of the VM Houses one of the prisms was pulled inward at the center, creating a V-shaped volume, while the other prism was bent at multiple points, creating a M-shaped volume (Figure 5). The Mountain had one of its corners lowered to ground level, creating the characteristic appearance of a mountain slope (Figure 5).

The third and the last step is about finalization of form which is related to context matching, involving further modifications to height and shape, and adding the details. The height of the VM Houses was reduced on the side adjacent to low-rise, single-family houses, while the full height was maintained on the side facing taller, multi-family residential buildings. Additionally, a two-story volume was added to the M-House to improve accessibility. Terraces were added: spiked, triangular terraces on the V-House and rooftop terraces on the M-House, effectively utilizing available open space (Figure 5). In the case of the Mountain, its height was already aligned with the surrounding context, so only the form was further refined to reflect the jagged silhouette of the M-House. The residential portion of the building was also articulated by projecting an orthogonal grid onto its top surface, guiding the following placement of individual housing units, resulting in a form resembling stepped pixels [18] (Figure 5).

One aspect of form is color, which plays an important role in subject buildings. In addition to materials such as glass, concrete, metal, and wood, which are characterized by their neutral textures and tones, vivid colors are selectively used in specific areas. Colors are applied in circulation and semi-public spaces, such as corridors, staircases, ramps, and parking garages. In VM Houses, the residential section contains three main corridors, each serving three floors. These corridors are distinctly colored: the lowest is painted green, the middle one yellow, and the highest orange-red (Figure 6). In The Mountain, there is a single continuous interior space for circulation that connects all levels. The colors change distinctly between floors, starting with green on the lowest level, progressing through yellow, orange, red, pink, and purple, concluding with blue on the highest floor (Figure 6). The use of color in both projects enhances users' spatial orientation and contributes to the visual identity of the buildings.



Figure 6. Color distribution - VM Houses (left) and The Mountain (right), source: [9, 19]

An essential architectural feature observed in both VM Houses and The Mountain lies in the conceptualization and integration of residential units are designed and combined into three-dimensional form, directly influencing appearance of the facade. In the case of VM Houses, there are approximately 105 different unit types, yet they are designed to combine seamlessly, forming a very simple overall shape and a uniform facade that does not reveal the complex internal organization (Figure 7). In contrast, The Mountain contains only a single standard residential unit type repeated throughout the structure with minor modifications along the perimeter. Despite this typological uniformity, the arrangement of these units creates a highly dynamic three-dimensional structure and a visually expressive facade (Figure 7). As Bjarke Ingels explained “once you force these sort of seemingly mutually exclusive concepts together, you actually get a new hybrid that somehow ends up looking different because it performs differently” [17]. This approach reflects studio BIG’s methodology of combining contrasts into cohesive architectural solutions [16].

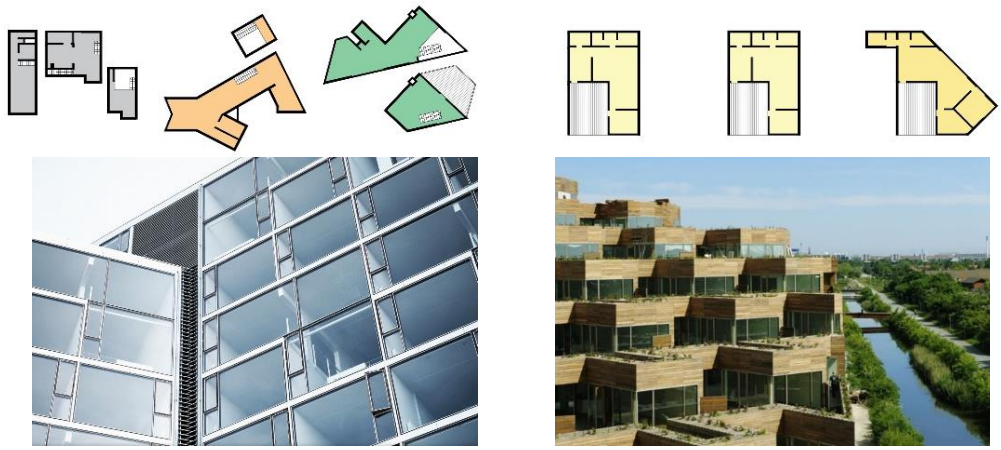


Figure 7. Residential units compared to the facade - VM Houses (left) and The Mountain (right), source: author, [9, 20]

Both projects prominently feature extensive glass surfaces on their facades, reflecting a thoughtful response to the local climate, a moderate maritime environment characterized by relatively few sunny days. Despite this shared contextual adaptation, the two projects present distinctly contrasting architectural approaches. VM Houses express openness through large, uniform glass surfaces on the facade, while The Mountain, with a significant portion of its facade dedicated to parking and the residential units positioned atop the structure, conveys a sense of privacy and enclosure from its surroundings.

Though fundamentally different, both buildings exemplify Bjarke Ingels’ belief that "In the big picture, architecture is the art and science of making sure that our cities and buildings fit with the way we want to live our lives” [9]. This diversity in architectural expression parallels the diversity of the inhabitants they serve. VM Houses represent a classic example of multi-family housing offering a variety of unit types distributed across multiple floors and maintaining openness to the exterior environment. Conversely, The Mountain presents a more private residential typology. Although it is multi-family housing, each unit mimics the form of a single-family home, complete with expansive terraces and green spaces reminiscent of private yards, accommodating a lifestyle centered around family living.

3. RESULTS AND DISCUSSION

The comparative analysis of VM Houses and The Mountain has revealed studio BIG's methodological approach to designing multi-family housing. Despite their shared location, function, and programmatic framework, the two projects demonstrate distinct conceptual and formal outcomes, resulting from different narrative design approaches.

Both buildings were shaped in direct response to their surroundings, demonstrating how contextual parameters can serve not as constraints, but as valuable design potentials. From a conceptual standpoint, storytelling emerges as a central design principle in studio BIG's work, where each project begins with a "what if" scenario that evolves through narrative-driven iterations. These distinctive conceptual strategies not only define the unique architectural identity of each project but also demonstrate studio BIG's commitment to integrating form, function, and context in innovative ways.

Contrast plays a key role in studio BIG's architectural approach, as seen in the VM Houses and The Mountain projects. Studio BIG achieves visual simplicity through a mix of diverse unit types in one project, while generating visual complexity using a single repeated unit in the other. Table 1 provides a comparative overview of architectural characteristics observed in the VM Houses and The Mountain projects. VM Houses consist of 225 units, encompassing approximately 105 distinct housing types, each spread across 2 to 3 floors, offering a wide variety of residential options. The facade is uniform and simple, enabling openness towards exterior. Open spaces are in form of balconies and few rooftop terraces. In contrast, The Mountain comprises 80 residential units, of which approximately 50 are identical. It is characterized by one main unit type with slight modifications. Facade is expressive and dynamic, but enables privacy. Open spaces consist of roof terraces for every single unit. All of these architectural characteristics reinforce a harmonious contrast between openness and enclosure, as well as diversity and repetition, highlighting studio BIG's capacity to create varied living experiences through distinct yet equally intentional residential design solutions.

Table 1. Comparation of architectural characteristic of VM Houses and The Mountain

architectural characteristics	**VM Houses**	**The Mountain**
building form	V-shaped and M-shaped	mountain-like slope
number of housing units	225	80
number of unit types	~105 different units	~50 identical units
unit layout across levels	units across 2-3 floors	single-floor units
facade	uniform and simple	expressive and dynamic
open spaces	balconies, rooftop terraces	roof terraces on all units
parking	in the surrounding area	inside the building
unit typology → visual expression	multiple unit types → simple exterior	one unit type → dynamic exterior
user lifestyle	openness and diversity	privacy and conformity

4. CONCLUSION

The design of residential buildings is a highly complex process influenced by the ideas, conceptual framework, context, and the architect's individual approach. The comparative analysis of VM Houses and The Mountain demonstrates that different design strategies, whether based on typological diversity or uniformity, can result in, yet equally successful architectural solutions. Within the framework of contemporary architecture, especially in studio BIG's projects, the relationship between form and function is inseparable.

By analyzing the design methodology of VM Houses and The Mountain, it is shown that the processes and methods of contemporary architectural design are changing. This paper reflects a broader transformation in contemporary architecture, where the emphasis is not only on the built outcome but also on the reasoning behind design choices. By focusing on methodology as an important part of architectural research, this study encourages further exploration of how architects can engage with complexity, contradiction, and innovation in the design of residential architecture.

Beyond the comparative examination of two case studies, this paper outlines key characteristics of current residential design practices, with an emphasis on the strategies employed by studio BIG. Future studies might expand this investigation by exploring other building typologies within studio BIG's portfolio or by analyzing comparable housing projects from different contemporary architectural studios.

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Research paper

ACOUSTIC TREATMENT OF SPACE BY IMPLEMENTING PARAMETRIC PANELS

Predrag Radomirović[1], Momir Praščević[2], Ivana Nikolić[3], Petar Jovanović[4]

Abstract

The development of software tools has enabled more detailed analysis of the acoustic properties of a space. Therefore, this research explores the possibility of improving the acoustic and aesthetic qualities of a space through the implementation of parametric wall panels. The research was conducted in two phases. As part of the first phase, the sound absorption coefficient was measured. The absorption coefficient of the intended material was tested by the experimental method using a Kundt's tube. For research purposes, the absorption coefficient of Styrodur XPS d=10mm, Styrofoam d=10mm, MDF d=10mm and MDF d=6mm sheet materials was measured. The second phase of the research includes the design of parametric wall panels, and then the analysis of the impact of their implementation on the reverberation time. Panel design was done using the software tool Rhinoceros and the Grasshopper plugin. The application of parametric design made it possible to easily generate different geometric forms. The influence of the implementation of parametric panels was examined by using the Odeon tool, using the software modeling method. Through the software modeling method, the impact of the depth of folds and the distance between the elements of the parametric wall panel (diffuser) on the acoustic properties of the concert hall was analyzed. The results of the research contribute to a new approach to the design of wall panels, the implementation of which would contribute to the aesthetic value of the space, as well as to the knowledge of how their implementation affects the acoustic characteristics.

Key words: *Parametric Design, Room Acoustic, Sound Absorption Coefficient, Reverberation Time, Wall Panels*

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1. INTRODUCTION

Acoustic quality is a crucial architectural attribute in venues designed for live performances such as theaters and concert halls. A large number of performance halls built in the past do not meet appropriate acoustic quality standards. In the present day, advancements in software tools have given engineers and designers the ability to analyze spaces with greater accuracy, opening new possibilities for enhancing acoustic performance. Acoustic quality is a key architectural feature, especially in venues designed for live performances like theaters and concert halls. However, challenges often emerge when trying to upgrade existing performance halls. Many of these halls weren't acoustically optimized in the past, largely due to the lack of proper tools. Today, to effectively improve a hall's acoustic performance, designers must be skilled in using advanced tools to evaluate current acoustic conditions. A central aspect of acoustic analysis is reverberation time—the amount of time it takes for sound to decay by 60 decibels after the sound source has stopped. Ideal reverberation times vary depending on the type of performance, typically falling between 0.6 and 2.2 seconds [1-3]. Many existing buildings face issues due to insufficient acoustic treatment during their original design. Although different types of performances require specific acoustic conditions, these halls were often not designed with a particular function in mind [4]. To ensure that such halls can support various types of performances while maintaining high acoustic quality, it is essential to optimize the reverberation time through targeted acoustic interventions. The primary factors that influence reverberation time are the volume of the space, the sound absorption coefficients and geometry of the interior surfaces. For this reason, the aim of this research is to propose the design of a parametric acoustic panel, whose geometry, material composition, and implementation at specific points within the interior would contribute to eliminating the phenomenon of sound focusing in the auditorium space.

In the initial stage of this research, experimental measurements were conducted to determine the sound absorption coefficients of selected panel materials: Styrodur XPS (thickness 10 mm), Styrofoam (10 mm), MDF (10 mm), and MDF (6 mm). The objective of these measurements was to evaluate the acoustic performance of each material and to identify comparable absorption characteristics, with the aim of selecting suitable candidates for the construction of acoustic panels. The measurements were carried out using a Kundt's tube (impedance tube) in accordance with standard testing procedures for small sample acoustic analysis.

This study presents a design proposal for parametric wall panels, divided into segments with varying fold depths. The dynamic geometry of the structure contributes to diffuse sound scattering and the formation of a more uniform sound field. The design process was carried out using Rhinoceros software in combination with the Grasshopper plugin. Using the Odeon Acoustic software tool, an analysis of the propagation of sound waves through space was performed. The ray tracing method identified the parts of the interior surfaces that reflect the highest percentage of sound energy and create focusing points of sound in the space. By placing acoustic panels at points that reflect the greatest amount of sound, a diffuse sound field is created and the possibility of creating focused sound spots in the hall is reduced.

2. SOUND ABSORPTION COEFFICIENT MEASUREMENT

This study investigated the acoustic performance of various building materials using the impedance tube method in accordance with [5]. The tested samples included MDF of different thicknesses, styrofoam, and extruded polystyrene (XPS). The measurement process, including calibration with correction factors, ensured accuracy and reliability of the data. These findings provide valuable insight for architects and engineers seeking to optimize sound absorption in built environments. Overall, the results support strategic use of both material selection and configuration to achieve desired acoustic outcomes.

2.1. Test Method and Test Samples

Laboratory measurements of sound absorption coefficients were conducted using an impedance tube, following the test method outlined in [5].

Table 1. The tested samples data

Identification	Description	Thickness [mm]
Sample 1	Medium density fiberboard (MDF)	6
Sample 2	Medium density fiberboard (MDF)	10
Sample 3	Styrofoam	10
Sample 4	Extruded polystyrene (XPS)	10
Calibration sample	Open-cell polyurethane foam	25

The test samples were mounted in a large sample holder (UA-1119), an aluminum tube with a movable piston, ensuring the sample's front surface was perpendicular to the tube axis. Measurements were conducted within the frequency range of 50 Hz to 6400 Hz.

A random sound source generated plane waves, and sound pressures were recorded at two microphone positions near the sample. The complex acoustic transfer function was calculated to derive acoustic properties [5-9].

The two-microphone method decomposes the broadband signal into incident (p_i) and reflected (p_r) components using pressures measured at two positions (Fig. 1.).

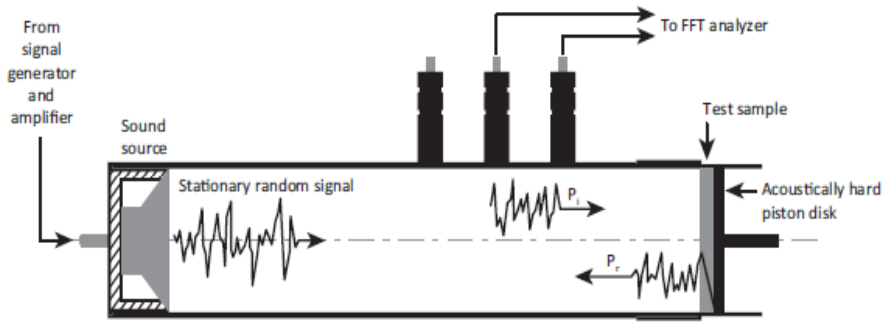


Figure. 1. Cut-away diagram of the impedance measurement tube [2]

The complex reflection coefficient (R) is computed as [5]:

$$\underline{R} = \left(\frac{\underline{H}_1 - \underline{H}_i}{\underline{H}_r - \underline{H}_1} \right) e^{2jk(l+s)} \quad (1)$$

where $\underline{H}_1$ is the frequency response function, $\underline{H}_i$ and $\underline{H}_r$ are incident and reflected components, *k* is the wave number, *l* is the distance from the first microphone to the sample (in mm), and *s* is the microphone spacing (in mm) [1].

The normalized impedance ratio ($z/\rho c$) and sound absorption coefficient (α) can be calculated from the following equations [5]:

$$\frac{\underline{z}}{\rho c} = \frac{1+\underline{R}}{1-\underline{R}} \quad (2)$$

$$\alpha = 1 - \left| \underline{R}^2 \right| \quad (3)$$

The frequency response function is obtained from the cross-spectrum of the two microphone signals. Any mismatch in phase or amplitude between the microphone channels can distort computed response. To correct for this, calibration involves calculating the frequency response function first with the microphone in one arrangement and then after swapping their positions. The geometric mean of these two measurements is used as a correction factor that can be applied to all subsequent tests, effectively removing errors caused by microphone channel mismatches.

Calibration corrected for microphone mismatches by calculating the frequency response functions in standard (H_{C1}) and interchanged (H_{C2}) positions, yielding a calibration factor ($\underline{H}_C$) applied to all measurements.

2.2. Analysis and Discussion of Test Results

Sound absorption coefficients were measured in one-third octave bands from 50 Hz to 6400 Hz, with results analyzed for different materials.

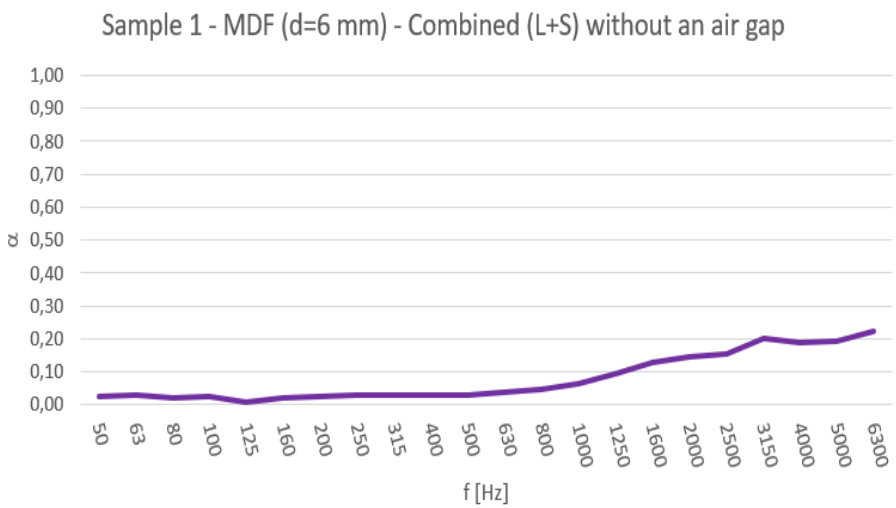


Figure. 2. Sound absorption coefficient of 6 mm MDF samples

Figure 2 shows the results of measurement of the normal sound absorption coefficient according to [5]. MDF, 6 mm, exhibited low absorption, especially at low and mid frequencies, with slight improvement above 1600 Hz.

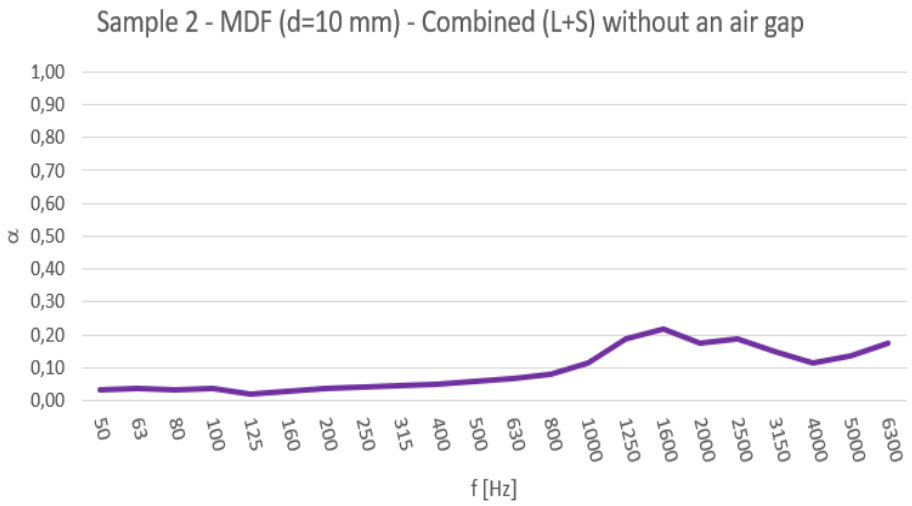


Figure. 3. Sound absorption coefficient of 10 mm MDF samples

Figure 3 illustrates the sound absorption coefficient of MDF (10 mm thick) across a frequency range of 50 Hz to 6400 Hz. Similar to 6 mm MDF, the 10 mm MDF demonstrated limited absorption, with marginal improvement at higher frequencies. However, it exhibited slightly better high-frequency absorption compared to the thinner sample.

According to reference [10], 18 mm MDF has greater stiffness, which increases acoustic impedance and reduces low-frequency absorption. Nonetheless, it performs better in the mid-frequency range (1–2 kHz), particularly when surface properties are optimized.

The comparison between 6 mm and 10 mm MDF samples shows that increasing material thickness leads to improved sound absorption at higher frequencies. This indicates that material thickness has a significant influence on absorption behavior, particularly in the mid-to-high frequency range.

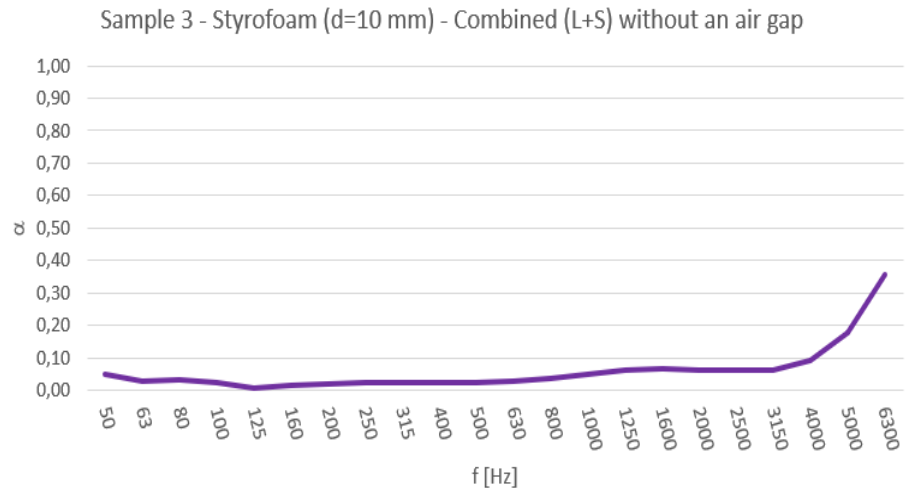


Figure. 4. Sound absorption coefficient of 10 mm styrofoam samples

Styrofoam had stable but low absorption coefficient (0.2–0.3), with a slight increase above 1500 Hz. Although both the MDF and styrofoam samples share the same thickness (10 mm), their absorption characteristics differ notably due to variations in composition. Styrofoam's higher porosity and lower density contribute to its relatively higher sound absorption in the upper frequencies, underscoring the importance of material structure.

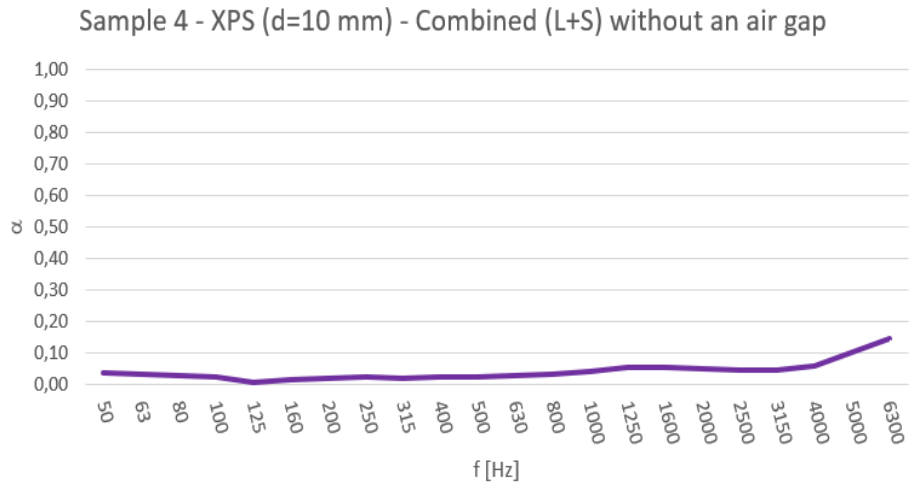


Figure. 5. Sound absorption coefficient of 10 mm extruded polystyrene samples

This figure shows that the 10 mm thick extruded polystyrene (XPS) sample has a very low sound absorption (<0.1) across all frequencies, with a slight dip at 100–200 Hz and minor improvement above 1500 Hz. This indicates that XPS performed poorly compared to styrofoam, indicating limited suitability as a standalone absorber.

3. ACOUSTIC TREATMENT OF THE HALL

For research purposes, a performance hall of the National Library in Ćićevac was analyzed. The hall, which is primarily rectangular in shape, has dimensions of 25.15 x 9.0 m, with a ceiling height that varies due to its curved form. It is designed to accommodate 202 people - 142 on the ground level and 60 in the balcony area. The total volume of the space is 1618.4 m^3. The interior surface materials, which significantly affect the room's reverberation time, are distributed as follows: the ceiling and the upper portions of the walls (above approximately 220 cm) is coated with a layer of plaster; the lower sections of the walls are finished with wooden paneling; the auditorium floor is covered with linoleum. The stage area features brick walls coated with plaster and partially draped in fabric; the stage floor is finished with wooden parquet, and the stage ceiling is coated with a layer of plaster applied directly onto the structural surface [2, 4, 11].

3.1. Analysis of the Current Situation

Room acoustics were simulated using the Odeon Acoustic software tool through a modeling approach. The using of "ray-tracing" and "hybrid" method enabled highly accurate predictions of the acoustic behavior of the space. These methods lead to the creation of secondary sound sources at points of sound wave reflection. The underlying algorithms calculate the proportions of diffusely reflected, directly reflected, and absorbed sound upon

interaction with interior surfaces. Additionally, incorporating geometric parameters enhanced the accuracy of the acoustic simulation [12, 13].

The simulation using the Odeon tool aims to analyze the existing state of the performance hall space, with a special focus on the graphical representation of the amount of sound wave exposure to surfaces in the interior. The importance of graphic analysis is reflected in the fact that based on the graphics we can determine which points in the interior reflect the greatest amount of sound. The results of software modeling will provide insight into which points of the interior surface require acoustic treatment. The geometry of the space affects the reflection of sound waves, and inadequate treatment of the space can lead to focusing of sound and the creation of a standing wave in the hall [4, 12].

The exposure of the interior surface to sound levels, based on the current state of the performance hall, is shown in the graph (Figure 6). The graph shows the distribution of sound pressure levels (SPL) [13]. In the graphs we can see increased exposure to sound waves in the balcony area on the side walls and the back wall. Greater exposure of interior surface areas also means a greater amount of reflected sound from those points. The distribution of sound reflection from surfaces depends on the geometry and materials in the interior. Uneven distribution of sound reflection is a common occurrence in halls with balconies and such halls require special approach of design. A higher amount of reflected sound, in this case in the balcony area, can lead to the sound being focused on certain points of the auditorium. Focusing the sound can create an uncomfortable feeling for the audience in that area. In addition, direct reflection of sound waves from the back wall can lead to the appearance of a standing wave in space, which also has negative consequences on the quality of performance [14, 15].

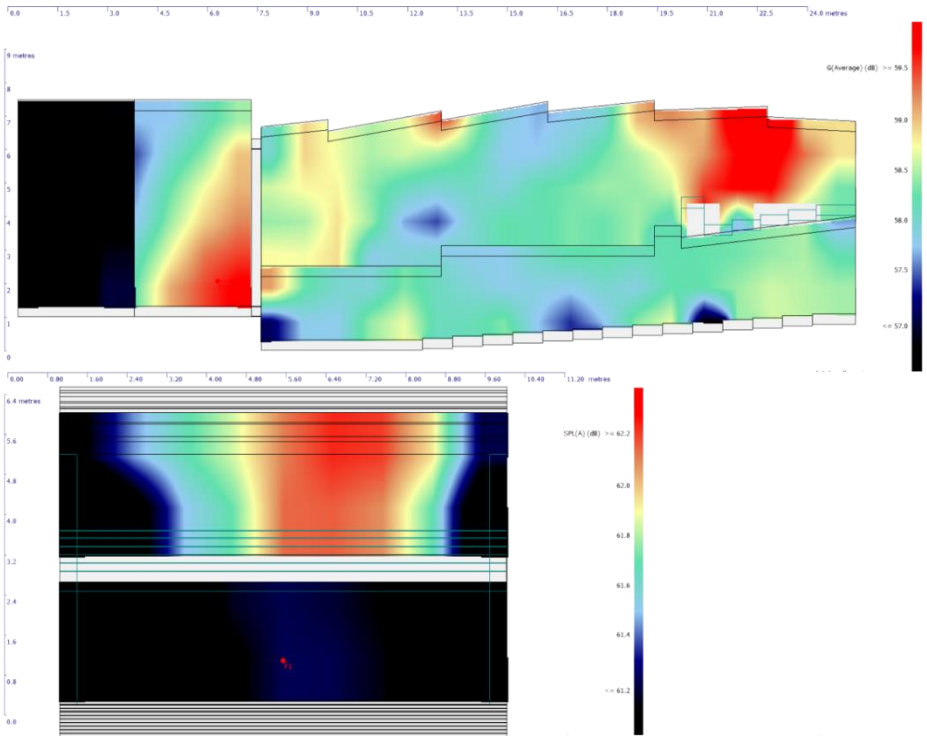


Figure. 6. Graphical representation of side and back wall exposure by sound pressure level

The software tool performed measurements in octaves for frequencies from 125 to 4000 Hz [13]. The graph shows the results for a frequency of 1000 Hz, at which the largest oscillations in the sound intensity level occur. In order to improve the acoustics of the space, it is necessary to carry out acoustic treatment of the hall by implementing diffuser panels on parts of the surface that are exposed to a greater amount of sound.

3.2. Parametric Sound Diffusion Panel Design

In architectural acoustics, interior elements are commonly classified as absorbers, reflectors, or diffusers, based on their acoustic properties, which are influenced by both the material type and surface geometry [1, 14]. The formation of surface folds affects acoustic performance by introducing diffuse sound reflections. A smaller spacing and greater depth of these folds increase the potential for surfaces to diffusely scatter sound, particularly at lower frequencies [14, 16].

A diffusion coefficient of $s = 1$ is used in calculations when the spacing between folds is $r = \lambda/2$ and the depth of the folds is $d = \lambda/2$, where λ represents the wavelength[5]. This equation suggests that, depending on the geometry, higher-frequency sound waves may be diffusely scattered, whereas lower-frequency sounds tend to be directly reflected. Furthermore, surface geometry can also enhance sound absorption due to multiple reflections occurring within surface cavities. This effect becomes more pronounced when the spacing between folds is sufficiently small and the fold depth is greater. With each additional reflection, the intensity of the sound energy returning to the listener decreases, owing to the absorption by the material upon which the sound wave reflects [14 - 16].

In order to improve the acoustics of the test performance hall, it is necessary to implement acoustic panels. At points where there is an increased amount of reflected sound, it is necessary to install wall acoustic panels for sound diffusion [14]. Due the points of exposure to higher sound pressure levels in the interior do not cover the same area, this research envisages the implementation of two types of panels, of the same design, one panel measuring 4.0 x 2.0 m and two panels measuring 2.0 x 2.0 m. The maximum depth of the fold on the panel is 15 cm (Figure 7).

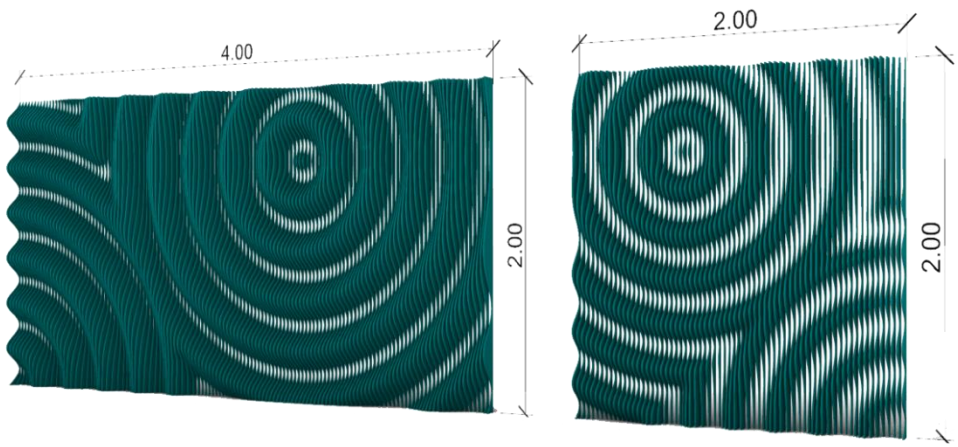


Figure. 7. Design of sound diffusion wall panels

[5] Wavelength - λ[m]

The acoustic panel design was carried out using Rhinoceros software tool with the Grasshopper plug-in. The panel materialization was planned using sheet-based materials. Accordingly, the sound absorption coefficient was measured for several samples made of wood-based and polystyrene-based sheet materials (described in chapter 2.2.). The acoustic panel design proposal was inspired by the waves created by the agitation of the water surface by throwing pebbles. The geometry of waves was randomly generated using the Grasshopper plug-in. The dimensions of the waves on the acoustic panel were generated so that the height and width of the folds were approximately 15 cm. By combining architecture, acoustics, and art, a unique interior element has been created - one that enhances both the aesthetics and acoustics of the space through the use of accessible materials shaped by intelligent design [16, 17]. Throughout the design process, parameters such as panel dimensions, wave height, and width were systematically controlled, whereas the final geometry was derived through stochastic generation. The proposed acoustic panel design has two advantages. First, its wavy geometry enhances sound diffusion in different directions. Second, cavities between panel elements contribute to sound absorption through repeated internal reflections, thereby reducing the amount of sound reflected from treated surfaces [14, 15].

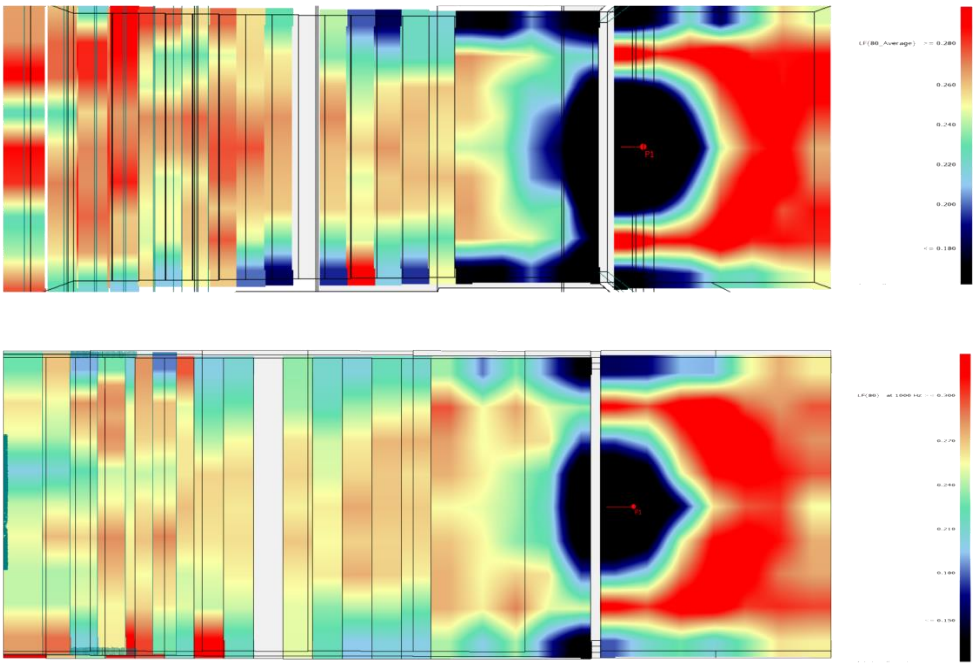


Figure. 8. Graphical representation of lateral sound reflections in the auditorium and balcony area - existing state (above), state after acoustic panels implementation (below)

Following the integration of the acoustic panel model in Odeon simulation of the performance hall, an analysis was conducted to assess their acoustic impact. Extruded polystyrene (XPS) boards were selected for panel materialization for its uniform sound absorption performance at all octave bands, their stability lightweight, and ease of shaping. Additionally, its function as a geometric diffuser within the panel context mitigates its material limitations. The selection was justified by minimal variation in the sound absorption

coefficients of the tested materials. Using the Odeon Acoustic software, the impact of the implementation of the proposed acoustic panels on the amount of sound reflected from the walls (lateral fraction – LF) was examined [13]. The graph (Figure 8) shows the amount of sound reflected from the walls. In the graphical representation of the existing condition (Figure 8, above), certain points within the audience area on the balcony can be identified where focused sound reflections occur, caused by reflections from the walls. With the implementation of the acoustic panels described in this chapter, the second graphical representation (Figure 8, below) shows a noticeable reduction in the amount of sound reflected from the walls toward the balcony area, compared to the existing condition. A comparative analysis of the results shown in the graph leads to the conclusion that the implementation of acoustic panels on targeted areas on the wall contributes to the elimination of sound focal points in the hall.

4. CONCLUSION

The aim of this study was to investigate the potential for eliminating sound focusing points in performance halls through a precise analysis of areas reflecting increased amounts of sound, followed by targeted acoustic treatment using diffusion panels installed at those critical points. By measuring the sound absorption coefficients of different materials and simulating sound behavior within a specific hall, critical points of sound reflection and focalization were identified in the performance hall of the National Library in Ćićevac. Based on the obtained data, a design proposal for acoustic panels with a dynamic, wave-like geometry was developed to promote sound diffusion and reduce the possibility of creating points with focused sound. Post-implementation software simulations showed a significant improvement in the distribution of sound energy within the space, particularly in areas with higher exposure to reflected sound, such as the balcony. By using lightweight materials like extruded polystyrene (XPS), additional economic value was achieved without significantly compromising acoustic performance. Based on the results obtained through software simulation using the Odeon tool, it can be concluded that the implementation of sound diffusion panels at critical wall points would eliminate the occurrence of points with focused sound in the audience area, which would lead to the improvement of performance quality in the hall.

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Research paper

REHABILITATION OF THE TUNNEL KOSMAN DURING THE CONSTRUCTION OF THE SMOKOVAC - MATEŠEVO HIGHWAY SECTION IN MONTENEGRO

Nikola Čađenović[1], Ivan Maretić[2]

Abstract

During the construction of the first section of the Montenegrin motorway from Smokovac to Mateševo, over 35 km of traffic tunnels were excavated. Such a volume of tunnel construction faced numerous challenges, with the primary task being to ensure the stability of the excavation.The most significant instability of the tunnel excavation was registered in right tube of the Kosman tunnel. During the underground excavation, in the portal zone, there was an intensive inflow of groundwater, which led to the collapse of the rock mass with the opening of a wide channel towards the surface. The Kosman tunnel was formed in soft rocks represented by tectonically altered flysch sediments, siltstones, marls and sandstones. At the moment of collapse, the rock mass was characterized as an excavation of the worst category, and all safety measures were applied according to the main design. Work was suspended and additional measures were implemented to secure the tunnel excavation. The paper analyzes the conditions that led to the collapse of the rock mass, as well as the applied remediation measures. It is estimated that the main reason for the instability was the intensive inflow of groundwater into the tunnel excavation.

Key words: *Kosman tunnel, flysch, rock mass, fracture, groundwater*

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1. INTRODUCTION

During the construction of the first section of the Montenegrin highway from Smokovac to Mateševo, more than 35 km of traffic tunnels were built. Such a volume of tunnel construction faced numerous challenges, with the primary task being to ensure the stability of the excavation.

One of the major problems arose in November 2016 during the excavation in the right exit portal zone of the Kosman tunnel, when the primary support was deformed, the excavation face cracked, and a wide channel opened up to the surface. This collapse was caused by a intensive inflow of groundwater and occurred despite all safety measures that were implemented in accordance with the main design [1, 2].

The contractor typically used a primary tunnel support of type Vpc to secure portal sections in quaternary sediments with low overburden. This type of primary support is used for the worst categoru of excavations, according to RMR classification (Rock Mass Rating - Bieniawski 1974). For the Kosman tunnel, the application of this type of primary tunnel support was planned for a length of 10 m from the exit portals. The initial collapse occurred 10 m from the tunnel portal in degraded and tectonically altered flysch sediments represented by siltstones, marls, and sandstones. The deformations rapidly progressed and in just a few hours they covered the tunnel's overburden, forming a channel 6-7m in diameter that reached the ground surface, Figure 1.



Figure 1. The soil that filled the right exit tube of the Kosman tunnel after the collapse of the excavation face

An analysis was conducted on the conditions that led to the collapse of the rock mass. It was concluded that the instability of the tunnel excavation was caused by an intensive inflow of groundwater. Under the pressure of the groundwater, the tunnel excavation collapsed, and since the layers of overburden of the rock mass were only a few meters, the surrounding ground also collapsed.

2. PRIMARY TUNNEL SUPPORT OF THE KOSMAN TUNNEL

The exit portal of the Kosman tunnel is formed in flysch sediments, dominated by siltstones, marls, and sandstones, the rock is tectonically damaged and very degraded at the surface. The general dip of the layers is towards the north with variations from northwest to northeast, and the general angle dip is about 30 degrees. Siltstones and marls are generally thinly layered (0.5-10 cm), while sandstone layers are thicker (2-50 cm). At the surface of the terrain, there is dusty clay with a thickness of 4-5 m, which is deluvial from the flysch rocks.

The collapse of the rock mass occurred during the underground excavation in the soft rock mass, which according to the geotechnical study has the following parameters: γ_z=23 kN/m^3, UCS=7 MPa, GSI=18, mi=6. The physical-mechanical characteristics of the rock mass were obtained using the RockData software package and using the tunnel excavation application assuming Mohr-Coulomb failure conditions.

The obtained cohesion was c=20 kN/m^2; the angle of internal friction was φ=38.5 ˚ and the deformation modulus D=41.9 MN/cm^2. The surface of the terrain consists of 4-5 m thick deluvial sediments which have the following physical-mechanical parameters: γ_z=21 kN/m^3, cohesion c=13 kN/m^2 and angle of internal friction φ=27 ˚.

Static calculations were performed using the finite element method, and numerical modeling was carried out in accordance with the excavation and installation phases of the protective structure. During the tunnel excavation, the RMR classification (Rock Mass Rating - Bieniawski 1974), method was used, and the primary support system used in the main design was based on the NATM concept. For the portal zones, a Vpc type structure was adopted, intended to secure the tunnel portal zones. The contractor excavated 35 km of tunnel, forming 10 double--tube tunnels, and the stability of the entire portal section in the quaternary sediments with low overburden was ensured by Vpc-type structures.The designer explained this attitude by the fact that in the portal zones, rock mass has cracked due to atmospheric influences and that a part of it has been turned into soil to a great depth.The remaining rock has poor physical and mechanical characteristics, resulting in very low stability after excavation.

These are poor conditions for tunnel excavation, which create great difficulties in construction with a high risk of collapse, which requires a strong supporting structure to ensure safety. The portal zones of tunnels in which the Vpc primary support type was implemented proved to be stable.

The primary tunnel support of the Vpc type involves applying 26 cm of shotcrete in layers, two layers of Q188 mesh reinforcement, installation of 4 m long SN anchors in a 200x60 cm grid, and the installation of steel lattice girders 115-30-36 cm at a distance of 60 cm. The excavation was carried out in phases, first the calotte and then benches, with the installation of a temporary invert. The tunnel face was secured by installing a forepoling/piperoof, formed from IBO anchor bar with a diameter of 76 mm and a length of 9 m. Piperoofs are installed with an overlap of 2 m and are formed at an angle of +5 ˚ to the horizontal plane.

The main design allows deformation of the primary support up to 18 cm. The entire pressure of the rock mass is received by the primary tunnel support and it is not intended that the secondary tunnel lining receives the pressure of the rock mass.

This type of support ensures the security of the portal zone formed in the quaternary sediments, however, after excavation progressed to degraded flash sediments, groundwater appeared at the contact of these two units. On the night of 18-19 November, after heavy rainfall, significant influx of groundwater was registered into the tunnel excavation. After only

a few hours, the primary support began to deform, and the rock mass along the tunnel face began to collapse. Deformations increased rapidly and the next day the terrain above the right exit portal collapsed into the tunnel excavation, creating a wide channel on the surface of the terrain with a diameter of 6-7 m, Figure 2.



Figure 2. Area above the right exit portal of the collapsed Kosman tunnel

3. APPLIED REMEDIAL MEASURES IN THE KOSMAN TUNNEL

During the excavation, successive geological mapping of the tunnel face was conducted, so the geological structure along the tunnel excavation was known. Geological reports characterized that the tunnel face was predominantly built by deluvial sediments, and in some places degraded siltstones with interlayers of marls appeared. After 9 m, face of the tunnel is built by soft rocks represented by siltstones, marls and sandstones. Tunnel excavation was carried out in the soft rock, and the contractor believed that the underground excavation conditions were improving. This largely corresponded to the data provided in the main design, where the primary type of tunnel support (Vpc) was used to secure the first 10 m of the tunnel excavation. Due to the high proportion of marls and siltstones, flysch sediments represent a hydrogeological barrier and groundwater appeared in contact with these sediments. The contractor noticed that the inflow of groundwater into the tunnel excavation was increasing, but did not immediately drill drainage boreholes, believing that the geological structure was improving and that the water volume would decrease over time.

After the first heavy rains, large quantities of groundwater appeared directly at the contact of deluvial and flysch sediments. The tunnel drained the water along the entire slope catchment area. The contractor attempted to reduce the water inflow by applying layers of shotcrete, however the water pressure increased and due to complete water saturation, water began to leak from the installed SN anchors. Larger pieces of shotcrete started to break and it was then noticed that several steel girders were deformed. Workers were evacuated from the worksite. The deformations rapidly increased, and within a few hours, there was a collapse of the tunnel face, as well as part of the installed primary tunnel support. The

overburden was only 8 m high and the next morning, a wide channel with a diameter of 6-7 m was observed forming on the ground surface above the right exit portal.

After the tunnel collapsed, water, soil, and stones flowed out of the tunnel portal for several days. The contractor immediately changed the main design of the Kosman tunnel. After conducting calculations, the contractor designed the primary tunnel support type Vpc-t. The rehabilitation of the Kosman tunnel began with the installation of fiberglass anchors with a diameter of Ø25 mm and a length of 9 m, which are installed with an overlap of 2 m. Then, drainage boreholes with a diameter of Ø50 mm and a length of 9m are placed at the face of the excavation. The contractor inspected the primary support of the tunnel that remained in place after the collapse and then geodetically determined its position. Then, to stabilize the slope, the contractor began to form a cut and cover section, in the right exit portal of the Kosman tunnel in a length of 10m as shown in Figure 3.



Figure 3. Formation of cut and cover section in the right exit portal of the Kosman tunnel in a length of 10m

When the secondary concrete lining in the tunnel portal area was completed, the phased excavation of the tunnel began, first the calotte, then the benches, with the sequential installation of a temporary invert.

Tunnel excavation was secured by installing of a primary support the Vpc-t type, which involves applying 26 cm of shotcrete, two layers of Q188 mesh reinforcement, the installation of SN anchors 6 m long in a grid of 150x60 cm, and the installation of steel arches type HE160A at a distance of 80 cm. Steel arches with extensions were formed at the contact between the tunnel calotte and the bench. The tunnel face was secured by installing a forepoling/piperoof, formed from IBO anchor bar with a diameter of 76 mm and a length of 9m. The piperoofs are installed with a 2 m overlap and are formed at an angle of +5 ˚ to the horizontal plane. The main design allows deformation of the primary support up to 10 cm. The deformations were below this value, so the contractor installed a secondary lining of reinforced concrete with a thickness of 45 cm, thus completing the remediation works.

4. CONCLUSION

The instability of the excavation that occurred during the construction of the Kosman tunnel was not caused by geological conditions. The geological structure was in accordance with the main design.

The type of primary tunnel support (Vpc), which is commonly used in the construction of portal sections of tunnels in the quaternary sediments, with low overburden has proven to be safe in numerous tunnels. In the first 9m of the Kosman tunnel excavation, no significant deformations were registered, until a large amount of groundwater appeared. The contractor did not immediately drill drainage boreholes, believing that the geological structure was improving and that the water volume would decrease over time. However, after heavy rains, the inflow of groundwater significantly increased, and the primary tunnel support cracked in just a few hours, not giving the contractor time to react.

The data presented in this paper indicate that the change in the stress state in the field is a result of complete saturation of the geological working environment with water [3,4, 5]. The remediation works were carried out over several months and required very high material costs.

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Research paper

INDUSTRIAL BUILDINGS IN TETOVO AND POSSIBILITIES FOR TRANSFORMATION

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Abstract

Existing industrial buildings and sites serve as reminders of the industrial past and the socio-economic transformations caused by industrialism. Nevertheless, all the architectural, cultural and historical values of these sites are being lost, as with the decline of production, abandoned buildings are demolished and replaced with new. Although many studies claim that the awareness of the values of industrial heritage and the possibilities related to them may have increased in recent years, Tetovo's continuous destruction of industrial buildings proves otherwise. This research is conducted in the city of Tetovo, North Macedonia, where in the first part of this paper, industrial buildings and sites, especially those that are underutilized or no longer have a manufacturing purpose, are identified, mapped and analyzed. While the second part of this paper explores the historical development and the current state of "Todor Cipovski Merjan" - Teteks, one of the largest Macedonian textile manufacturers. The historical development is researched to understand the value of this location for the city of Tetovo and the collective memory of our citizens. The analysis of the layers of the buildings in terms of flexibility, creates a picture of the existing situation and provides insight into the potential for transformation and opportunities for reuse. The aim of this research is to promote Tetovo's industrial heritage as a key element for urban and regional development, by supporting the process of cultural recognition and protection of industrial buildings and complexes.

Key words: *Industrial buildings, Heritage, Values, Transformation, Reuse*

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1. INTRODUCTION

The greatest industrial development in Macedonia occurred after World War II, during the socialist period, in spite of the fact that the first industrial capacities appeared at the end of the 19th century. Industrialism impacted the lives and memories of citizens, because of all the changes that brought in the country's economy, architecture, urban planning, education, etc. Industrial buildings are the bearers of this era's history, and as such, they should be preserved, especially if the original production function is discontinued and the building is no longer used [1-2].

A characteristic of industry in Macedonia is the inconsistency in development, whether in relation to time periods, or territorial distribution. There have been constant crises and the process of industrialization was slow, but in the post-war period the volume of industrial production increased by five times compared to the pre-war level. Around the sixties, in addition to Skopje, Tetovo, Bitola, etc. industrial centers were also established in smaller Macedonian cities and the number of employees increased [3].

After the division of the Yugoslav federation, there followed an enormous decline in industrial production. As a result of the crisis, only a portion of industries managed to recover and continue production, the rest faced a continuous decrease that ended with their closure, consequently a large number of industrial abandoned locations appeared, namely brownfields [4,5].

These inactive industrial locations, if left unused for a long time, not only risk decline in their historical and cultural values, but also become dangerous areas within the city. Therefore, adequate management of brownfields is very important, both in terms of the protection of cultural heritage and in the development and planning of the city [5].

In most cases, the buildings are demolished to make way for new ones, without documenting or assessing their potential. But recently, with the growing awareness of the values of industrial heritage and the importance of reuse in today's times, industrial buildings are seen as resources with high potential to receive new urban programs and functions that enable contemporary spatial and economic development.

Although there is proof of the significance and advantages of adaptively reusing existing structures; of the possibilities for transformation that lie in their site area, enormous volumes and structures, there are also many obstacles that must be taken into account. After all, not all buildings are optimized to receive new programs in the future [6].

Several studies claim to identify the barriers that appear during adaptive reuse and strategies to deal with them, however, there is no agreement on the criteria that should be taken into account when evaluating the potential for the future adaptive reuse of structures or how to weigh the criteria in different contexts. This is considered a significant shortcoming in current knowledge [6].

Thus, the objective of this research is to analyze and verify a flexibility assessment tool that helps towards decision-making process for future adaptive reuse of industrial locations in Tetovo.

2. METHODOLOGY

One of the biggest challenges in researching abandoned industrial buildings is the lack of documentation, regardless of whether the buildings remain unused or have taken on new functions, many documents are lost because no one feels responsible for them in the period between new and old use. Consequently, even though archival research (drawings, project documentation, photographs) has been used, as a basic method for heritage protection research, for significant information about the industrial and economic context in Macedonia, numerous books from economic fields have been considered.

After identifying industrial locations through the study of general urban plans, observational research (sketching, measuring, drawing, digital photography) was used to assess the current state of the facilities, spatial quality and the interaction with the surrounding area and community.

To determine the value and capacity of the industrial heritage for further use, many methods have been analyzed. Since according to various studies, flexibility was seen as a key factor that can help or hinder the transformation process, the method used in this research is Flex method.

This method allows to analyze the flexibility and the possibility of reuse. Flex is a method presented by Rob Geraedts and his associates, which breaks down the building into 5 layers: location, structure, skin, services, spatial plan. Each of these layers has its own group of questions that are numerically weighted and valued. The end result is a ranking in flexibility classes from class 1: inflexible, to class 5: very flexible. There are currently several versions of Flex, 1.0 to 4.0; a method combining Flex 2.0 light and Flex 4.0 was used for this research. The selection of the indicators/questions is based on literature research on the most important physical factors in the transformation of industrial capacities, while the assessment of the value is based on the guidelines of Geraedts [7], and the research of Amiri [8].

The data analyzed in this study are communicated and presented through text discussion, tables and figures.

3. TETOVO AND THE DEVELOPMENT OF INDUSTRY

3.1. Historical Analysis of Industry in Tetovo

Tetovo, as a settlement where trade and crafts (weaving, tailoring, soapmaking, carpentry, butchery, saddlery, etc.) take place, was first mentioned in legal documents from 14th century, when this settlement entered the Ottoman Empire. As the main administrative center of Kalkandele vilayet, Tetovo experienced rapid development in the 19th century when the so-called Tanzimat reforms took place, and the Ottoman society wanted to get out of its isolation and catch up with the developed western countries. Many new crafts were developed, shops, schools, religious buildings were opened, and so on. The first data from this period can be found in the many manuscripts of European travelers that passed through the Balkans during this period [9].

After the departure of the Ottoman Empire in 1912, Tetovo's economic and business importance was developing at a fast pace, however, the only industrial capacity was the Polog Mill, built in 1906 along the river Pena. In the upcoming period 1912-1918, Macedonia faced many difficulties as a result of wars. In Tetovo during the interwar period there were 4 industrial facilities and several warehouses for tobacco fermentation. One of these facilities

was Polog Mill, while the other three were: Petar Lekic's cord factory, Mishkovski brothers' leather processing company, and TIAD Hydropower plant. The industrial facilities of this period were mainly built inside the city and along the course of river Pena [10].

The post-war period brought an industrial revolution to Tetovo and Macedonia. By the end of 1947, the physical volume of industrial production had tripled since 1953 and doubled since 1939. Even the old facilities were equipped with new tools to replace or repair outdated or broken ones. Electro-metallurgy, textile and food industries had a leading role in the economic growth of the city of Tetovo. [11] Tetovo had implemented highly efficient actions for the improvement of its industrial companies, among them the most famous were: “Jugohrom”, “Teal”, The factory for medical products, “Teteks”, “Edinstvo” fashion confection, “ZIK”, “Jugotutun”, “Napredok” Printing House, “Nemetali”, “SHIK Jelak”, etc. [12]

The independence of the Republic of Macedonia, after the fall of the Socialist Federal Republic of Yugoslavia, was accompanied by numerous challenges as a result of poor developed infrastructure and a high unemployment rate compared to the former Yugoslav nations [13].

The Macedonian economy began to grow again in 1997, but in 2008, faced the global financial and economic crisis, which spread to the industrial sector. Production was reduced, some facilities were closed, and many employees were laid off. Following the lead of other nations, the Government of the Republic of Macedonia implemented a set of policies aimed at solving the crisis, which turned out to be successful to some extent [14].

3.2. Spatial Analysis of Industry in Tetovo

According to the data from the State Statistics Office, the industry in Tetovo covers the following three areas: A. Mining and quarrying, B. Processing industry and C. Supply of electricity, gas, steam and air conditioning. In 2020, the number of industrial facilities from the processing industry in Tetovo reaches 420, out of a total of 431 industrial enterprises, while the location of these industries is mainly on the outskirts of the city or in the surrounding areas [15].

In the General Urban Plan of the city of Tetovo, of 2003, the industrial sites cover an area of over 600,000 m^2. From the field observations, it was concluded that only a small part of these sites has preserved their primary function, most of them are former industrial sites, which are rented out for industrial or other purposes, and some of the sites (abandoned or partially active) are planned to be demolished for the construction of new buildings.

In this process, not only important documents and data about these sites are lost, but it also happens that the new proposed functions are in conflict with the needs of the community. The position within the city’s structure and the current state of these industrial locations is described in the following illustration.



Figure 1. Spatial layout of the industrial locations in Tetovo, by the author
Industrial sites, ===== River, City centre

Many industrial facilities built in the socialist period are located within the city and have the potential to be reused and integrated into the urban fabric. With the passage of time and the change of generations, one can notice their gradual loss from the structure of the city. Today, a small part of the industrial facilities in Tetovo are active or converted, and the others where they still exist are inactive and empty, and their condition is deteriorating while they await a decision on their fate.

The largest industrial site, listed as number 1, TETEKS AD - spans a total land area of 250,000 m^2, with 140,000 m^2 occupied by buildings. The company provides industrial infrastructure, including electricity, technical steam, and rental space available in various sizes. Of the total constructed area of 140,000 m^2, numerous businesses have so far leased a total of approximately 22,000 m^2 of industrial space, 4,000-5,000 m^2 have maintained their primary purpose, while the rest of over 113,000 m^2 is available for rent, suitable for industrial or other functions [16].

Table 1. List of industrial locations in Tetovo

Site number	Site name	Type of industry originally formed	Current state	Site area
1	Todor Cipovski Merjan - TETEKS	Textile industry	Part leased/part for rent	250000 m^2
2	Teal	Electromechanical industry	Active industry	70180 m^2
3	Pofix	Construction industry	Active industry	23000 m^2
4	Edinstvo/ Pofix	Textile industry	Rented (by Pofix - Construction industry), planned to be demolished for construction of new facilities	27500 m^2
5	Godel-Velur	Leather industry	Part leased/part for rent	40000 m^2
6	SHIK Jelak	Wood industry	Inactive	71 000 m^2
7	ZIK	Food industry	Part leased/part for rent	36000 m^2
8	Žito Polog	Food industry	Active industry	20000 m^2
9	Macedonia Tabak	Tobacco industry	Part inactive, part rented (Pofix)	
10	Medical plastics	Chemical industry	Inactive, demolished for construction of new facilities	52000 m^2
11	Printing house Napredok	Graphic industry	Part leased/part for rent	3000 m^2
12	Polog Mill	Food industry	Inactive	3000 m^2
13	Auto progress	Metal industry	Inactive	19000 m^2
14	Nemetali	Construction industry	Rented	13500 m^2

4. TETEKS AND TETOVO

In the period after the Second World War, "Todor Cipovski Merjan" - Teteks employed almost a third of the locals of Tetovo, which by that time was an important industrial center.

Four large factories operated in Teteks: Yarn and Wool Factory built in 1951, Fabric Factory in 1954, Garment Factory in 1963, and Knitwear Factory in 1968. Teteks was a major supplier to the Yugoslav market and abroad. Besides providing fabrics, blankets, suits, coats and jackets, sweaters, pullovers, knitwear sets, uniforms for first responders and other professions, Teteks had its own infrastructure which consisted of various amenities such as own sources of electricity and heat energy, canteen, transportation, an ambulance, its bank, a kindergarten, a bakery, a shop and a showroom for the presentation of products [17].



Figure 2. Map of Teteks, by the author

Legend: 1 gate, 2 ambulance, 3 administrative building, 4 canteen, 5 yarn and wool factory, 6 fabric factory/ knitwear factory, 7 telephone central, 8 plumbing and compressor station, 9 substation, 10 administrative building, 11 machine and electrical workshop, 12 technical warehouse, 13 factory and warehouse, 14 bakery and warehouse, 15 metal structures and warehouse, 16 warehouse, 17 warehouse, 18 blanket factory, 19 warehouse for raw materials, 20 regenerate factory, 21 fuel oil tanks, 22 construction operations and warehouse, 23 warehouse, 24 energy centre, 25 garage with workshop, 26 fabrics and knitwear warehouse, 27 garment factory old part, 28 garment factory new part, 29 clothing warehouse, 30 canopy.

In 1970 through 1985, Teteks reached its peak performance participating with 30- 42 percent in production in the Municipality of Tetovo, and employing one third to half of the total number of industrial workers. [15] In June of 1991, Teteks was transformed from a social enterprise into a mixed joint-stock company, with mostly private capital. During this period, the production in China and other countries, negatively impacted the textile production in Macedonia, so despite attempts to survive the crisis, Teteks stopped textile production on 10.02.2020 [16].

Nowadays, the company offers many spaces that can be rented, accompanied by various industrial, technical or technological services, but also maintenance, accounting and printing services [16].



Figure 3. Current situation of Teteks, by the author
Active, Rented, For rent

To define the class of flexibility, architectural plans and direct access to the buildings are necessary, so in this research only 5 objects will be studied in more detail since only for them sufficient data have been found to develop the analyses. The buildings included in this study are:

1. Blanket factory (no.18 in the map)
2. Warehouse for raw materials (no.19 in the map)
3. Warehouse for fabrics and knitwear (no.26 in the map)
4. Yarn and wool factory (no.5 in the map)
5. Fabric factory/ knitwear factory (no.6 in the map)

5. RESULTS- ADAPTIVE CAPACITY OF BUILDINGS THROUGH THE FLEX METHOD

The 5 objects highlighted earlier were analyzed according to the Flex method and based on the result they were categorized into flexibility classes.

First-class of flexibility are objects with very little flexibility that are not suitable for implementing new functions. Second class facilities also show a low flexibility score and adaptation can be realized with greater difficulty. Buildings belonging to the third class are buildings with limited flexibility, that can be repurposed but may not be suitable for all functions. The buildings of the fourth class are objects with good flexibility, which can be easily transformed. Class 5 facilities have high flexibility, with excellent capacity for adjustment.

Table 2. Flexibility class table

Flexibility Class Score Chart	**Range of results**
Class 1: Not flexible at all	17-54
Class 2: Hardly flexible	55-108
Class 3: Limited flexibility	109-163
Class 4: Good flexibility	164-218
Class 5: Excellent flexibility	219-272

Analyzes with the flex method are done by dividing the building into 5 layers where for each layer we have a certain number of indicators that must be evaluated. The weighting value was taken from Amiri's research, [8] while the assessment value was specifically evaluated for each indicator according to the current state of the building and the specifications for evaluation given by Geraedts. [7] The result for each indicator is obtained by multiplying the weighting and assessment value, which are added together and their sum represents the result of flexibility based on which the class can be assigned.

Table 3. The adaptive capacity of Teteks facilities according to the Flex-method

Layer	**Flexibility perfomance indicator**	Weighting	**Building**									
			1 (no.18 in the map)		2 (no. 19 in the map)		3 (no.26 in the map)		4 (no. 5 in the map)		5 (no. 6 in the map)	
			Assessment	Result	Assessment	Result	Assessment	Result	Assessment	Result	Assessment	Result
Location	1. Does the site have excess undeveloped space?	4	3	**12**	3	**12**	3	**12**	3	**12**	3	**12**
	2. Is the location capable of supporting multiple functions such as offices, housing, care, shops, etc.?	3	4	**12**	4	**12**	4	**12**	4	**12**	4	**12**
Structure	3. What is the free height of the building?	4	4	**16**	4	**16**	4	**16**	4	**16**	4	**16**
	4. To what extent has centralized access to the building been implemented?	2	3	**6**	3	**6**	1	**2**	4	**8**	3	**6**
	5. What is the size of the usable floor area?	3	4	**12**	3	**9**	4	**12**	4	**12**	4	**12**
	6. Do the supporting elements represent an obstacle for adaptation?	3	3	**9**	3	**9**	3	**9**	3	**9**	3	**9**

	7. Is it possible to add new stairs/elevators to the building and reuse the existing ones?	2	3	**6**	2	**4**	3	**6**	3	**6**	3	**6**
	8. What is the shape of the pillars in the building?	1	4	**4**	4	**4**	4	**4**	4	**4**	3	**3**
	9. Is it possible to extend the building horizontally for a new expansion of the user unit?	3	3	**9**	2	**6**	2	**6**	2	**6**	2	**6**
	10. Is it possible to extend the building vertically for new floors or a new basement?	4	1	**8**	2	**8**	2	**8**	2	**8**	2	**8**
	11. Is it possible to set aside part of the building for sale/lease to third parties?	2	4	**8**	3	**6**	4	**8**	4	**8**	3	**6**
Facade	12. How is the thermal and acoustic insulation of the façade?	2	1	**2**	1	**2**	1	**2**	1	**2**	1	**2**
	13. How are the facade openings positioned and shaped?	2	3	**6**	2	**4**	4	**8**	4	**8**	2	**4**
Services	14. Is it possible to adjust: temperature, ventilation, electricity, ICT?	3	2	**6**	2	**6**	2	**6**	2	**6**	2	**6**
	15. Does the building have specific capacity for hot/cold water distribution, treatment, cooling and gas?	4	3	**12**	3	**12**	3	**12**	3	**12**	3	**12**
Space plan	16. To what extent are the internal walls in the building easily replaceable?	4	2	**8**	2	**8**	2	**8**	2	**8**	2	**8**
	17. Is it possible to apply suspended ceilings or raised floors and adapt them to different user requirements?	2	4	**8**	4	**8**	4	**8**	4	**8**	4	**8**
Flexibility result			**144**		**132**		**139**		**145**		**136**	
Flexibility class			**3**		**3**		**3**		**3**		**3**	

Based on the analysis of the adaptive capacity of Teteks, using the flex method, the level of flexibility ranges from 124 to 145, in which case they belong to the third class. These facilities may receive new uses, but may not be suitable for all functions, for this reason they are part of the class of objects with limited adaptive capacity.

6. DISCUSSIONS

Flexibility as one of the most important characteristics of any structure plays a big role in the reuse of industrial heritage, it can even define how much an object or site with industrial heritage has the potential to be reused. The Flex method, chosen for this research, helps to examine the transformation issues at different levels/layers and then obtain the result for the entire object.

According to the analyses presented in Table 3, it is noted that the advantages of the buildings in Teteks are mainly: the potential for mixed use development, where all buildings reach maximum value, the height of the building, which is also accompanied by the possibility of adding suspended ceilings, the size of the usable floor area, and in most cases the shape of the structural elements. As for the disadvantages, although they vary from facility to facility, it is noted that most have difficulties with thermal and acoustic insulation, as well as the ability to expand horizontally or vertically on other floors.

According to the results of this study, it is observed that buildings with similar typology show similar flexibility results, even if their size or shape changes. Yarn and wool factory and Blanket factory show higher flexibility scores compared to warehouses; but all facilities fall into the category of facilities with limited flexibility.

Regarding the evaluation results, it is important to note that it is more than acceptable that the buildings may have limited flexibility because they were formerly designed for specific programs. And while these buildings can adequately meet the needs for which they were created, in the process of adaptive reuse, where we move from one function to another, it is normal for difficulties to arise.

These analyses reveal the capacity for future changes without considering the new functions, and according to some earlier studies, while some buildings may show low results in general flexibility table, their flexibility class may improve when evaluation shifts from a general to a specific type of function. So, in upcoming researches, implementing Flex method with specific indicators, will allow to evaluate of which new programs these buildings show greater levels of flexibility, and define more precisely which new programs can be received by these objects and which cannot.

7. CONCLUSIONS

The industry in Macedonia and in Tetovo developed most intensively after the Second World War. The buildings built during that period are witnesses of the industrial development and contain great historical and cultural values. In recent years, as a result of numerous changes, most of these buildings have remained abandoned and are often in danger of demolition.

In Tetovo there are many buildings from this period, most of which are located within the city and have the potential to be reused and integrated into the urban structure. One of the

locations with the highest industrial values is Teteks, the textile factory, where a significant part of the buildings has been leased, while others are being prepared for this process.

Many methods were studied for the evaluation and reuse of industrial facilities, but also of other types of facilities, and in the end, it was chosen to continue with the Flex method as it allows to define the class of flexibility in existing objects in general, regardless of the new function; or to precisely define whether a building is suitable for a specific new program or not.

By analyzing the location of Teteks and its buildings, it turned out that these facilities are suitable for accepting new functions, but with some limitations. Therefore, further research and analysis are planned according to the latest version of the Flex method (4.0) in order to define which new uses are more suitable for this location.

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Research paper

CONTEMPORARY BULGARIAN DORMITORIES: A COMPREHENSIVE ANALYSIS OF KEY FEATURES AND TYPOLOGIES

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Abstract

The paper examines the main types of dormitories in Bulgaria: those for high-school students, university students and workers. The author's classification is based on the differences in resident characteristics including age, educational degree, financial resources, duration of residence and other relevant factors. Despite certain similarities in the spatial organisation of these types of residences, the specific characteristics and needs of their occupants necessitate distinct approaches in building planning and design. These differences are particularly apparent in aspects such as location within the urban structure, residential unit configuration and common space organisation. The paper is based on a comparative analysis of contemporary residences for high-school students, university students and workers within the Bulgarian context. It synthesises key characteristics and principles for designing the built environment of these different typologies, considering both urban planning and functional design perspectives. The study provides a basis for further research on the architecture of temporary accommodation for students and workers – an area that remains largely unexplored in Bulgaria and lacks a comprehensive contemporary database. Moreover, in recent years, this issue has gained relevance not only in this country, but also on a global scale.

Key words: *Dormitories, Student Residences, Worker Residences, Temporary Accommodation, Classification, Typologies*

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1. INTRODUCTION

Dormitories are residential structures that provide temporary long-term accommodation (typically ranging from several months to several years) for high school and university students as well as for workers. These buildings integrate various functions, including office, recreation and services, while emphasising residential use as their main function.

The topic of this research paper is both current and important due to the increased interest in comfortable and affordable temporary housing for students and workers worldwide [1]. Furthermore, a significant part of Bulgaria's existing building stock is in poor condition; ongoing interventions include only minor improvements, and there are no adequate modern design standards or building codes for this type of buildings.

The temporary accommodation of students and workers in dormitories has grown rapidly in recent years on a global scale *(Figure 1)*. This growth is a result of several factors, including: globalisation and international mobility and the increasing number of international students and workers in developed regions [1]; a rise of the number of students educated at the undergraduate, graduate and doctoral level [2]; the growth in some industries which require large numbers of temporary workers who need accommodation for a certain period of time; the varying needs and lifestyles of people nowadays who necessitate affordable, convenient and flexible accommodation options, etc.

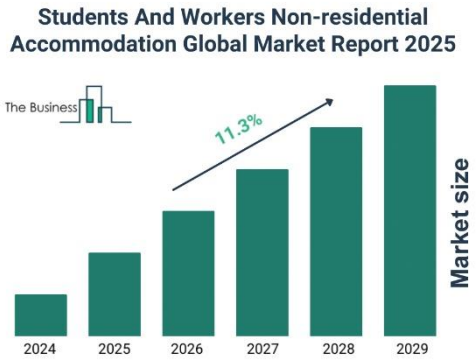


Figure 1. Non-residential accommodation for students and workers, *2025*
Source: https://www.thebusinessresearchcompany.com

Considering the importance of the topic, in the context of present-day Bulgarian case studies, the author systematises several principles and guidelines that are universal and applicable in both Bulgarian and international practice.

The main typologies of dormitories in the country are categorised on the basis of the type of residents:

- Dormitories for high-school students.
- Dormitories for university students.
- Dormitories for workers.

There are notable similarities in certain architectural aspects among these three typologies [3]; however, significant differences also exist due to the demographic and socioeconomic characteristics of residents, including age, educational degree, financial resources, duration of residence, and other relevant factors.

2. METHODOLOGY

The methodology of the study is based on the following components:

- Identifying the key characteristics of the residents in the three basic typologies of Bulgarian dormitories;
- Determining the main requirements for the built environment for high school students, university students and workers, based on the key characteristics of the residents;
- Analysis of typical case studies from contemporary Bulgarian practice;
- Summarising fundamental guidelines for the development of the built environment of Bulgarian dormitories for high-school students, university students and workers – applicable both nationally and internationally.

2.1. Demographic and socioeconomic characteristics of dormitory residents

In order to define the specifics of the types of student and worker residences in Bulgaria, as well as to outline the similarities and differences in their structure, it is important to look at the main characteristics of their residents.

A shared feature of the three groups of occupants is the need for affordable temporary accommodation for a relatively long period of time - usually between several months for workers to several years for pupils and university students. All three social groups need comfortable living conditions, combined with provision of a set of services.

The focus of the present study are the differences rather than the similarities between the three groups of occupants as they provide the basis on which the built environment is shaped to meet their needs *(Table 1)*.

In the first group, high-school students, who are still minors, do not have personal income and are to a significant extent dependent on adults, i.e. their parents or guardians. Pupils need a sense of security and safety. The environment they live in needs to be controlled. Communication with peers and the creation of close friendships is essential and has a positive impact on the psychological and social adaptation of adolescents [4]. During this period, school children are also oriented towards specialised training related to their future career.

In the second group, university students, who are adults in a period of transition from adolescence to adulthood, are mainly independent individuals. A fully controlled environment is not necessary, but some control is advisable. A significant proportion of students are partly financially independent, having personal financial resources in addition to support from their parents (scholarships, work parallel to education). Most university students tend to be single. They create new connections, often based on professional interests, as communication, socialisation and a sense of community are important for their future development. Their world (emotional and material) changes significantly as they structure and integrate their personal and professional identity [4].

In the third group, workers, typically adults over 25 - 30 years old, are completely independent individuals, relying solely on personal income. They do not need a controlled environment. Some are already married, and their social environment depends on their career. It is important to note that the personal contacts of the social segment that has to use temporary accommodation related to work are quite dynamic due to the frequent change of

their living environment. Creating a sense of belonging and stability as well as the possibility of nurturing communities is also essential for this group of occupants. Their age is characterised by the so-called "phase of stability" [4], in which the lifestyle, professional orientation and personality of the individual are relatively constant.

Table 1. Characteristics of dormitory occupants

	Age	Educational degree	Family status	Financial resource	Need of control	Priorities
High-school students	14 - 19	Basic education	single	Financially dependent	Yes	Family School Friends
University students	20 - 26	Upper education	Mostly single	Partially financially dependent	Partially	University Friends Family
Workers	18+	Basic, Secondary, High	Single, married	Financially independent	No	Family Work Friends

2.2. Basic requirements for dormitories for high school students, university students and workers, based on the key characteristics of the occupants

Based on the key characteristics of the occupants summarised above, the following conclusions can be made on the impact these characteristics have on the built environment for temporary living.

The built environment in dormitories designed for high-school students should have a high level of control and constant adult supervision should be provided. The residential units should be planned for at least two students. The common space facilities should provide opportunities for learning, interest-based activities, dining, sports, recreation, socialisation within the building, enabling students to remain on the dormitory premises at all times.

The built environment in dormitories designed for university students should be subject to partial control, therefore the presence of a concierge or security guard at the entrance of the building is typically sufficient. The residential zone should offer varying levels of privacy, “as a balanced sense of privacy is essential for individuals well-being” [5]. Residential units may be designed as single or double rooms (or family apartments that are a rare choice). Dining options could be made available both within and outside the dormitory premises. An important part of the living environment are workspaces (individual and group areas), common areas that encourage social interaction among students, create a sense of community, and offer opportunities for sports and recreation.

The built environment in dormitories for workers does not require a high level of control. Similarly, to the typologies described above, in the residential zone of this type of dormitories, levels of privacy should be provided. Residential units could be planned as single and double rooms and family apartments. Providing cooking facilities for residents is essential. While workspaces are not necessary, areas that encourage social activities and foster a sense of community are required [3].

2.3. Method of financing - public or private - as a factor influencing the built environment

An essential factor that determines some differences in the buildings for temporary accommodation of students and workers is the method of financing. The construction of student dormitories is mostly a social activity [3], financed and implemented in Bulgaria by means of funds from the state budget, municipal budgets, as well as from various European funds and programs. State initiatives nowadays are mostly focused on the renovation of existing buildings rather than on the construction of new facilities.

In recent years, private-financed initiatives for the building of student dormitories have also emerged in the country. These are typically hybrid structures *(Figure 4)* that combine temporary accommodation for students with hotels, restaurants, co-working centres and other functions. Alternatively, some investors build apartment buildings that lack common spaces and include residential units for both rent and sale.

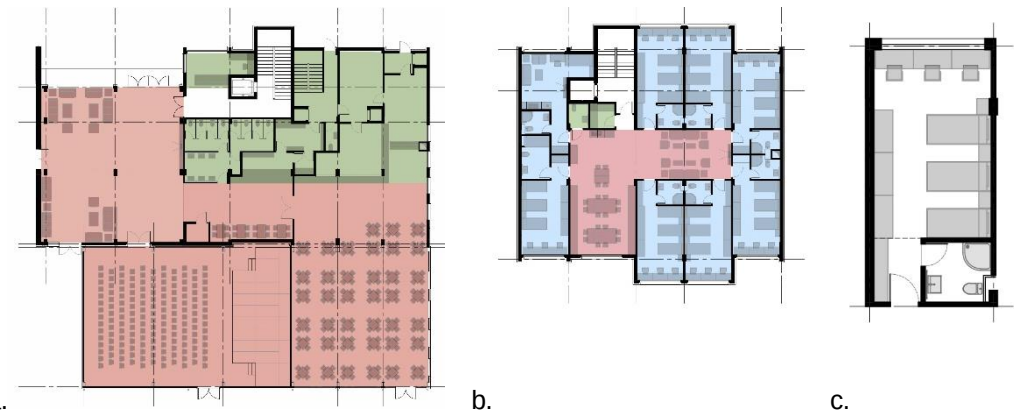
The construction of dormitories for workers is primarily within the realm of private initiatives by entrepreneurs or large industrial companies [3], whose priority is to maximise the density of residential units at the expense of service facilities.

2.4. Typical dormitories from contemporary Bulgarian practice

This paper presents and analyses several case studies featuring dormitories for high school students, university students and workers from contemporary Bulgarian practice, implemented over the last ten years. This analysis aims to clarify the diverse characteristics and requirements for planning the built environment associated with these types of buildings.

2.4.1. High-school student dormitory, Stara Zagora

The building is designed as a semi-detached structure adjacent to the High School for Computer Science and Mathematical Analysis in Stara Zagora. The underground level includes service rooms - such as a kitchen, laundry, storage areas, technical rooms and facilities for the staff. The ground floor comprises a communal zone for all residents, featuring a reception foyer with a security guard, a dining hall and a multifunctional hall. The residential area is designed on the next three floors and contains residential units for three students, each approximately 22 square meters in size, with en-siute bathrooms. The residential levels also incorporate common spaces designed for the group of residents occupying each floor, which consist of a spacious living room, a study area, and a dedicated room for a tutor.



a. b. c.



Figure 2. High-School Dormitory, Stara Zagora, 2020
Author: SIDEA Architectural Design, arch. Siyana Yancheva
Source: Arch. Yancheva's Personal Archive; https://www.buildingoftheyear.bg,
Photographer: Tsvetelina Belutova: https://www.capital.bg/
a. ground floor plan, b. typical floor plan, c. students room, d. underground,
e. section, f. view, g. students room view

2.4.2. Dormitory for university students, Plovdiv

The building represents the first of four prototype dormitories within a student complex (campus) developed around an attractive landscaped park environment situated in close proximity to the Plovdiv University Paisii Hilendarski.

A communal zone accessible to all residents is provided on the ground floor, while common areas on the upper levels are designated for smaller groups of students (usually those living on that storey). Although the communal facilities have been minimized, there is a notable emphasis on the integrated use of services from adjacent facilities, such as a multifunctional sports hall, retail stores and cafes. The residential units consist of double rooms, with an area of 18 square meters each, equipped with en-suite bathrooms. Notably, access to these units is unconventional for Bulgarian residential buildings, featuring a wide, open gallery that also serves as a terrace for residents during the warmer seasons.

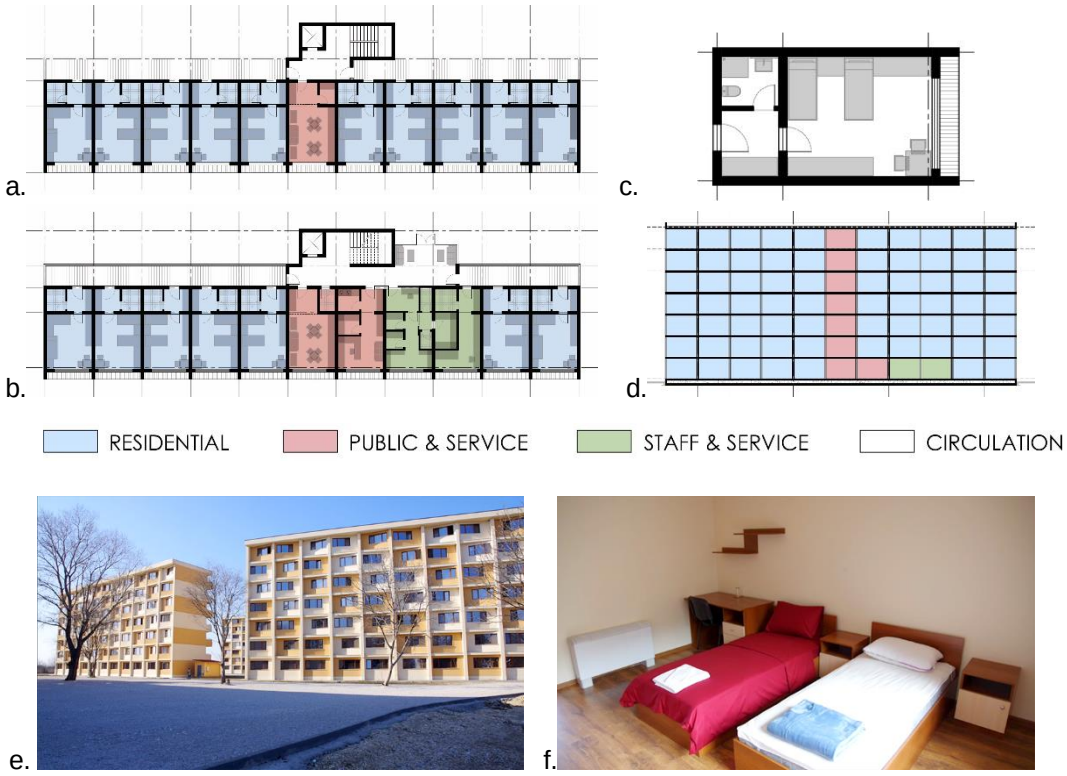


Figure 3. Student dormitory, Plovdiv, 2015
Author: arch. Antoaneta Topalova, arch. Nikolay Andreev
Source: Arch. Topalova's Personal Archive, https://uni-plovdiv.bg/pages/index/1611/
a. ground floor plan, b. typical floor plan, c. students' room, d. section,
e. view, f. students room interior view

2.4.3. Student Dormitory and Hotel Campus 90, Varna

Campus 90 is a "hybrid type of urban formation" which appeared in the context of higher requirements of people to the quality of the living environment and to the diversity of housing types [6]. It is located in Varna within a walking distance of two major state universities. It effectively combines student housing, hotel accommodation, and a conference centre within a single building „through vertical mixing of functions" [7].





Figure 4. Academic Hub „Campus 90“, Varna, 2022
Author: E-ARCH STUDIO, Galina Baleva, Ina Dineva, Martin Hristov
Source: Author's Personal Archive: https://e-arch.bg, https://www.buildingoftheyear.bg; https://miesarch.com//5164
a. ground floor plan, b. first floor plan, c. typical floor plan, d. section, e. students' room, f. view, g. students room interior design

The concept of the “academic hub” is to provide not only excellent living conditions but also to facilitate interaction, communication and teamwork among students. The two underground levels accommodate parking spaces, service areas, storage, and technical facilities. The communal area, which comprises an extensive lounge, six multifunctional halls of varying sizes, a restaurant, and a fitness centre, is designated for the first two above-ground levels and is accessible to both inhabitants and visitors. Part of this public area includes wide terraces – “in-between spaces” [8] between the interior and the exterior environment that enable various activities in close contact with nature. The residential zone is designed as a highly compact structure, comprising single and double residential units equipped with kitchenettes and en-suite bathrooms, providing a high level of living comfort. Each floor also includes a small lounge for a group of residents.

2.4.4. Worker dormitory, Sofia City

The building is located in an easily accessible area of Sofia, with numerous transportation options, ensuring a convenient commute to and from the workplace. The underground level accommodates the necessary number of parking spaces, as well as service rooms, storage, and technical rooms. This level also includes a residential group in an area that allows for

natural light. The ground floor features a foyer, a communal lounge for all occupants, and residential units. The residential zone is developed vertically and consists of compact apartments designed for two occupants or a family.

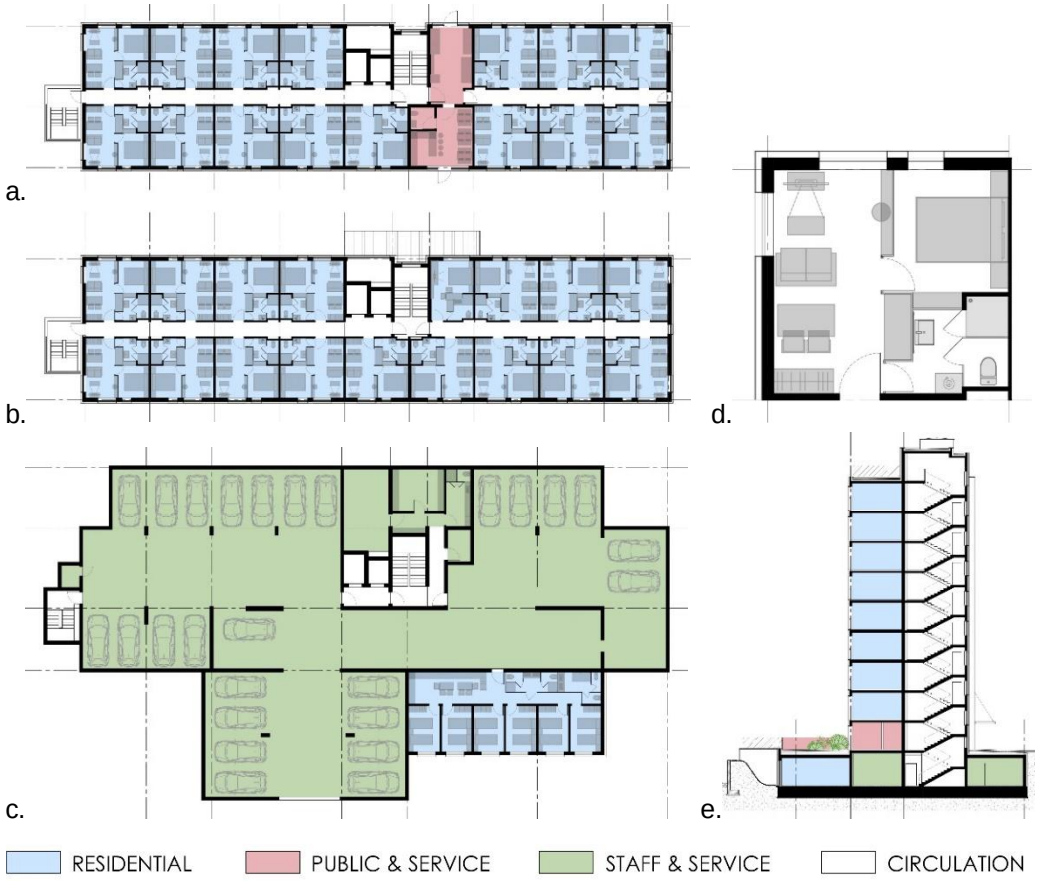




Figure 3. Worker Dormitory „Tarsis Residence“, Sofia, 2021
Author: arch. Rumen Aleksandrov
Source: Arch. Aleksandrov's Personal Archive
a. ground floor, b. typical floor plan, c. underground, d. typical apartment, e. section, f. view, g. apartment interior design

The project serves as a notable example of the application of “small residential forms”, where the reduction of living space does not compromise the functionality of the units or diminish the quality of living comfort [9]. The designed roof-top terraces could be an attractive part of the communal area as in-between spaces, offering opportunity for social interaction and recreation.

3. RESULTS AND DISCUSSION

This comprehensive analysis of dormitories for high school students, university students, and workers within contemporary Bulgarian practice indicates some similarities in certain aspects, while significant differences are evident in others.

3.1. Common characteristics

Dormitories for high-school students, university students and workers are developments that embody the characteristics of shared living, integrating both individual and collective lifestyles [10]. Desire to engage in or avoid social contact and interaction with others varies, so residents should be able to control levels of privacy in their living environment. Balanced privacy and social interaction are key elements for the well-being of people living in dorms [5]. Therefore, such buildings are designed to include diverse functional elements - both private and communal spaces that offer opportunities for different levels of privacy as well as socialisation, recreation and entertainment.

The functional configuration of the buildings delineates **two primary zones – a residential and a communal one** - interconnected by horizontal and vertical **circulations** [11]. Additionally, a **service zone** is planned, primarily implemented at the underground level (when such a level is designed).

- **Residential zone** generally consists of units designed for a small number of occupants (one to three) with en-suite bathrooms. These spaces offer a high level of privacy for occupants.
- **Communal zone** consists of multifunctional spaces utilised by all occupants or small groups of tenants. A characteristic feature, common to all three types of buildings, is the living room or lounge, which exhibits variations in both size and functionality across the different typologies.
- **Service zone** in all types of buildings includes storages, technical rooms, premises serving the staff, laundry and parking lot.

3.2. Differentiating characteristics

The differentiating characteristics of dormitories for students and workers can be systematised into several aspects as follows:

- **Location within the urban area**

Buildings for the temporary accommodation of high-school students are required to be located in close proximity to the schools they serve, ensuring the safety of pupils’ transportation. Proximity of location for university student and worker dormitories is also a priority; however, physical closeness is often not required, but rather direct and convenient access to transportation.

Table 2. Dormitory types specifics

	Location	Residential	Communal / service
High-school students	In direct contact with the school, usually in the school yard	- a 2-3 student room - a living room - a study room - a tutor room	- a concierge - a canteen - laundry facilities - a hall
University students	With convenient access to the university	- a single, double room - a family apartment - a living room with kitchenette - a working space	- a concierge - a café/canteen - laundry facilities - a hall
Workers	With convenient access to work	- a single, double room - a family apartment - a living room with kitchenette	- an automated access system - laundry facilities - a common living room

- **Safety and security of the environment**

In high-school student dormitories, a high level of security is maintained, with access control serving as a fundamental measure to ensure the safety of pupils. In student dormitories, the level of control is less stringent, whereas in dormitories for workers such oversight may be minimal or entirely absent. Worker dormitories normally feature an automated access control system that eliminates the need for a concierge or security guard, utilising card-based access for security.

- **Residential zone**

The number of occupants per residential unit in student dormitories ranges from two to three, whereas in the other two types, it ranges from one to two, with the addition of apartments designated for couples. Each floor in high-school student dormitories is designed to include a room for a dormitory supervisor. The lounge and study area are essential components of the floor plan. In university student dormitories, the residential area also includes lounges with kitchenettes and also workspaces for small groups of residents (typically those living on the same floor). In buildings for the temporary accommodation of workers in Bulgaria, common areas on each floor are often absent, or if included, their sizes are minimal.

- **Communal zone**

Analysing the dormitories built in Bulgaria over recent years, it is communal zone that exhibits the most significant differences among the various typologies. This zone includes a diversity of functions in buildings for students, whereas in those for workers, it is almost absent or has been reduced to a minimum.

A mandatory element of the communal zone in high-school student dormitories is a common dining room with a kitchen (the latter as a part of the service premises). This facility may be absent only if access to the school canteen is provided. In university student dormitories, a canteen may also be included, as well as a restaurant accessible to external visitors; however, this component is generally lacking in worker dormitories.

Other components of the communal zone are determined by the location of the buildings within the urban environment, the availability of nearby amenities, and the potential for the integrated use of functions. In the first typology, external access is distinctly separate.

- **Service zone**

The key elements that distinguish the service zone in the three types of dormitories are the kitchen and parking facilities. In high-school student dormitories, a kitchen is typically included in conjunction with the planned dining hall (unless, as mentioned above, integrated use of services with the school that the dormitory serves, is anticipated). A parking lot for residents is not required.

On the contrary, in the other two typologies, specialised kitchens are typically the exception. In university student dormitories kitchens are rarely designed and in worker residences these are absent. The provision of parking spaces for occupants is mandatory

3.3. Discussion

On the basis of the author's analysis and research interests concerning student dormitories, the following guidelines for the future development of these building typologies can be systematised:

Planning different types of temporary accommodation for different social groups as students and workers within the urban structures is vitally important, because when properly planned and integrated within a certain territory, those buildings could enhance neighbourhoods and boost the local economy [12].

Two primary functional zones are delineated – residential and communal one, interconnected by horizontal and vertical circulations.

The residential zone should provide the necessary levels of privacy for residents through optimally planned living units (rooms or apartments), packed with en-suite bathrooms and accommodating small number of tenants (one to three).

On each floor, in addition to this zone, it is essential to include diverse common spaces for small groups of occupants, because “sociologically best designs of dormitory space organization comprise existence of spaces for common facilities, intended for small groups” of residents [13] (usually living on that same floor). These premises could be defined as “semi-private”, hybrid zones between private and public, aimed at facilitating learning or work, communication, interest-based activities, and the creation of sustainable communities.

The quality of life in dormitories is influenced not only by private or semi-private spaces but also by the design of communal areas for all the residents. They should offer a comprehensive range of activities and services which usually depend on the location and the availability of nearby amenities. They have to comprise a variety of active and passive zones designed to facilitate social interactions, entertainment, work, sports and relaxation.

Common spaces could be situated on the ground floor, as well as on various floors within the building, or on the upper levels with differing level of accessibility [2]. The planning of common spaces on each floor offers the advantage of achieving an even distribution of residents throughout the building, rather than concentrating them to the lowest or highest storeys [14].

Flexibility and adaptability, alongside with green building practices, are essential features of the sustainability of the built environment in the dynamic, high-tech modern world. Buildings should be planned for the rapidly changing needs of population as well as for various economic and environmental conditions. They should address demographic, economic, technological and environmental requirements by utilising modular constructions, prefabricated options, environment-friendly materials etc. [12].

4. CONCLUSION

Combining a diversity of functions and activities, dormitories represent a “micro-living environment” [15] that reflects the specifics of the constantly changing modern world. The pathway to achieving quality and sustainability in dormitory architecture lies in creating flexible and adaptive to future functional changes designs that meet the increasing demands of modern residents regarding living standards and available services.

The systematisation of basic dormitory typologies, along with their similarities and differences, as well as the formulation of fundamental guidelines, provide a solid foundation for future in-depth scientific studies of each typology. This classification also serves as a prerequisite for enhancing the living environment as well as optimising the codes concerning the design of such buildings.

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Research paper

BEYOND THE BUILT ENVIRONMENT: THE SOCIAL LIFE OF PUBLIC SPACES

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Abstract

This research explores the dynamic social life of public spaces, focusing on the relationship between spatial organization, human territoriality, and community well-being. By examining the physical characteristics of public spaces such as street networks, squares, and other urban environments, the study aims to understand how these elements influence social interaction, place identity, and the quality of life within communities. Central to this investigation is the concept of "third places" – informal gathering spots outside of home and work – and their role in fostering a sense of belonging and community cohesion. The study seeks to identify the key factors shaping the spatial organization of public spaces, such as design features, accessibility, and functional diversity, and how these contribute to social behavior and territorial practices. Additionally, it investigates how the configuration of public spaces affects users' perceptions of identity and attachment to place. The research contributes to a deeper understanding of how the built environment goes beyond physical infrastructure to support social networks and cultural identity, offering insights into designing public spaces that better serve communities. Through a comprehensive analysis of spatial characteristics and human activity, this work provides a framework for evaluating the social performance of urban public spaces and the ways in which they can be enhanced to improve community quality of life.

Key words: *Urban public spaces; Social life; Social networks; Social interaction; Spatial organization; Human territoriality*

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1. INTRODUCTION

The built environment is understood as the material and spatial context created by humans, encompassing not only buildings and infrastructure but also intermediate zones—parks, squares, streets, and other urban spaces, altogether forming a complex network of public and private territories. In architectural and urban discourse, it is perceived not only as a physical phenomenon but also as a cultural, social, political, and economic construct that defines ***societal functions and interactions***. Today, public urban spaces are regarded as places for social activity, recreation, and cultural exchange; ***in various studies, they are even described*** as social “containers” where identity and a sense of belonging are constructed [1, 2].

The contemporary definition of public spaces is multilayered and ***remains*** a subject of intensive debate, encompassing both the physical characteristics of the space and its social, political, and cultural functions. These concepts ***have been evolving*** alongside transformations in the modern city and occupy a central place in the research of leading theorists and scholars [3, 4, 5, 6].

As early as the late 19th century, utopian models such as Ebenezer Howard’s garden cities [7] and Frederick Law Olmsted’s democratic parks [8] laid the foundation for socially oriented urban planning. Nevertheless, with the rise of modernism and functionalism during the first half of the 20th century, the concept of public space acquired a more utilitarian character. Jacobs [2] states that architects such as Le Corbusier and Mies van der Rohe primarily envision public spaces as functionally segregated zones, prompting sharp criticism ***concerning the diminished role of immediate street-level interactions*** as a foundation for social vitality

From the second half of the 20th century onward, social theories further developed the perspective of public space as a "social construct." Henri Lefebvre [9] formulated the concept of "produced space", reflecting and generating social conflicts, while Michel Foucault [10] introduced the notion of "heterotopias"—alternative spaces that disrupt dominant societal orders. Concurrently, sociologist Ray Oldenburg [11] proposed the theory of "third places"—informal environments between home and work where civic status and a sense of community are cultivated. In the contemporary era of urbanization, sustainability, and digitalization many researchers claim that the focus has shifted toward ***human-centered, inclusive, and digitally augmented*** public spaces [12, 13, 14, 15].

Through the prism of these historical layers, the present study examines and traces the main social and intangible aspects, beyond the built environment and its physical characteristics that are crucial for the spatial organization of public spaces. The research ***conducts a theoretical overview*** of the "human-space" relationship, employing a complex methodology that tracks and synthesizes various theoretical perspectives and studies on the subject.

2. THE CONCEPT OF TERRITORIALITY: A THEORETICAL OVERVIEW

The concept of territoriality has become a **crucial interdisciplinary tool** for understanding how space is produced, controlled, and contested across different social contexts. **Fundamentally**, it integrates biological, anthropological, psychological, and architectural perspectives to reveal the complex interrelations between material structures,

cultural practices, and power relations. In today's rapidly urbanizing, mobile, and digitized world, territoriality gains **new dimensions**, as it evolves from a mere description of "physical" territory into an ongoing process of reshaping and negotiation [16, 17].

2.1 Origins of the Concept: Biological and Behavioral Context

The notion of "territoriality" first emerged in ethology, describing the innate impulse of animals to mark and defend areas for survival and reproduction [18, 19]. ***However, in human societies,*** the concept is enriched by cultural and social dimensions. Early behavioral and cultural-anthropological studies initiated the expansion of the concept beyond biology. In his research from 1966 Edward T. Hall [20] explored how different cultures use spatial distance as a form of social regulation. According to him, the space around the body functions as an extension of personal territory and is subject to cultural modulation.

Building on his study, Hall introduced proxemics, demonstrating that through four zones of interpersonal distance (intimate, personal, social-consultative, and public), cultural norms regulate interactions between individuals and their "personal territory." ***Thus, Hall shifted the focus*** from describing "physical distance" toward understanding space as a socially constructed reality, where every boundary carries symbolic and regulatory functions. He distinguished two types of spaces: **sociopetal** (social-communicative) and **sociofugal** (socially non-communicative) [21].

Hall's boundaries for the different space types were based on his own research, interviews, and surveys, gathering information about the cultural and social aspects of various communities. Although this raises questions regarding their universality across cultures, these measurements ***serve as fundamental references*** for assessing the social sustainability of architectural spaces.

According to Lui [22] such perspectives also include the visualization of the social distances defined by Hall. This supports interpreting proxemics both as physical territory (the spatial arrangement of objects relative to humans) and as personal territory (the interpersonal distances in social interactions).

When defining spatial organization and, consequently, architectural form (geometry and scale) factors such as proximity, arrangement, and furnishing shape become crucial. ***On a broader level,*** it is necessary to define environmental models and structures as processes: passive (observation) and active (action-movement) uses of space.

2.2 The Social-Psychological Theory of Territoriality

While Hall established the foundations of cultural proxemics, Irwin Altman [23] developed the idea further by considering territoriality a social-psychological mechanism for controlling access to space and protecting personal and group identity. The first systematic study of territoriality as a social-psychological phenomenon was conducted by Altman [24] in his book *Environment and Social Behavior: Privacy, Personal Space, Territory, and Crowding* (1975). According to him, territoriality is the way individuals and groups regulate access to space to achieve control, security, and identity. He identified three primary types of territories and Edney [25] believes that they have become a ***classic typology***:

- **Primary territories**: Spaces with a high degree of personal ownership and control, such as the home.

- **Secondary territories**: Semi-public spaces regularly used by specific groups, such as offices or schools.
- **Public territories**: Open-access spaces like parks or streets, where control is minimal and temporary.

Altman emphasized that territorial behavior involves both preventive actions (e.g., marking a space) and reactive actions (e.g., defending against encroachment). His theory laid the foundation for understanding territoriality as a ***dynamic, situational, and socially mediated*** process rather than fixed possession. Altman's theory is fundamental to understanding the interaction between people and space, particularly in urban environments and public spaces.

2.3 Territoriality in Architecture and Urbanism

The concept of territoriality has found ***rich and diverse applications*** in architecture and urbanism, where it helps interpret and design urban environments as culturally structured and socially regulated spaces. One of the first major contributions was Oscar Newman's *Defensible Space: Crime Prevention Through Urban Design* (1972), where territoriality was identified as a key factor in creating safer residential environments [26]. Acording to Donnelly [27] Newman argued that clearly defined boundaries and a strong sense of ownership among residents stimulate active surveillance and maintenance of spaces—a conclusion he illustrated through his analysis of the Pruitt-Igoe housing project in St. Louis.

Alongside Newman's architectural-functional approach, Amos Rapoport [28] developed a cultural-anthropological perspective, emphasizing the idea of understanding space as an expression of the inhabitants' cultural logic. According to him, territoriality is not imposed by external authority but arises through culturally meaningful practices that imbue the architectural environment with symbolic value [28]. Thus, architectural forms are interpreted as carriers of cultural codes articulating social norms, identities, and rituals.

Tim Ingold [29] extended the view of space as a process rather than a fixed structure, criticizing the concept of space as a "container". Instead, he described space as a flow of interrelations among people, materials, and environments. This approach seeks to shift architectural thinking toward designing flexible, adaptive spaces that evolve in line with urban life rhythms and usage patterns.

Similarly, Margaret Crawford in *Everyday Urbanism* emphasized the micro-practices of residents, from informal arrangement of street elements to individual tactics for personalizing public space [30]. Her empirical observations demonstrate how everyday acts of appropriation transform urban spaces, imbuing them with meaning and building collective identity.

The contributions of Ingold and Crawford expanded classical notions of territoriality by adding concepts of ***processuality, fluidity, and individual expression***. They highlight the significance of everyday interactions in constructing socially vibrant spaces.

At the beginning of the 21st century, these ideas evolved into more complex socio-material and temporal frameworks, exemplified by Kärrholm [16, 31] and his concept of "territorial complexity," analyzing how material elements—benches, barriers, pathways—and rhythms of use create and stabilize multilayered territorial structures in public settings. Kim Dovey [17] contributed with the notion of public space as a socio-spatial assemblage where identities, power relations, and everyday tactics co-shape processes of "reterritorialization"

and "counter-territorial" practices. His analysis highlights how social and spatial structures are ***deeply interconnected and constantly renegotiated***.

In architecture and urbanism, contemporary territoriality studies go beyond conventional defense and boundary-demarcation models.. They incorporate cultural-symbolic, processual, and tactical dimensions, through which public spaces become a stage for continuous social production. Analyzing the different theoretical approaches and their intersections is essential for deepening our understanding of social dynamics within urban environments.

3. SOCIAL DYNAMICS OF PUBLIC SPACES: SPATIAL-TERRITORIAL SIGNIFICANCE

In the context of architectural theory and urbanism, territoriality is no longer perceived solely as a *"psychological"* possession of space (as in the classical paradigm) but rather as a dynamic, multidimensional, ***socially-networked***, and material process. Studies of human territoriality have traditionally focused on physically defined space [32]. Significant shift in the conceptualization of human territoriality occured in the 1980s, when it began to be understood as serving to organize human behavior [33]. Within these perspectives, physical space is associated with social and communal functioning, in relation to individual and personal behavior. The primary theories are based on, and examine, human perception of space, particularly concerning personal boundaries, definitions, and accessibility.

In this context, contemporary research on public urban space observes a shift from a focus on ***linear models of territoriality*** to more nuanced, multidimensional approaches. Rather than focusing on unilateral access regulation, these approaches emphasize on ***the coexistence and cooperation of multiple spatial "productions."***

3.1. The Influence of Altman's Theory on Public Space Studies

The theory of territoriality formulated by Altman represents a significant conceptual framework for analyzing spatial behavior and its reflection on social dynamics. This theory finds broad application in architecture, urbanism, and ecological and organizational psychology. According to Brown & Altman [32], territoriality functions as a mechanism for regulating social distance and personal space by structuring three primary types of territories—primary, secondary, and public. Contemporary interpretations by Gehl [5] and Wortley & McFarlane [34] employ this three-tiered taxonomy to analyze and design public spaces aimed at enhancing ***feelings of security, social cohesion, and belonging***.

In the urbanist context, the application of the theory emphasizes the role of physical indicators—such as benches, vegetation, and visual barriers—in shaping "personal zones" within public space. These elements facilitate social regulation and can help reduce crime, in alignment with the principles of "defensible space" formulated by Newman [26].

Territorial behavior also finds applications in other disciplines. In organizational psychology, it manifests through the personalization of workspaces, a factor that according to Hole et al [35] and Wells [36] enhances employee satisfaction and productivity. In an urban study from Iran Mohammadi et al [37] trace how the architectural connectivity between buildings and public spaces supports social cohesion and the functionality of the urban fabric.

Contemporary empirical research confirms the relevance of Altman's theory. In a study by Huang et al. [38] the territorial typology is applied to residential complexes, emphasizing the importance of the emotional and cultural aspects of primary territory previously explored by Brown & Capdevila [39] and Taylor [40]. In a systematic review of over 150 empirical studies Wang et al. [41] , identified territoriality as a key factor for ***social connectedness and collective identity*** in public environments.

The importance of spatial design has also been highlighted by Taylor [42], who, using the Role Construct Repertory Grid technique, analyzes the applicability of the territorial taxonomy across various urban contexts. His analysis underscores ***centrality and temporal stability*** as essential dimensions in the social organization of space.

Modern developments of the theory incorporated new methodological approaches. Sepe & Fletcher [43] as well as Hole et al. [44] propose a theoretical synthesis between territoriality and the concepts of sociopetal and sociofugal configurations. Nguyen & Correa [45], employing the Space Syntax approach, demonstrate how physical and tactile boundaries assist in the stabilization of secondary and public territories, fostering social interaction and security in the urban environment.

In summary, Altman's theory continues to serve as a relevant and interdisciplinary analytical framework for understanding and designing urban public spaces. Its applicability extends beyond its original psychological context, encompassing architecture, urbanism, social theory, and organizational culture, thereby emphasizing the need for complex, interdisciplinary approaches in contemporary urban planning.

3.2 Proxemics – The Hidden Dimensions of Communication

Proxemics, introduced by Edward T. Hall [20, 21], offers a foundational framework for analyzing nonverbal communication and social dynamics in everyday and public spaces. Hall defined four primary zones of interpersonal distance—intimate, personal, social–consultative, and public—that structure the ways in which people interact and position themselves within space. Building on these ideas, Jan Gehl [12] adapted the proxemic model into the concept of “human scale”—the capacity of the urban environment to combine movement and pause through forms and dimensions corresponding to Hall’s defined zones. In his classic analysis of the Piazza del Duomo (Santa Maria del Fiore) in Siena, Gehl demonstrates how the proportions of space support both social–consultative and public interactions by creating conditions for encounters and mobility.

Contemporary urban design continues to apply proxemic principles in the development of inclusive spaces. According to the Gehl Institute [46], modern approaches distinguish between “zones of proximity” (around benches and street furniture) and “zones of accessibility” (along pedestrian corridors), aiming to ensure an ergonomically and psychosocially comfortable environment for diverse user groups.

The COVID-19 pandemic prompted a rethinking of these traditional frameworks. Mehta [47] introduces the notion of a “new proxemics,” adapting Hall’s classical zones to the need for 1.5–2 meter physical distancing. Solutions such as ground markings, mobile barriers, and modified street furniture have been proposed to preserve social interaction without compromising safety.

New norms for social distancing have also been integrated into urban practice through proxemic diagrams. For example, the Urban Design Lab [48] employs visual codes to designate different zones, which aids in the clear zoning of urban spaces.

In the context of urban density research, Chen et al. [49] introduce the concept of “density intensity,” related to the feeling of overcrowding or spatial openness. Their analysis shows that the deliberate use of proxemic zones can mitigate the negative effects of high built density. With the evolution of digital technologies, the idea of “digital proxemics” has emerged, expanding the classical zones through virtual layers of interaction, such as the use of chatbots in intimate zones or geolocated social hubs in public spaces, described by McArthur [50].

Proxemics is one of the “hidden dimensions” of communication—a spatially structured yet often unconscious foundation of social interaction. By defining interpersonal distances, it shapes how we express closeness, power, or belonging. In the urban context, proxemics serves not only as an analytical tool but also as a design framework for creating socially active spaces. From the scale of the piazza to digital interactions, proxemic principles continue to mold the cultural and technological transformations of publicness and coexistence in the city.

3.3 Territorial Complexity: Overlapping and Cooperation

The theory of ***"territorial complexity"*** redefines urban public space, presenting it not as a homogeneous "public" or "private" zone but as the result of multiple interwoven relationships among various actants and material interventions. In his 2005 study of three squares in Lund, Sweden, Mattias Kärrholm [31] introduced his concept and tested it by analyzing public space as a product of diverse forms of territorial production. .

At the core of this theory lies the understanding of territoriality as ***"spatially divisible forms of control"***, characterized by specific rules or recurring behaviors. Kärrholm [31] distinguishes four primary forms of territorial production (Table 1):

Таблица 1: Forms of territorial production by Mattias Kärrholm

	Impersonal control	Personal control
Intended production	Territorial strategy: *planned and delegated mechanisms of control*	Territorial tactics: *immediate acts of marking or appropriation*
Production through use	Territorial association: *conventional uses and functions associated with particular groups or activities*	Territorial appropriation: *production through repetitive use without explicit intent to own*

Methodologically, Kärrholm approaches public space as a multilayered configuration resulting from processes of production, stabilization, and complexity. According to him, territorial complexity arises from the overlapping of different territorial layers that develop across time and space. Thus, the same location can serve a variety of functions, marketplace, parking lot, site for social protests, or recreation area, through the interaction between material elements (e.g., benches, pavements, signage) and societal norms of use [31].

Kärrholm's empirical observations demonstrate how minor architectural interventions, such as the organization of street furniture, can significantly influence the types of territorial production. A notable example is the transformation of Mårtenstorget in Lund during the

1990s, where subtle material interventions (so-called "open institutions") proved more effective in creating open and accessible public spaces than neutral, unmarked zones [31].

In 2007, Kärrholm [16] expanded his theory by integrating the notion of material actants and the Actor-Network Approach (ANT), highlighting their roles in the formation and stabilization of territories. In doing so, he built on classic theoretical frameworks - Hall's human ethology [20], Sack's political geography [51], and and Lefebvre's social production of space [9] - through the lens of Latour's Actor-Network Theory [52]. ***By transcending the traditional public–private dichotomy, Kärrholm [31] offers a dynamic, processual, and materially engaged vision of public space.*** The concept of territorial complexity finds broad application in contemporary research, examining how territories are formed and transformed through social practices, events, and temporal rhythms. For instance, Lu [53] explores the temporal aspects of territoriality, while Citroni [54] emphasizes the role of events as factors that ***complicate rather than simplify territorial structures***. In specific urban case studies such as Turro (Milan) and Norra Fäladen (Lund) districts, Citroni and Karrholm [55] trace how bordering public and commercial zones lead to increasing territorial complexity. Meanwhile, Plant [56] applies the idea of managing complexity in the context of sustainable territorial planning.

Therefore Kärrholm's theory is established as an effective framework for analyzing and designing urban spaces, ***uniting material conditions, social interactions, and spatial design into a cohesive analytical model***.

4. DISCUSSION - PUBLIC SPACES AS A SOCIAL PROCESS

The conclusions drawn from the previous sections emphasize that public spaces function not merely as physical territories, but as social processes, in which territoriality manifests through dynamic interactions between people, objects, and meanings. They are neither fixed nor unambiguous; rather, they serve as multidimensional scenes of coexistence, where boundaries, identities, and forms of belonging are continuously negotiated. The comparative analysis of the three discussed concepts reveals both complementary and contrasting perspectives on the social dynamics of space. While Hall and Altman focus on more structured and regulatory models—through distance and access control—Kärrholm, in contrast, presents a procedural and networked vision of territoriality, emphasizing co-use, rhythms, and material mediation. Proxemics contributes an understanding of spatial communication and the human scale, crucial for ergonomics and social comfort. Altman's theory emphasizes identity and a sense of security, defining clear types of territories. Kärrholm builds on these approaches, presenting public space as a field of overlapping territorial practices that are formed and transformed according to use and context.

In summary, contemporary understandings of territoriality in public spaces demand a shift from fixed categories to a dynamic, situational, and materially engaged perspective. A successful public space is not defined by rigid zoning, but rather by its capacity to be flexible, accessible, and socially polysemous—a space for collective belonging, temporal rhythms, and multiple uses. These comparisons clearly show that territoriality is no longer seen solely as "ownership" but as a relationship—between human and non-human factors, social practices, and material conditions. In contemporary architectural and urban theory, it is defined as:

- Networked – rather than isolated;
- Processual – rather than static;
- Temporary and situational – dependent on use, time, and meaning;
- Infused with power – from state regulation to spontaneous actions;
- Materially mediated – through objects, infrastructure, and rhythms of use.

5. CONCLUSION

In the creation of contemporary public spaces, a key role is played not only by shaping the physical environment, but also by understanding its "social biography"—the ongoing interaction between people and place, manifested through overlapping territorial practices, inhabitation, memories, and everyday gestures. The design of public spaces should be understood as a dynamic process of social construction, weaving together cultural norms, historical layers, and power relations. It shapes the physical boundaries of publicness, while simultaneously mediating symbolic representations, social memory, and collective identity. As Lefebvre emphasizes [3] [9], space is not a neutral fact, but rather a product of the interaction between environment, use, and power. In this context, territoriality, as this study shows, has evolved from a static model of possession to a multidimensional, processual, temporary, and materially mediated practice. Public spaces acquire meaning not only through their architectural form but through how and by whom they are used—becoming a stage for social rituals, a dialogue between past and present, and a field for negotiation between individual and collective identities. As Tim Ingold [29] writes, "Places do not exist as fixed locations but arise as nodes in the flow of life"

Future research should focus on a deeper understanding of the discussed interconnections—between space, use, culture, and memory—as well as the development of methodologies to capture the fluidity of public territoriality in the context of continuous urban transformation.

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Review paper

TYPES AND AMOUNTS OF METALS PRESENT IN THE RAILWAY BODY

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Abstract:

Heavy metals, polycyclic aromatic hydrocarbons and pesticides were frequently identified as compounds hazardous to human life and health when soil testing results in the area of railway lines were investigated. Our own investigations have revealed the existence of heavy metals that are harmful to human life and health, as well as the presence of other metals. This article has a particular emphasis on these other metals. The majority of registered metals are not included by the Republic of Serbia's Regulation on maximum allowable values of metals in soil. A relatively small number of metals, included by this Regulation, did not exceed the maximum allowable values but their presence was confirmed. In order to gain a complete understanding of the metals released into the soil as a result of railway operations and their possible sources, these data must be evaluated.

Key words: *Railway, Railway Pollution, Metals, Environment.*

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1. INTRODUCTION

Contrary to previous beliefs that rail is an environmentally friendly mode of transport, it is now possible to argue that this is not entirely true when considering the pollution that railway traffic causes to the surrounding environment [1–4]. Serious environmental contaminants from the influence of railway traffic include heavy metals, polycyclic aromatic hydrocarbons and herbicides, according to a number of studies that highlighted the findings of soil tests conducted both on the railway body and in the surrounding area [1]. A significant number of those studies emphasize heavy metals, since they have detrimental effects on human health.

The main reason heavy metals are harmful is that they can accumulate into the human body through the food chain through contaminated food or water.

The primary objective of this research was to determine the presence and quantity of lead in the railway track. Due to the peculiarity of the formation source and the mode of migration, lead is one of the most frequently registered metals that exceeded the allowed amounts. According to current studies, this metal is the most commonly registered metal in the soil surrounding railways, in addition to cadmium [5–10].

Interest in lead arises as a result of long-term research into the impact of lead on human health. A single exposure to lead has been proved to have a wide range of harmful consequences on human health like fatigue, dizziness, arthralgia, impaired memory, nausea, sleep disorders, dermatological disorders, coxarthrosis, balance disorders, paresthesia, abdominal pain and others [11].

Most studies concerning environmental contamination caused by railway traffic indicated the permitted amounts of heavy metals in the soil, without paying special attention to metals that did not exceed the permitted values, but were recorded in the soil. Since the method of heavy metal migration through the soil has not been completely clarified, it is hard to identify the actual released quantities, i.e., what amounts entered the soil and were transported further, perhaps into ground water.

Based on the own research [12], the most important conclusions regarding the concentration of lead within the railway body were highlighted and a comparison was made with the results of other researchers, when it comes to this metal.

In addition, another goal of the present study was to list all registered metals for which the relevant legislation have established a regulated permissible values.

2. SOIL SAMPLING AND EXAMINATION TECHNIQUES

Soil sampling, for the purpose of examining the presence of heavy metals in the railway body, was carried out on two cross-sections (cross-section 1 and cross-section 2) in the embankment on the Belotinac–Medjurovo section of the Serbian railway line Niš–Preševo–border with the Republic of North Macedonia, from km 253+072.00 to km 253+283.00, which was in the reconstruction stage and which enabled the implementation of these tests.

Initially, sampling was carried out in top subgrade layer on characteristic positions: in the track axis (samples: 1’ for cross-section 1; 1’’ for cross-section 2) and at the positions on the feet of the ballast (samples: 3’ and 4’ for cross-section 1; 3’’ and 4’’ for cross-section 2). In addition, soil was sampled in the drainage channels on the both sides of the embankment (samples: 7’ and 8’ for cross-section 1; 7’’ and 8’’ for cross-section 2).

In order to determine the degree of infiltration of heavy metals into the soil, at a depth of 1.3 m, the soil was sampled at the projection of the sampling point on the substructure itself (axis (samples: 2' for cross-section 1; 2'' for cross-section 2) and feet of the ballast (samples: 5' and 6' for cross-section 1; 5'' and 6'' for cross-section 2)),

Soil samples were examined using X-ray fluorescence (XRF) spectrometry and optical emission spectrometry with induced coupled plasma (ICP-OES). The concentration of heavy metals in the samples in its original form was recorded using the XRF method. Using the ICP-OES technique, the samples were treated with water and hydrochloric acid for testing, and there were certain protocols involved in sample preparation.

The results of both methods were analyzed according to the maximum limited values of polluting, harmful and hazardous substances in soil prescribed by the Regulation of the Republic of Serbia (RS Regulation) [13] and according to the maximum values recommended by the EU Directive in the countries of the European Union [14]. The values prescribed by the EU Directive represent a recommendation for the range of permissible values of cadmium, chromium, copper, nickel, lead, zinc and mercury. EU Directive is not literally obligatory, since each of the EU member states can make corrections, most often in accordance with the pH value of the observed soil of a country or a specific area. Concentrations of metals not covered by the EU Directive were considered according to the RS Regulation. Maximum allowable concentrations (MAC) of polluting, harmful and dangerous metals in soil according to the RS Regulation and the recommended maximum values of individual heavy metals according to the EU Directive are presented in Table 1.

Table 1. Maximum allowable concentration of heavy metals in soil

Metal (symbol)	MAC* (ppm)	EU Directive** (ppm)
Cadmium (Cd)	0.8	1.0–3.0
Chromium (Cr)	100	100
Copper (Cu)	36	50–140
Nickel (Ni)	35	30–75
Lead (Pb)	85	50–300
Zinc (Zn)	140	150–300
Mercury (Hg)	0.3	1.0–1.5
Arsenic (As)	29	-
Barium (Ba)	160	-
Cobalt (Co)	9.0	-
Molybdenum (Mo)	3.0	-
Antimony (Sb)	3.0	-
Beryllium (Be)	1.1	-
Selenium (Se)	0.7	-
Thorium (Th)	1.0	-
Vanadium (V)	42	-

* Concentrations allowed by the Regulation on the maximum concentrations of polluting, harmful and hazardous substances in soil in the Republic of Serbia [13]

**European Union Directive 86/278/EEC [14]

3. CONCENTRATIONS OF LEAD OBTAINED BY XRF AND ICP-OES TECHNIQUES

The registered amounts of lead (Pb), obtained by the XRF technique, exceeded the permitted value prescribed by the EU Directive in several samples. The highest exceeded values were recorded at the foot of the ballast (samples 3' and 4") and at the point of drainage channel within the cross-section 1 (sample 7'). According to the RS Regulation (MAC), the measured amounts of Pb in ppm units (ppm ±5%) were within the permitted value (Figure 1).

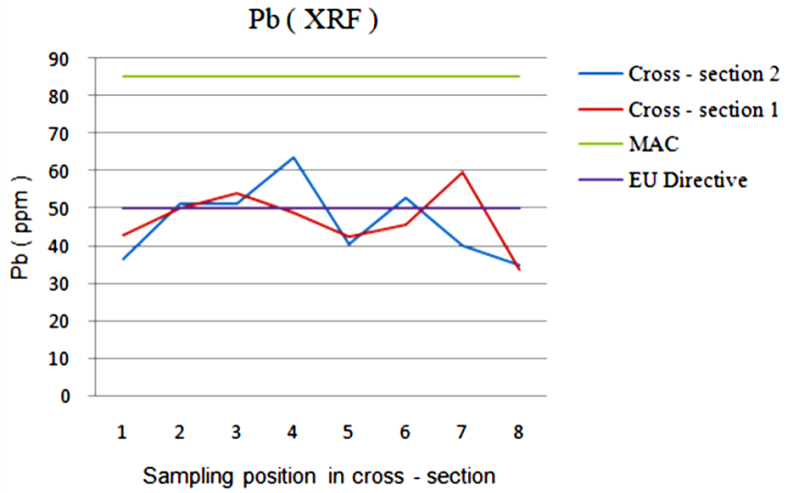


Figure 1. XRF-registered concentration of lead (Pb) on the cross-section 1 and cross-section 2 in comparison with the maximum allowable concentration (MAC) according to the RS Regulation and the maximum value recommended by the EU Directive

Using the ICP-OES technique for determining Pb concentration in ppm units (ppm ± 5%), on the other hand, no exceedance of the allowable value was found according to both the EU Directive and the MAC (Table 2). It was observed that the highest concentration of Pb in this case was in the samples from feet of the ballast (samples 4' and 4'').

Table 2. ICP-OES-registered concentration of lead (Pb) on the cross-section 1 and cross-section 2 in comparison with the maximum allowable concentration (MAC) according to the RS Regulation and the maximum value recommended by the EU Directive

Pb			Pb		
MAC (ppm)		85	MAC (ppm)		85
EU Directive (ppm)		50	EU Directive (ppm)		50
Cross-section 1	1'	10.1	Cross-section 2	1''	15.0
	2'	20.2		2''	21.1
	3'	21.9		3''	12.1
	4'	28.9		4''	33.0
	5'	13.1		5''	19.6
	6'	23.9		6''	20.7
	7'	19.8		7''	20.5
	8'	11.7		8''	13.5

A review of the available literature including soil testing on the railway track and surrounding environment, as well as other track elements, has established that, in addition to cadmium, lead stood out as one of the most examined metals.

A number of studies have confirmed that Pb concentrations increase with distance from the track, indicating lead origin from exhaust gases [5–10].

Significant number of researchers also confirmed that the concentration of Pb did not decrease at a distance of 50 m from the track. This characteristic distinguishes lead from other heavy metals, due to the manner in which it is emitted into the environment. The region of lead dispersion into the environment is slightly narrower near the cut, suggesting that lead emission through the air is the most likely mode of migration [9].

According to the results of the present research, while screening with the XRF technique, the allowable levels for lead were exceeded, but when analyzing with the ICP-OES technique, the lead values were below the recommended ranges. Lower values of Pb obtained with the ICP-OES spectrometer can be explained by the fact that the soil sample was diluted with a moderate solution (deionized water - HCl) rather than concentrated hydrochloric acid. The solution prepared only with hydrochloric acid would result in a larger concentration of Pb.

Studies that included a wider area next to the railway track led to conclusion that the registered amounts of lead could be exceeded multiple times with the distance from the railway body. In this regard, it is very important that even when the measured quantities do not reach the permissible values, it is necessary to consider the known facts related to the behavior of the metal itself and the ways of emission of the observed metal into the environment.

4. CONCETRATIONS OF OTHER METALS OBTAINED BY XRF AND ICP-OES TECHNIQUES

Another part of this work was a special analysis of metals that are covered by the relevant legislation regarding the permitted concentration in the soil, but according to these criteria they did not exceed the permitted values.

As part of the own research [15], concerning the examination of the presence of heavy metals in the railway body, the results regarding heavy metals that exceeded the permissible values according to the MAC and the EU Directive were already highlighted. There was no discussion concerning metals, for which limited content in soil is defined, but they did not exceed these limits.

According to Table 3 and examination carried out by the XRF technique, such metals were arsenic (As), selenium (Se), molybdenum (Mo) and mercury (Hg). In the case of determining the presence of heavy metals in the soil using the ICP-OES technique, these metals were again arsenic (As), as well as chromium (Cr), vanadium (V) and barium (Ba) (Table 4).The reason that the values obtained by the XRF technique are higher than those obtained by the ICP-OES method is identical to the determination of Pb levels and is related to the solution.

Comparing the measured values at the surface and at depths of 1.3 m, significant metal infiltration was demonstrated into the railway body regardless of the measurement technique used. The concentration of several metals was found to be higher at a depth of 1.3 meters (samples: 2', 5' and 6' for cross-section 1; 2'', 5'' and 6'' for cross-section 2) in comparison with the values recorded in the surface layers (samples: 1', 3', 4', 7' and 8' for cross-section 1; 1'', 3'', 4'', 7'' and 8'' for cross-section 2). In the case of the XRF technique, this behavior was observed for As (the samples 2', 6' and 2'' compared to the samples 1', 4' and 1'',

respectively) and Se (the sample 2'' compared to the sample 1''). According to the ICP-OES technique results, this phenomenon was identified in the cases of As (the samples 2', 6' and 2'' compared to the samples 1', 4' and 1'', respectively), Cr (the sample 5'' compared to the sample 3''), V (the samples 2', 6', 2'' and 5'' compared to the samples 1', 4', 1'' and 3'', respectively) and Ba (the sample 6' compared to the sample 4').

Table 3. Metal quantities determined by XRF in ppm units (ppm ± 5%)

Metal		As	Se	Mo	Hg
MAC (ppm)		29	0,7	3	0,3
EU Directive (ppm)		-	-	-	1
Cross-section 1	1'	16.0	0.3	0.8	0.1
	2'	17.3	0.3	0.8	0.1
	3'	18.2	0.3	0.9	0.1
	4'	16.9	0.2	0.7	0.1
	5'	15.6	0.3	0.9	0.1
	6'	18.5	0.1	0.4	0.1
	7'	20.2	0.3	0.9	0.1
	8'	13.1	0.1	0.9	0.1
Cross-section 2	1''	14.2	0.2	0.8	0.1
	2''	17.6	0.3	0.8	0.1
	3''	19.0	0.3	0.9	0.1
	4''	21.9	0.2	0.8	0.1
	5''	14.2	0.3	0.8	0.1
	6''	17.8	0.2	0.8	0.1
	7''	13.6	0.2	0.7	0.1
	8''	13.5	0.1	0.7	0.1

Table 4. Metal quantities determined by ICP-OES in ppm units (ppm ± 5%)

Metal		As	Cr	V	Ba
MAC (ppm)		29	100	42	160
EU Directive (ppm)		-	100	-	-
Cross-section 1	1'	5.2	30.2	32.3	94.1
	2'	5.5	28.5	33.1	82.4
	3'	6.6	29.2	29.8	88.8
	4'	6.7	25.5	27.2	66.1
	5'	4.8	24.7	28.3	78.9
	6'	7.2	24.0	30.2	82.5
	7'	7.1	29.1	32.0	91.5
	8'	4.5	25.6	25.7	75.2
Cross-section 2	1''	5.3	33.0	36.7	106.6
	2''	5.6	32.9	37.8	65.3
	3''	6.7	29.8	31.0	85.4
	4''	6.9	30.4	34.3	96.7
	5''	4.7	30.7	34.7	101.3
	6''	5.7	29.1	33.7	95.9
	7''	6.7	30.1	33.3	89.2
	8''	5.5	32.4	33.7	96.8

5. CONCLUSION

According to the results of the previous own research on the concentration of heavy metals in the railway body, an analysis of the presence and concentration of lead was performed in the present study, as well as an analysis of the amount of metals that did not exceed the permitted values prescribed by the corresponding current regulations.

The concentration of lead obtained by the XRF technique exceeded the permitted value prescribed by the EU Directive at the sample points within the feet of the ballast and the drainage channels. According to the RS Regulation, the measured amount of lead was within the permitted value. In the case of results obtained by the ICP-OES technique, there were no exceedances of the permitted values for lead with regard to both regulations. It is feasible to anticipate much higher levels of the tested metals, which would beyond the allowed limits, if the solution was prepared only with HCl. In this case, the maximum concentration of lead was registered in the samples from the feet of the ballast.

The values determined in this study as acceptable and not exceeding the permitted values should be interpreted with care, as numerous authors who have examined the concentration of lead in the area around the railway have demonstrated that the concentration of lead increases with distance from the railway track.

Additionally, while developing environmental protection measures against the adverse effects of railway traffic, significant consideration must be given to metals for which there is a legally controlled permissible limit, although it has not been exceeded. The extent of infiltration of these metals into the soil clearly demonstrated their intense migration into the subsurface, and further, into the surrounding area.

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Research paper

THE TRANSFORMATIVE ROLE OF MOBILITY FOR SUBURBAN CENTRE – CASE STUDY OF SREMSKA KAMENICA, SERBIA

Marina Carević Tomić[1], Ranka Medenica Todorović[2]

Abstract

The paper explores the transformative role of mobility in suburban center of Sremska Kamenica, within the urban area of Novi Sad, Serbia, where a transit road passes through the heart of the settlement center. Throughout history central functions of the settlement were developed along the main road and thanks to its busyness. However, population growth together with the rise of the motorization rate and the share of motor traffic in modal split caused the traffic congestions and threatened the pedestrian and social activities recently. The imminent construction of a new bridge, as part of a ring road around Novi Sad, stands as a pivotal intervention that promises to divert traffic flows away from the overloaded center, ushering in a new era of pedestrian-friendly public spaces. Finalization of this bridge would divert traffic flows – presumably, the traditional center, now overloaded with transit traffic, would be less busy, and at the same time, as shown in Space Syntax analysis, accessibility at the local level wouldn't fall. The key objective is to understand the development of the centrality in Sremska Kamenica through time and to predict how changes in mobility patterns will affect further public space usage and livability. The research approach is based on the combination of Space Syntax tool, site surveys, contextual analysis and planning documents reading. The paper shows how the traffic diversion facilitated by the new bridge gives the opportunity for urban planners to reimagine public spaces, prioritizing vibrant, walkable spaces that promote social interaction and improve overall urban experience.

Key words: *Suburban center, mobility patterns, Space Syntax*

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1. INTRODUCTION

Various authors [1, 2, 3, 4] define the urban center in different ways, lacking a unified analytical framework. Nevertheless, the center of a settlement is generally taken for granted, typically referring to a focal point characterized by a concentration and mix of land uses and activities in a prominent location. Since the precise delineation of urban centers exceeds the scope of this work, the aim here is to understand the development of centrality in Sremska Kamenica through Bill Hillier's concept of centrality as a spatio-functional process, rather than to describe it as a static condition [5].

Suburban centers are specific per se, for their dependance on the main city center on one side and the expectation to be sustainable economically and environmentally and to provide local economic activities in order to minimize travel and to support cohesive and vibrant communities [6]. Vibrancy[3] is one of the key qualities of cities, most prominently expressed in their central areas. However, the specific scope and dynamics of central urban functions are shaped by the broader settlement network and the local socio-economic context.

In the case of Sremska Kamenica (Figure 1a), earlier studies [9] have shown that both historical and contemporary factors have played a decisive role in the distribution of land uses. The old core of the settlement (Figure 1b) functions as the traditional center of identity and urban life, accommodating trade, administration, culture, education, hospitality, and more. The role of this center has evolved and strengthened over time, adapting to changing conditions. Another important aspect is accessibility, as areas with higher accessibility tend to support a greater mix of uses. For a long time, the socio-economic situation in Sremska Kamenica has remained stable, as have the patterns of primary uses, building types, and residential densities, with no indication of imminent change. However, mobility patterns are expected to shift due to the construction of two new bridges, and the aim of this paper is to explore how such changes in mobility may affect public space usage and overall livability.



Figure 1. (a) Sremska Kamenica within the urban area of Novi Sad. Red line indicates the location of the planned fourth bridge, while yellow line marks the position of the fifth bridge. (b) Central area of Sremska Kamenica, according to the detailed regulation plan [10] (author: M. Carević Tomić, source of a map: Google Earth).

[3] Jane Jacobs explains urban vibrancy as an active street life comprised of the presence of pedestrians at all hours of the day, that way encouraging activities and interactions [7], while for Jan Gehl [8] urban vibrancy does not only refers to the number of people and inhabitants, but to the feeling that the place is inhabited and being used.

2. METHODOLOGY

Previous research on central areas has highlighted the diversity of issues and the complexity of relationships among various urban phenomena across different types of settlements. In the center of Sremska Kamenica, the current arrangement of land uses and activities is likewise shaped by multiple factors, with accessibility standing out as one of the most significant [9]. Accordingly, this research combines Space Syntax analysis, site surveys, contextual analysis, and reviews of planning documents to explore the complex interplay between mobility flows and spatial organization in the urban center.

As both a theory and method, Space Syntax offers a rational and qualitative approach to investigating urban spatial networks. It has been widely applied in urban studies over the past several decades [11]. In this study, it is used to gain insight into spatial configuration and future mobility patterns, particularly accessibility, under the assumption that it can simulate changes to the urban network resulting from the construction of two new bridges. The analyses cover the entire urban area of Novi Sad, comparing the current state with a projected state that includes the new bridges. Both axial and segment analyses were employed. Axial analysis was used to measure changes in the importance of the main street within the system and the movement flows along it (via the choice measure), while segment analysis assessed how the construction of the new bridges could influence centrality processes in Sremska Kamenica. Global analysis was used to simulate vehicular traffic, while a 400-meter radius was applied for examining pedestrian accessibility.

3. HISTORICAL AND SPATIAL DEVELOPMENT OF SREMSKA KAMENICA CENTRE

Sremska Kamenica developed on the northern slopes of the Fruška Gora mountain, extending to the right bank of the Danube. In its oldest parts (Figure 2)—formed on a lower plateau and later along Karađorđeva Street—the indigenous urban matrix and traditional plot organization have been largely preserved. These areas differ from the newer parts in their morphological characteristics, the positioning of houses along the regulation line, and the prevalence of narrow, winding streets, which are typical of settlements on Fruška Gora. The area is also characterized by low housing density, with around 40 inhabitants per hectare [9], a figure not expected to change significantly in the future.



Figure 2. Historical photos of Sremska Kamenica, area of Kralja Petra I Square (unknown author) [12]

The functional structure of the original center (today Kralja Petra I Square and its surroundings (Figure 2)) in the past consisted of public uses—such as a church, old school, local community office, library, post office, and café—some of which remain today. The expansion and displacement of the center from an oldest historical core took place gradually towards the upper plateau and Trg Zmaj Jove, along the main route that connected Sremska Kamenica with Petrovaradin and Novi Sad. After World War II, the settlement became part of the Novi Sad and Petrovaradin municipality, leading to increased dependence on Novi Sad. The spatial connection was further strengthened by the construction of the Most Slobode bridge over the Danube in 1981, which encouraged further development.

In the decades following World War II, urban planning envisioned the development of a conurbation consisting of Novi Sad on one side of the Danube and Petrovaradin and Sremska Kamenica on the other. One of the main goals was to concentrate public facilities, residential areas, and workplaces on the right bank, creating a new development pole. However, this vision was never fully realized due to specific social, political, and economic circumstances, especially after the 1990s. Nevertheless, certain unique functions—such as the institutes for oncology, pulmonary and cardiovascular diseases, the Basic Police Training Centre, and SOS Children's Village—make Sremska Kamenica a distinct sub-center within the Novi Sad area [13]. Apart from these unique functions, most non-residential uses serving the essential needs of the population are concentrated in the traditional center, encompassing central services, education, childcare, health, culture, and religion. The range of activities in the center of Sremska Kamenica is broader than in other parts of the settlement but remains limited, as the rest of the area is predominantly residential. Previous research in the central area[4] recorded 86% housing, 7% primary non-residential, and 7% secondary non-residential uses[5]. A significant increase in non-residential uses occurred in the 2000s, during the post-transition period, when the population of Sremska Kamenica grew[6] notably due to suburban sprawl.

On the other hand, according to the Study of Housing [17] from 1995 to 2009 the share of commercial space in the total built area decreased—presumably a result of large-scale residential construction in peripheral zones. This period also coincided with the stabilization of the country's economic and political situation following the turbulent 1990s, likely contributing to a more favorable environment for business and service development. The growth of entrepreneurship during this time also led to an increase in retail outlets, with portions of houses facing the street being converted into business premises in the center and adjacent streets. Despite these developments, daily commutes to the center of Novi Sad remain intensive.

The strengthening of the historical center eventually led to a saturation point, as Trg Zmaj Jove—given existing structures and preservation guidelines—reached its capacity for accommodating new, large-scale programs. This led to the elongation of the traditional

[4] The area of a Detailed Regulation Plan of the Center of Sremska Kamenica [10].
[5] The methodology used for land-use analysis was Mixed-use Index, defined by van den Hoek [14] and here used redefined version where uses are classified on residential, primary non-residential and secondary (non-residential) uses [9], based upon Jane Jacobs's theory. Primary uses are those that bring people to a specific place because they are anchorages (housing, offices, schools etc.). The purpose of the secondary uses is to serve the people drawn by the primary uses – those are the enterprises that grow in response to the presence of primary uses [7].
[6] In 2002 number of inhabitants was 11205, which is for 40% more than in 1991 [15]. According to current data, 12632 inhabitants live in Sremska Kamenica, which is five times more than in 1948, when the first population census was conducted [16].

center, a process accelerated by the construction of new faculties and multifamily housing, which in turn spurred the development of secondary programs in one of the entrance zones to Sremska Kamenica [18] and new linear center has begun to emerge along the busiest streets, especially Vojvode Putnika Street. Notably, most of the premises along this stretch are retail or services dependent on what Hillier and colleagues refer to as "passing trade" [19], in this case primarily car-based, long-distance traffic (e.g., car washes, plant and tool stores). This route continues through the traditional center and connects suburban settlements along the Danube's right bank with Novi Sad.

Recently, the trend of concentrating non-residential uses along this main road has extended toward suburban settlements upstream from Sremska Kamenica, near the projected landing point of the new bridge on the Danube's right bank. The future completion of the fourth bridge may divert traffic away from the current central route, making the future ring road and surrounding areas more accessible, busier, and therefore more attractive for non-residential development [20].

According to the current detailed regulation plan [10], the development concept envisions preserving the ambient character of the center while simultaneously allowing for the integration of missing functions. The goal is to concentrate central activities around Zmaj Jove Square and establish a connection with the terrain along the Danube, thereby creating conditions for direct access to the river. Unfortunately, these objectives have not been realized, and the main square is currently experiencing the degradation of its built heritage due to inappropriate architectural interventions (Figure 3).



Figure 3. Sremska Kamenica today; (a) Kralja Petra I Square, (b, c) Zmaj Jove Square (author: M. Carević Tomić)

4. MOBILITY ANALYSIS

The busiest road passing through the central zone of Sremska Kamenica follows the line of Vojvode Putnika Street, Zmaj Jove Square, and Karađorđeva Street (Figure 1b and Figure 4). This corridor connects Novi Sad not only with Sremska Kamenica itself but also with other settlements upstream on the right bank of the Danube—such as Ledinci, Rakovac, and Beočin—whose residents commute daily to the city. This stretch, along with Železnička Street, is also the most locally accessible area, making it unsurprising that the two main squares were formed here and that the majority of non-residential facilities are located along this route.

However, the high volume of people also brings intense motor traffic, which acts as a limiting factor for developing vibrant public life in the center. The existing urban fabric, shaped in earlier periods, is no longer capable of accommodating current traffic demands[7]. In addition, the heavy traffic contributes to increased levels of noise and air pollution, making

[7] According to the Smart Plan [21] motorization rate and the share of car usage in Novi Sad is in constant raise.

the experience of staying in public spaces less pleasant—even though many key public facilities are located in this area. As a result, the squares generally do not function as gathering places, but are instead used primarily for transient activities, such as shopping, waiting for the bus, or other brief, utilitarian purposes.

5. THE NEW BRIDGE: A GAME-CHANGER

Currently, two parts of the urban area of Novi Sad are connected by three bridges, but for many decades urban plans envision a total of five. Recently, construction of the fourth and fifth bridges has begun. The fourth bridge—most relevant to this paper—is intended to connect the western parts of Novi Sad with the settlement of Sremska Kamenica. It will also form part of a key route linking the city to its broader surroundings via the E75 highway and other national roads. It is expected that the construction of these new bridges will significantly alter the functioning of the city. To assess the potential impact on the center of Sremska Kamenica, Space Syntax analysis was employed. The analyses were conducted for the entire urban area of Novi Sad (Figure 4a, 5a), with a zoomed-in view of the Sremska Kamenica center provided for clarity (Figure 4b, 5b). Due to space limitations, only the axial analyses are presented graphically, while key numerical results are summarized in tables.

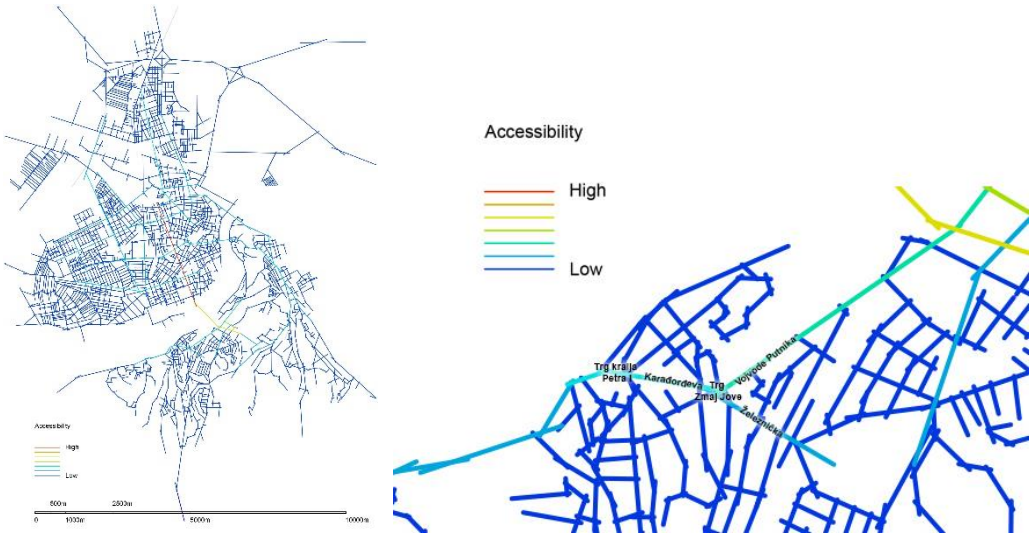


Figure 4. Axial map of Novi Sad – choice analysis (global radius). (a) Full city view; (b) central area of Sremska Kamenica (author: M. Carević Tomić)

Visual inspection and comparison of Figures 4 and 5 suggest that the new connections within the urban matrix positively affect the global choice pattern in the center of Sremska Kamenica. The numerical data (Table 1) support the visual interpretation: the construction of the new bridges is expected to significantly reduce the traffic load on the main transit corridor, particularly on Vojvode Putnika Street. This implies that the route will become less likely to serve as the preferred path for through-movement (i.e., transit traffic) between different street segments in the urban area.

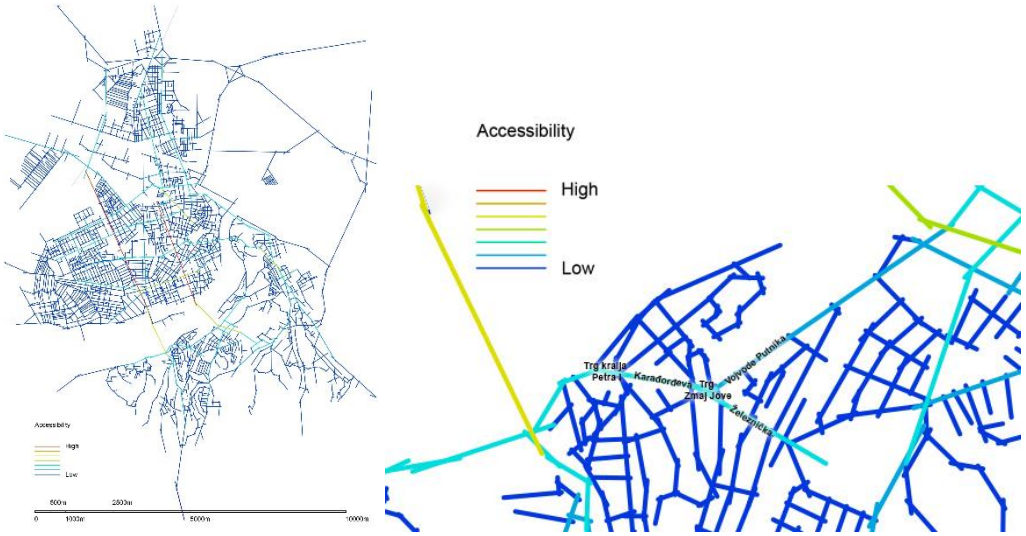


Figure 5. Axial map of Novi Sad after construction of two new bridges – choice analysis (global radius). (a) Full city view; (b) central area of Sremska Kamenica (author: M. Carević Tomić)

Table 1. Axial analyses for Vojvode Putnika Street

	Axial Choice (global radius)
Current accessibility	0,354561
Future accessibility	0,089264

On the other hand, a comparison of integration values indicates that locally (within a 400m radius), the center will maintain its significance. Moreover, at the level of the entire urban area (global radius), it is expected to become even more accessible. This suggests that the central area will remain attractive and retain the high potential to be the destination for movement.

Table 2. Segment analyses for the center (20 segments)

	Integration (global radius)	Integration (r=400m)
Current accessibility	807,734	0,575404
Future accessibility	948,862	0,575404

6. DISCUSSION AND CONCLUSION

The case of Sremska Kamenica highlights the multifaceted and transformative role of mobility in shaping suburban centers. Historically formed along a key transit route, the central area has developed a layered identity as both a functional core and a passageway. However, this dual role has increasingly led to tensions between vehicular mobility and the spatial and social qualities essential for vibrant urban life. The dominance of motorized through-traffic, particularly along Vojvode Putnika Street and Zmaj Jove Square, has compromised the potential of public spaces to serve as places of gathering, interaction, and everyday sociality.

As the Space Syntax analyses reveal, the finalization of the fourth bridge—a critical component of the Novi Sad ring road—will significantly alter existing mobility patterns.

Specifically, the analyses show a notable decrease in global choice values for Vojvode Putnika Street, which confirms the expected redirection of through-traffic away from the traditional center. This shift alleviates the current pressure on the central streets, thereby reducing noise, air pollution, and motor traffic dominance.

Importantly, the research also shows that while the transit function of the central area will diminish, its spatial integration, as one of the indicators of centrality, will remain stable or even improve. This indicates that the traditional center of Sremska Kamenica will maintain its accessibility and potential as a destination, not just as a route. This finding carries important implications for urban planning and design. Reduced transit pressure opens opportunities for reclaiming central public spaces for pedestrian use, social functions, and green infrastructure. In turn, this can elevate the quality of life, improve environmental conditions, and strengthen the spatial identity of the center. Furthermore, the potential redistribution of non-residential functions—especially those relying on high accessibility and visibility—towards the new infrastructure corridor suggests a spatial reorganization that could relieve current land use saturation in the historical center. Yet, the outcomes of such infrastructural shifts are not automatic. Planning responses will be crucial to steer the transformation toward inclusive and sustainable goals. Without proactive urban design and policy support, the freed-up space could risk underutilization or ad-hoc commercialization. On the other hand, a coordinated approach—integrating traffic calming, pedestrian prioritization, and heritage-sensitive design—could revitalize the central area and reinforce its role as a livable, multifunctional hub. Strategies such as a "road diet"—reducing the number or width of traffic lanes—could help repurpose space for pedestrians, greenery, and non-motorized mobility, fostering a more human-centered environment.

The study also identifies a spatial phenomenon of center elongation along the main roads, primarily in the direction of Novi Sad. This linear extension of central functions, increasingly occupied by "passing trade" land uses, reflects the strong functional dependence of suburban settlements on the central city. As this process is shaped by mobility flows, it raises important questions about the long-term viability of these uses in a post-diversion scenario. With a decline in passing traffic, some of these premises may lose their commercial relevance and be replaced by more locally oriented or residential uses. Future research could explore whether this spatial and functional dynamic is a common characteristic of suburban centers and how it might inform broader planning strategies.

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Research paper

DIMENSIONING OF STRUTS FOR REINFORCED CONCRETE DIAPHRAGM WALLS TO SECURE EXCAVATION OF ADJACENT STRUCTURES

Radovan Perić[1], Dragana Turnić[2], Marija Spasojević Šurdilović[3], Srđan Živković[4]

Abstract:

Modern architectural solutions in densely populated areas require structures with multiple underground levels. With advancements in construction technology, numerous solutions have been developed to secure the excavation of foundation pits and adjacent structures. The most rational solution adopted is the securing of the excavation and adjacent structures with reinforced concrete diaphragm walls supported by steel struts at two levels. The paper outlines the specifics of the structural solution, with a detailed analysis of the steel struts. Special emphasis is placed on the stability control of the struts, which was conducted using various methods outlined in Eurocode 3. The control of flexural buckling was performed through the application of the equivalent column method, the use of equivalent geometric imperfections, and the implementation of both geometrically and materially nonlinear analysis with imperfections.

Key words: *Stability, Flexural Buckling, Eccentric Compression, Equivalent Column Method, Reinforced Concrete Diaphragm Walls*

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1. INTRODUCTION

In contemporary urban environments, modern architectural solutions increasingly demand the construction of buildings with multiple underground levels, especially in densely populated areas. These conditions present significant challenges in both structural stability and excavation safety. At the same time, the advancement of construction technologies has enabled the implementation of efficient and reliable methods for deep excavation and soil retention. Among these, the use of reinforced concrete diaphragm walls, installed along the excavation perimeter and supported by steel struts at multiple levels, has emerged as one of the most rational and widely adopted solutions for safeguarding both the construction site and neighboring structures.

Diaphragm walls with strut supports represent a structural-retention system that combines load-bearing walls with additional elements, typically steel struts, designed to improve load distribution and increase resistance to lateral earth pressures. These systems are commonly employed in both residential and commercial developments, as well as in specialized civil engineering projects where high safety standards and long-term performance are essential.

This paper will examine the fundamental characteristics of reinforced concrete diaphragm walls with strut supports, the principles of strutanalysis and design, as well as the theoretical background related to structural instability. Additionally, a practical case study will be presented alongside a numerical model of the strut system, which will serve as the basis for a parametric analysis.

2. THEORETICAL BACKGROUND AND PREVIOUS RESEARCH

The problem of flexural buckling of an axially compressed member within the elastic range was first addressed by Leonhard Euler in 1744. The fundamental assumptions underlying Euler's theory of linear elastic buckling are as follows:

- the material is homogeneous, isotropic, and behaves in a linearly elastic manner;
- the member is perfectly straight, with no geometric imperfections;
- both ends of the member are pinned (hinged) supports;
- the member is subjected to concentrically axial forces at its ends;
- the cross-section is constant and monolithic along the member's length;
- torsional deformations are fully restrained.

In addition to the previously stated assumptions, it is also considered that the curve describing the relationship between axial force and lateral deflection is bilinear. As long as the applied axial force remains below the critical value ($N_{ed} < N_{cr}$), no deflection occurs. Upon reaching the critical force, buckling initiates and deformations tend toward infinity, which characterizes the phenomenon of bifurcation instability.

The differential equation of the elastic curve is a homogeneous differential equation with constant coefficients, expressed as:

$$v'' + k^2 v = 0 \tag{1}$$

Solving this equation yields the expression for the minimum value of the critical force:

$$F = \frac{\pi^2}{L_i^2} EI = N_{cr} \tag{2}$$

where:

- *v* is the lateral deflection of the member,
- *k* is a constant related to the buckling mode,
- *EI* is the flexural rigidity of the member,
- *F* is the axial force applied at the ends of the member,
- L_i is the effective buckling length of the member.

The given expression defines the buckling behavior of a column within the elastic domain, valid as long as the critical buckling stress does not exceed the proportional limit of the material from which the column is made. The corresponding slenderness ratio at the proportional limit, denoted as λ_p serves as a clear boundary between the elastic and plastic domains. This limit is defined by the following expression:

$$\lambda_p = \pi \sqrt{\frac{E}{235}} \varepsilon \tag{3}$$

The expression provided by equation (2) can be applied to columns with slenderness ratios greater than λ_p. In such cases, the problem is purely geometrically nonlinear, while the material remains within the elastic range.

Since real structural elements in civil engineering are often characterized by relatively low slenderness, it becomes necessary to introduce material nonlinearity into the analysis. Numerous researchers, including Tetmajer, von Kármán, Engesser, Shanley, and others, have sought to develop more accurate σ–λ relationships in the plastic domain by accounting for the variability of compressive force during the process of stability loss.

Starting from the differential equation derived from equilibrium conditions for an axially loaded column with initial geometric imperfections:

$$v'' + k^2 v = -k^2 \delta_0 \sin\left(\pi \frac{x}{L}\right) \tag{4}$$

and assuming boundary conditions corresponding to a column pinned at both ends (first buckling mode), the critical force is obtained using Equation (2). The total mid-span deflection of the column is given by:

$$\delta_{tot} = \delta_0 \frac{1}{1 - \frac{N}{N_{cr}}} \tag{5}$$

Assuming that the column remains in the elastic domain, the following condition must be satisfied:

$$\frac{N_u}{A} + \frac{N_u \cdot \delta_{tot}}{W} \leq f_y \tag{6}$$

Introducing the dimensionless parameters defined as:

$$\eta = \frac{\delta_0 \cdot A}{W}, \ \chi = \frac{N_u}{N_{pl}}, \bar{\lambda} = \sqrt{\frac{N_{pl}}{N_c}} \tag{7}$$

leads to the Ayrton–Perry function, which forms the basis of modern design standards:

$$\chi^2\bar{\lambda}^2 - \chi(1+\eta+\bar{\lambda}^2) + 1 = 0 \quad (8)$$

Solving this quadratic equation under the condition of real solutions yields the general expression for the nondimensional buckling reduction factor χ:

$$\chi = \frac{1}{\Phi+\sqrt{\Phi^2-\bar{\lambda}^2}} \quad (9)$$

where:

- δ_0– initial geometric imperfection,
- δ_{tot} – total mid-span deflection,
- N_u– ultimate buckling force,
- A – cross-sectional area,
- f_y – yield strength of the material,
- W – elastic section modulus,
- χ – nondimensional buckling reduction factor,
- $\bar{\lambda}$– relative (nondimensional) slenderness for the considered buckling axis,
- η – auxiliary coefficient,
- Φ – auxiliary coefficient dependent on the imperfection factor α for European buckling curves.

In addition to the method based on European buckling curves i.e., the equivalent column method, Eurocode also allows for stability verification using the initial geometric imperfection method. For elastic global analysis, the equivalent geometric imperfection for a specific case is taken as L / 200, and the failure criterion is defined by stresses calculated according to second-order theory. In addition to flexural buckling, eccentric compression must also be checked, as noted in [1], while local buckling effects are not explicitly considered. Structural safety with respect to local instability is ensured by selecting an appropriate cross-section class.

2.1. Influence of Imperfections

The critical axial force calculated using Equation (2) is approximately three times higher than the actual buckling load observed in practice. This discrepancy arises primarily due to material and geometric imperfections. Common material imperfections include residual stresses and variations in the mechanical properties of the material, such as yield strength and modulus of elasticity. Geometric imperfections typically include cross-sectional irregularities, initial curvature or deviation of the member axis from straightness, and load eccentricity.

To address these factors, a wide range of deterministic and stochastic methods for sensitivity and uncertainty analysis have been developed [2]. The deterministic approach relies on parametric analysis, where the influence of a single varying parameter on the result is examined. In contrast, stochastic methods provide a better understanding of the influence of variable parameters by offering insights into standard deviation, mean deviation, and other statistical measures.

Vrednost faktora amplifikacije zavisi od više faktora, ali ukazuje na to da krajnje odsupanje ose štapa može biti do četiri puta veće od početne geometrijske imperfekcije [3].

The value of the amplification factor depends on several parameters, but it indicates that the final deviation of the member axis can be up to four times greater than the initial geometric imperfection [3]. Initial geometric imperfections are influenced by various factors, among

which material quality, manufacturing process, and surface finishing techniques are among the most significant. The material from which the profiles are made plays a major role in determining the magnitude of these initial imperfections.

Testing of 24 specimens revealed deviations ranging from L/756 to L/23,605, with an average value of L/5,805, indicating that profiles made of high-strength steel (HSS) exhibit significantly smaller initial imperfections. When applying the buckling curves provided in [1], conservative results are obtained, with a deviation of approximately 33% [4], highlighting the conservative nature of the current design code when sizing members fabricated from high-strength steel (HSS). The manufacturing process has a significant influence not only on residual stresses, but also on geometric imperfections. The adverse effects of production-related imperfections can be minimized through the use of HSS, as confirmed by the experimental results presented in [5]. The influence of welding and surface finishing does not play a dominant role in the occurrence of either local or global buckling in steel grade S355, as indicated in [6]. Spirally welded steel pipes are increasingly used in the construction industry due to the possibility of producing pipes in greater lengths and achieving optimal diameter-to-wall-thickness ratios. Previous studies have primarily focused on their application in linear infrastructure projects, such as oil pipelines, excavation support systems in combination with Larsen sheet piles, and in cased piles [7].

The imperfections in these profiles largely depend on the welding method. Welding can induce significant residual stresses, and weld shrinkage can result in local geometric imperfections [8]. These initial local imperfections are considered the primary cause of stability loss in spirally welded pipes [9], [10], [11]. Longitudinal deformation can lead to cross-sectional ovalization, a phenomenon also known as the Brazier effect. Ovalization reduces the pipe's bending stiffness due to flattening, increases the local cross-sectional radius in regions of highest compression, and introduces biaxial stress states due to ring bending, ultimately leading to premature failure of the pipe.

As bending deformation increases, structural instability may arise in the compressed region of the pipe in the form of local buckling, commonly referred to as "local buckle," "wrinkle," or "kink." Pipes with D/t ratios below 70 exhibit a gradual development of local instability, and collapse is not as sudden as in pipes with higher D/t ratios.

The welding method used in the fabrication of spirally welded pipes significantly affects the distribution of residual stresses. Longitudinal residual stresses influence the load-bearing capacity, fatigue performance, brittle fracture resistance, and stress corrosion cracking, with these effects being particularly pronounced in moderately slender pipes [12], [13], [14]. Due to the high production cost of hot-rolled pipes, they are typically used in installations that require fluid-tightness. As a result of their manufacturing process, hot-rolled pipes exhibit a more favorable residual stress distribution and lower initial geometric imperfections. Comparative analyses between cold-formed and hot-rolled profiles indicate that cold-formed profiles deliver satisfactory performance, especially when their significantly lower production costs are considered [15].

The ultimate strength and ductility of a profile depend heavily on its buckling resistance. Local buckling of a single member can critically affect the overall behavior of the structural system [16]. In order to minimize the risk of catastrophic failure, numerous researchers have proposed modifications to the Eurocode buckling curves [17].

3. CASE STUDY OF A STRUT SYSTEM MODEL FROM PRACTICE

The planned commercial building (2Bas+Gr+8) is located in Belgrade, cadastral municipality of Dorćol, and is surrounded by neighboring structures with heights of Gr+9 and Bas+5. The proximity of the Danube River influences the groundwater level, which varies with river stages and ranges from 2.60 m to 5.50 m relative to the ground floor elevation. Based on geotechnical field and laboratory investigations, the soil profile has been identified as Danube alluvium, predominantly composed of highly permeable sandy soil.

As the optimal solution for securing the excavation of the foundation pit and protecting adjacent structures, reinforced concrete diaphragm walls with a thickness of 60 cm (locally increased to 80 cm) were adopted. The diaphragm wall thickness was determined by the location of the regulatory boundary line and the dimensions of the newly designed building. Due to a foundation depth of 14.20 m, the construction is planned to be executed in phases, with two levels of strut support. The struts are nominally pinned at both ends and are primarily subjected to axial compressive forces. An axonometric view of the strut layout is shown in Figure 1.

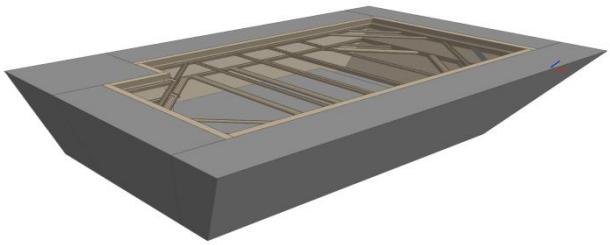


Figure 1. Axonometric view of the strut support system for the foundation pit

The struts span 16.50 meters and are subjected to high-intensity axial compressive forces, which lead to buckling. They are fabricated from spirally welded, cold-formed steel pipes with a diameter of 800 mm and a wall thickness of 16 mm. In the event of strut instability, a global loss of stability of the entire retaining system, as well as damage to adjacent structures, may occur. This highlights the need for a detailed limit state analysis. The stability of these elements is significantly influenced by the initial geometric imperfection [2].

According to national standards, the initial out-of-straightness must not exceed a limit value of L / 1000 [18], [19]. However, field inspections of completed structures have revealed initial curvatures that exceed these limits, which may result from excessive initial curvature, localized overloading, construction errors, or other unforeseen factors [3]. Due to geometric nonlinearity, the amplitude of initial curvature may amplify, ultimately leading to loss of stability. When the initial imperfection exceeds L / 1000, the load-bearing capacity can no longer be verified using current design codes. Moreover, the relationship between initial curvature and axial capacity is nonlinear and influenced by multiple factors, such as member slenderness and residual stresses, which must be carefully considered [4], [6].

4. NUMERICAL MODEL

To better evaluate the influence of geometric imperfections, this study includes a parametric analysis of the effects of initial geometric imperfections. The static system of the analyzed strut is modeled as a simply supported beam. The strut connections are idealized as pinned joints, incapable of transferring bending moments. The load transferred through

the reinforced concrete diaphragm is considered centrically applied, and diaphragm rotation during strut instability is neglected.

The values of initial imperfections are adopted based on experimental results from [3] and [20], as well as from construction tolerance limits defined in [18], ranging from L/2000 to L/75. The self-weight of the strut is included in the analysis due to its impact on initial imperfections. Initial geometric imperfections were modeled as half sine waves with varying amplitudes, as shown in Table 1. Material imperfections are not considered in this study.

Table 1. Initial Geometric Imperfections

n	3000	2000	1900	1800	1700	1600	1500	1400	1300	1200	1100
δ_0	10.10	12.85	13.29	13.77	14.31	14.92	15.60	16.39	17.29	18.35	19.60
n	1000	900	800	700	600	500	400	300	200	100	75
δ_0	21.10	22.94	25.23	28.17	32.10	37.60	45.85	59.60	87.10	169.6	224.6
The initial imperfection is represented as L/n δ_0- Initial imperfection with corresponding deflection impact [mm]											

The numerical analysis was carried out using the FEM software package Femap with NX Nastran v12.00, applying the finite element method [21]. The element size was determined through a convergence study, which showed that accurate results are achieved when the beam is divided into 18 finite elements. Modeling was performed using beam-type finite elements. The structural analysis was conducted using GMNIA (Geometrically and Materially Nonlinear Analysis with Imperfections).

Material nonlinearity was modeled with an elastic–perfectly plastic stress–strain relationship, without strain hardening, using a yield strength of 235 MPa. A geometrically nonlinear analysis was performed using 100 load increments, with displacement-based convergence via the Full Newton-Raphson method. The corresponding stress distribution is shown in Figure 2.

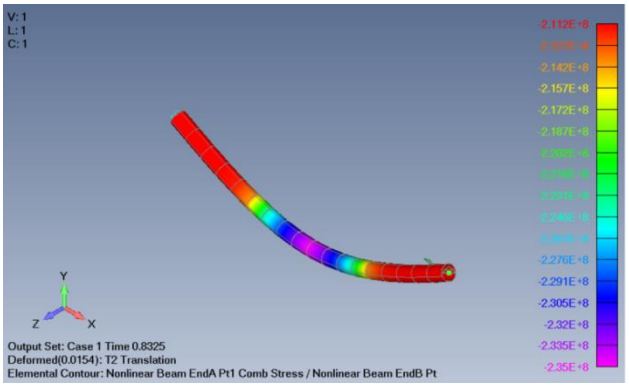


Figure 2. Representation of the element at critical load for L/1000 imperfection

5. RESULTS AND DISCUSSION

To investigate the influence of initial geometric imperfections on the critical force leading to global stability loss, a total of 22 numerical models were analyzed. The results are presented in Table 2.

Table 2. Critical buckling force

n	3000	2000	1900	1800	1700	1600	1500	1400	1300	1200	1100
N_{cr}	8769	8653	8631	8613	8591	8566	8538	8506	8469	8428	8381
n	1000	900	800	700	600	500	400	300	200	100	75
N_{cr}	8325	8256	8175	8075	7944	7775	7538	7184	6600	5394	4847
The initial imperfection is represented as L/n N_{cr} –critical force causing buckling [kN]											

To facilitate interpretation of the results and to observe the trend in the variation of the critical force as a function of the initial geometric imperfection, the results are presented graphically in Figure 3. The analysis reveals that the critical buckling force decreases sharply for initial geometric imperfections exceeding L/600.

The critical buckling force obtained using Equation (2) is 23060 kN, while the axial load-bearing capacity of the cross-section under concentric compression, as per [1], is 9260.91 kN. When comparing this value to the critical force corresponding to an initial geometric imperfection of L/3000, it can be observed that such a small imperfection has minimal influence on the overall load-bearing capacity.

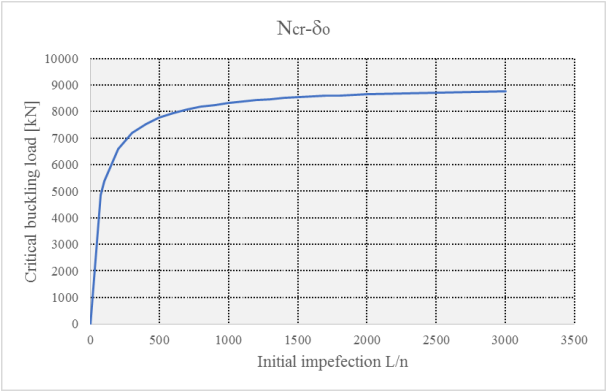


Figure 3. Relationship between critical force and initial geometric imperfection

The flexural buckling capacity, calculated using the equivalent column method in accordance with Eurocode, is 7084 kN, which closely corresponds to an initial imperfection of L/300. The bending moments induced in the member are of low intensity, and their contribution to global stability loss is minor. The results of the eccentric compression check also align with the imperfection value of L/300.

According to [2], the permissible deviation of a structural member from the ideal straight line is L/1000. Numerical analysis yielded a critical force of 8325 kN, at which a lateral deflection of 15.4 mm occurs. The corresponding stress distribution is shown in Figure 5.

The presented results indicate that Eurocode provides conservative estimates, with a deviation of approximately 17.5%, which is consistent with the findings reported in [3].

6. CONCLUSION

This study investigated the stability of excavation struts for the foundation pit of a newly designed structure, considering various initial geometric imperfections. The axial load capacity of the strut members was evaluated as a function of initial imperfection using both

analytical and numerical methods. A geometrically and materially nonlinear analysis with imperfections (GMNIA) was conducted using the finite element method. The theoretical background of the applied methods, types of structural instability, key equations, and strength criteria were presented.

A parametric analysis was used to assess the sensitivity of the critical buckling force to initial geometric imperfections. The GMNIA results yielded slightly higher critical forces compared to those calculated in accordance with Eurocode. The rational application of Eurocode design provisions could be improved through modifications to the current buckling curves.

When analyzing reinforced concrete diaphragm walls supported by struts, proper dimensioning of the struts is of crucial importance. GMNIA provides a more realistic representation of stress states, deformations, and displacements under various load levels, enabling more efficient and reliable design of both struts and diaphragm walls. A significant impact of initial geometric imperfections was observed for values greater than L/600.

Further research could include the influence of material nonlinearity, particularly the effects of residual stresses. Given the increasing use of spirally welded pipes due to their cost-effectiveness, it would be beneficial to explore their application in conventional engineering structures. Additionally, since boundary conditions significantly affect the critical buckling force, where a fully fixed strut exhibits up to four times higher capacity than a pinned one, the influence of semi-rigid connections remains a promising direction for future investigation.

ACKNOWLEDGMENTS

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Research paper

THERMAL REGIME OF BOVAN LAKE

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Abstract

Bovan Lake is a significant water resource in southeast Serbia, used mainly for water supply, flood protection and recreation. The purpose of this study is to better understand seasonal variations in water temperature by examining the thermal characteristics of the lake at various depths within the intake tower. Water and air temperatures were recorded at five different heights within the intake tower, with hourly measurements taken from December 2020 to November 2021. The results revealed that there were notable seasonal oscillations in the temperature of the water, with upper layers undergoing more fluctuations than deeper levels. A strong correlation among air temperature and surface water layers signifies a considerable external climatic impact, but deeper layers show enhanced thermal stability. This analysis contributes to a better understanding of the thermal dynamics of Bovan Lake and can serve as a basis for more efficient water resource management.

Keywords: *Thermal Stratification, Monomictic Reservoir, Seasonal Variation, Vertical Mixing*

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1. INTRODUCTION

Thermal stratification of reservoirs and lakes is an essential process for both hydrology and ecology. Lake and waterway ecosystems, including their physical and chemical components, depend on temperature influences. Temperature influences how easily substances dissolve in water, affects biological activity, and causes the water to form thermal layers. This layering leads to uneven distribution of oxygen and nutrients and can also change the timing of chemical reactions in the water [1, 2]. Temperature regimes of lakes—where temperature is one of the primary determining parameters—are strongly influenced by climatic setting. Lakes located in temperate continental regions, particularly those with a monomictic regime, exhibit strong seasonal variation in thermal structure, governed by solar radiation, air temperature, and wind-driven mixing [3, 4].

Bovan Lake, geographically located in eastern Serbia, is an artificial reservoir. Monomictic lakes have a predictable stratification pattern in warm months with development of layering (e.g., thermocline) during summer stratification, and a full turnover in winter or early spring [3]. In this context, Bovan Lake is significant due to its role as a water supply source, but also as a multipurpose reservoir. Understanding the lake's thermal behavior is essential for hydrological and ecological planning. However, limited research has focused specifically on Bovan Lake with respect to vertical thermal dynamics and their temporal variation [5].

Climate change is increasingly altering the thermal dynamics of lakes and reservoirs across the globe. Changes in air temperature and the surface meteorological conditions in both space and time are impacting the timing, duration, and strength of thermal stratification in inland water bodies. Warm temperate monomictic lakes are very temperature-sensitive and show early warming and spring season thermal stratification onset dates and later stratification breakdown dates which reduces seasonal mixing. More recently, this phenomenon has been highlighted as a global pattern with many lakes experiencing increased thermal stratification duration, extended reduced frequency of full turnover, and increased atmospheric forced impacts to surface waters [6, 7]. These changes emphasize the importance of long-term and high-resolution temperature datasets, especially for reservoirs, such as Bovan Lake, with multiple ecological and hydrological roles.

This research paper adopts a systematic approach to analyze and interpret the seasonal dynamics of hourly water temperature in Bovan Lake, based on measurements taken from the intake tower between December 2020 and November 2021. The subsequent sections present a seasonal analysis of temperature variation and vertical stratification, as well as the influence of atmospheric conditions—particularly air temperature—on thermal behavior at depth. By identifying stratification phases and vertical gradients, this study contributes to a deeper understanding of the lake's thermal response to climatic forcing, providing support for improved reservoir management decisions. In addition, the study integrates recent insights on climate-induced thermal alterations observed in temperate-zone lakes, aiming to assess the potential vulnerability of Bovan Lake to ongoing climate change trends [6, 7].

2. STUDY AREA AND INPUT DATA

Bovan Lake is an artificial reservoir located in eastern Serbia, formed by damming the Moravica River between 1978 and 1984 to meet multipurpose demands, including regional water supply, flood control, and recreation. The reservoir lies within the Južna Morava River

basin and holds a strategic role in local hydrological planning [5]. The dam structure is of the gravity type, and the resulting reservoir covers a surface area of approximately 4.10 km², with a total length of about 8 km and a maximum width of around 500 m. The deepest point, situated near the dam wall, reaches a depth of approximately 52 m [6].

The lake's morphology features a narrow, elongated profile with steep shorelines and a pronounced longitudinal depth gradient, which facilitates thermal stratification during warmer months. The surrounding catchment is predominantly rural, with limited urban development, which minimizes direct anthropogenic thermal input and allows for clearer detection of natural temperature dynamics [5, 6]. Given these physical and geographical features, Bovan Lake can serve as a representative site for studying thermal behavior in monomictic reservoirs exposed to seasonal climatic forcing.

The intake tower, positioned adjacent to the dam structure, provides a stable environment for systematic temperature monitoring. This vertical structure is equipped with submerged temperature sensors installed at four discrete water depth levels: T1 (238.5 m a.s.l.), T2 (243.5 m), T3 (248.5 m), and T4 (253.5 m), while an additional air temperature sensor (T5) is placed above the water surface. These sensors enabled continuous, high-frequency (hourly) temperature measurements over a full hydrological year, from December 2020 to November 2021, capturing both vertical and temporal dynamics of thermal stratification.

The collected dataset contains 6758 temperature readings per depth point, providing a robust basis for analyzing short-term fluctuations, seasonal trends, and depth-dependent thermal behavior. This high-resolution time series allows for a detailed examination of the lake's vertical temperature structure, and serves as a foundation for further investigation into mixing processes and surface–depth thermal interactions. The data also offer valuable insight for modeling responses to external drivers, particularly in the context of climate variability and reservoir management.

3. METHODS AND PROCEDURES

A year-long seasonal temperature dataset and time series was recorded at Bovan Lake (December 2020 - November 2021) using loggers placed at four depths of water (T1 = 238.5 m, T2 = 243.5 m, T3 = 248.5 m, T4 = 253.5 m) and an air logger located just above the water surface (T5). Each logger recorded hourly values, providing 6758 measurements per logger. Temperature was continuously recorded, allowing for a detailed view of how water temperature changed over time and at different depths throughout the seasons.

The original temperature data were, then, processed in part by descriptive statistics to summarize temperature behavior at each depth (mean, min, max, standard deviation, and interquartile range (IQR)). The original temperature data were, then, processed in part by descriptive statistics to summarize temperature behavior at each depth (mean, min, max, standard deviation, and interquartile range (IQR)).

Boxplots illustrated variability and central tendencies (boxplot indicators are for outliers, variability measures, upper and lower quartiles, and not min or max ranges) of each depth, with variability different across the depths, but more variability observed in the upper depths (T3 and T4) and less variability in the thermally stable lower layers (T1 and T2). Heatmaps provided a clear visual representation of stratification, mixing events, and how thermal layers changed over time.

Pearson correlation coefficients were calculated between air temperature and water temperatures at different depths to assess how temperature changes are related through the water column. The analysis showed that surface layers responded more strongly to atmospheric conditions, while deeper layers exhibited weaker correlations due to greater thermal inertia. Additionally, monthly average temperatures at each depth were used to track seasonal changes and identify the timing and strength of stratification.

All computations were performed using Python, employing libraries such as NumPy, pandas, seaborn, and matplotlib for statistical analysis and data visualization. Stratification patterns were assessed based on visual inspection of vertical temperature profiles and their temporal changes, rather than using a strict numerical threshold (e.g., >1 °C gradient). Although no formal criteria were enforced, transitions between stratified and mixed conditions were interpreted qualitatively by examining the layering and breakdown of temperature across depths. This approach allowed for capturing seasonal thermal dynamics in line with physical expectations and comparative trends observed in similar reservoir studies.

4. RESULTS AND DISCUSSION

Table 1. Descriptive statistics

	T1 238.5 m a.s.l.	T2 243.5 m a.s.l.	T3 248.5 m a.s.l.	T4 253.5 m a.s.l.	T5 air
count	6758	6758	6758	6758	6758
mean	9.04	11.51	12.62	12.058	14.33
std	4.11	5.91	7.40	8.13	9.32
min	4.07	3.32	3.66	-0.33	-7.14
25%	4.89	5.53	5.12	4.51	6.64
50%	8.70	11.43	11.76	10.16	13.30
75%	12.64	17.02	19.22	19.22	21.23
max	16.54	21.71	25.63	27.04	42.14

Descriptive statistics helped outline temperature patterns at all measured depths and confirmed consistent seasonal variation in air temperature. A total of 6758 hourly measurements was obtained for each depth (T1–T5), enabling a reliable statistical evaluation of the results. The mean temperature gradient exhibited the vertical angling, increasing from 9.04 °C at T1 (deepest layer) to 12.06 °C at T4 (surface layer) and the average air temperature at 14.33 °C (T5). The results indicate the influence of solar heating and weather conditions on the upper water layers. The standard deviation (std) values followed that same trajectory, ranging from 4.11 °C at T1 and 8.13 °C at T4 with the maximum variability at the surface. The air temperature had the largest std (9.32 °C) as well, indicative of extreme daily and seasonal variability associated with direct exposure to climate change forces. (Table 1.)

Extreme values (min-max) also indicated stratification and atmospheric influences. At T1, temperature range was between 4.07 °C and 16.54 °C, whereas T4 (shallowest) fluctuated from −0.33 °C to 27.04 °C, and from −7.14 °C to 42.14 °C for air. The inter-quartile range (IQR), derived by taking the difference between the 75th and 25th percentiles, describes the

central spread of the values and closest degree of variability near surface: T4 (IQR ≈ 14.71 °C) and T1 (IQR ≈ 7.76 °C). These results corroborate that surface waters can be highly sensitive and respond more readily to external atmosphere forcing, with deeper layers being more thermally stable and to providing buffering capabilities, especially when warming or potentially stratification occurs, during colder periods. (Table 1.)

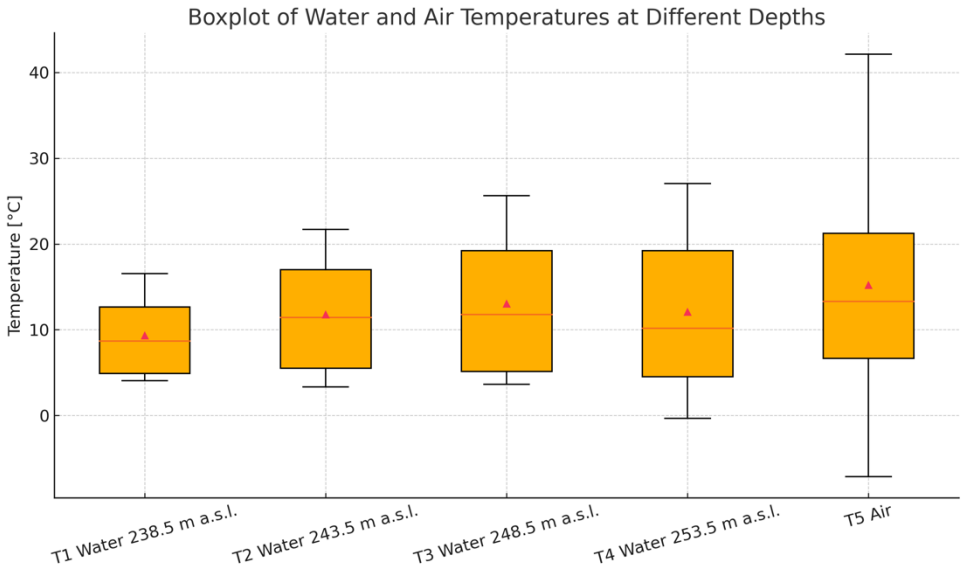


Figure 1. Boxplot of Water and Air Temperatures

The boxplot in figure 1 illustrates the distribution of temperatures in water and air for all measurements levels (T1–T5) through the minimum, 25th percentile (Q1), median, 75th percentile (Q3), and maximum values. The boxplot makes it clear that the upper layers (T3 and T4) have a wider interquartile range (IQR) of values indicating greater seasonal and instantaneous variability due to their direct relationship with the atmosphere. The deeper layer (T1) has a narrow interquartile range (IQR) and a small difference between minimum and maximum values, indicating strong thermal stability. Although the air temperature (T5) shows the widest overall temperature range—and thus the highest variability—the boxplot illustrates its role as a key external factor influencing the heating of surface waters. Overall, the boxplot shows that Bovan Lake has clear temperature differences between layers and noticeable seasonal changes, with deeper layers staying more stable and less affected by quick temperature shifts caused by weather conditions at the surface.

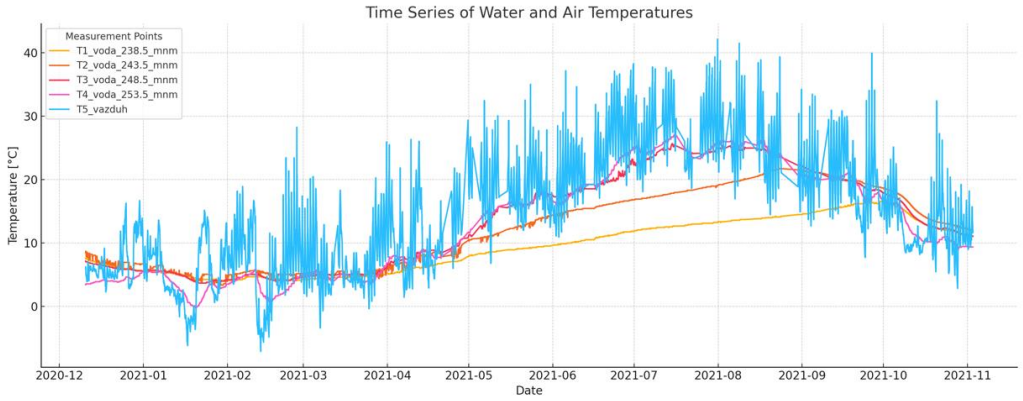


Figure 2. Time Series of Water and Air Temperatures

Figure 2. presents the time series representing hourly temperature data for the water at four depths (T1–T4) and air temperature (T5) collected in Bovan Lake from December 2020 to November 2021. This figure illustrates the seasonal trend of temperature with water temperature increasing gradually during the spring to peak summer months, then declining during autumn.

Air temperature (T5) fluctuated considerably in short spikes, demonstrating its high sensitivity to daily atmospheric conditions at all depths. Water temperature at depth smoothed out these spikes and took time to respond to air temperatures. The upper layers (T3 and T4) were more synchronic with air temperature and had more reciprocal influence from the atmosphere such as sun and wind; In contrast, the bottom layers (T1 and T2) showed slower temperature changes, indicating greater thermal stability.

This time progression also serves as temporal evidence for the onset and breakdown of thermal stratification. The divergence in surface and bottom temperature during the warming period (May - September) shows that thermal stability developed into stable stratification and the subsequent convergence of temperatures in winter or early spring (December - March) illustrates that stratification had ceased and mixing was taking place, which is the typical conditions for monomictic reservoirs. [1]

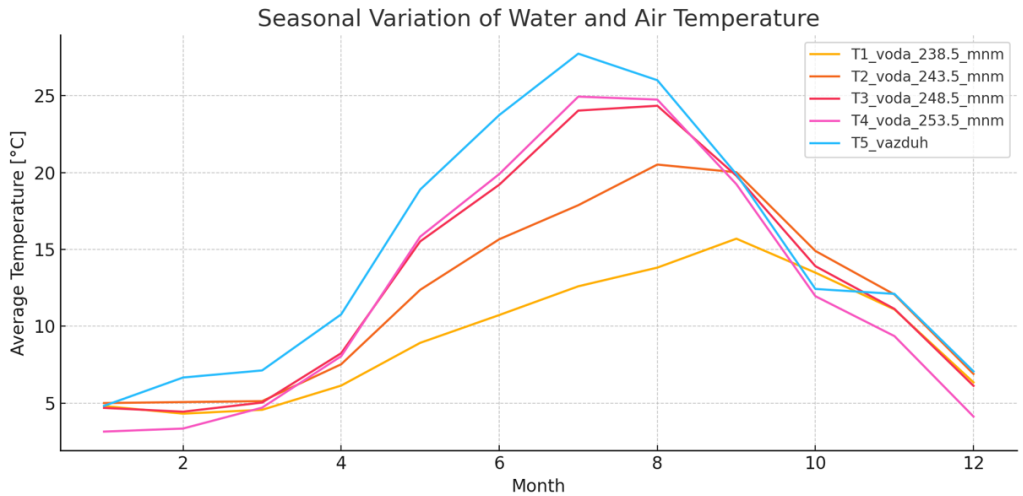


Figure 3. Seasonal Variation of Water and Air Temperature

Figure 3. shows the monthly average temperatures for water and air, showing clear seasonality. Temperatures rise steadily from March to July, reaching peak values in mid-summer. The surface water (T4) and air (T5) exhibit the highest average temperatures, with air temperature peaking at nearly 28°C and surface water around 25°C in July. Conversely, the lowest values are observed in January and February. This pattern clearly illustrates the influence of atmospheric conditions on the lake's thermal regime and confirms the existence of a stratified state during warmer periods.

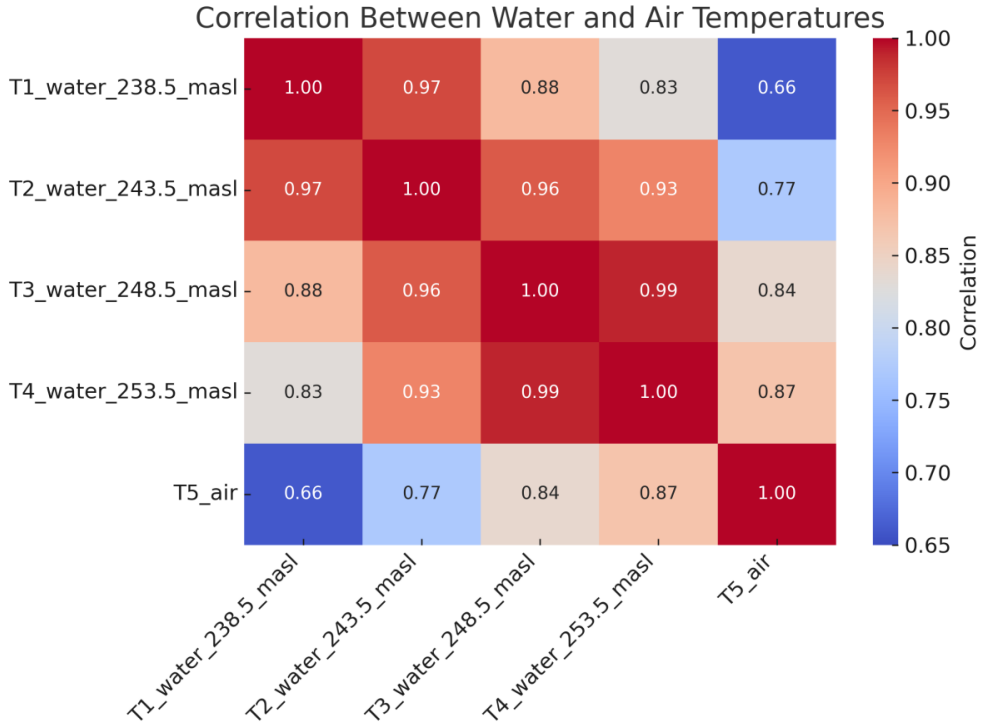


Figure 4. Correlation between water and air temperatures

The correlation matrix (Figure 4.) illustrates the Pearson correlation coefficients between air temperature (T5) and even versus water temperatures from three various deep positions below the body of water. As depth increases, the strength of the correlation decreases and vertically structured relationship is displayed, which indicates stratification in the water. The strongest pair-wise correlations were exhibited in shallow depth, T3 and T4 (r = 0.99). This indicates the water layers T3 and T4 behaved similarly thermally in the upper part of the lake when stratification was evident. The pair-wise correlation of air temperature (T5) to the bottom layer of water temperature (T1) suggests a weak correlation (r = 0.66).

This indicates similar short term thermal influence of atmosphere on the bottom layers of the body of water are insulated. Thermal response to atmospheric conditions has an inverse relationship with depth, since the surface water layers exhibit air-temperature heat exchange more dynamically throughout the year, while deeper water layers are thermally insulated.

The analysis confirms that Bovan Lake exhibits seasonally driven thermal stratification. Strong correlations between neighboring depths reflect stable vertical coherence in temperature profiles throughout the stratified period.

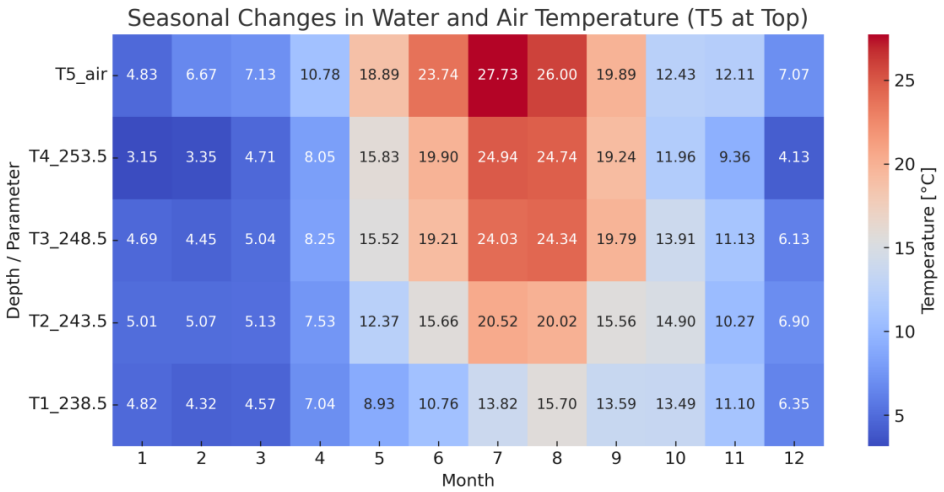


Figure 5. Heatmap of Seasonal Changes in Water and Air Temperature

Figure 5. shows the seasonal variation of mean monthly temperatures for air (T5) and water at four depths (T1-T4) in Bovan Lake for the year 2021. The patterns of temperature show an increase from January (mo. 1) until the peak in July and August (mo. 7-8) and then a decrease towards December. The air temperature (T5) peaked at a value of 27.73 °C in July while surface waters (T4) peaked just below, at 24.94 °C. The T1 and T2 had significantly lower temperatures and slower responses peaking from 18-20 °C.

The data reflects the observation of a stratified non-mixed regime throughout the summer months, meaning warmer and lighter water occupies the upper layers of the lake while cooler denser water remains near the bottom part of the reservoir. The smallest temperature amplitude exists at T1, the lowest depth measured, with mean monthly temperature values ranging from 4.82 °C in January to 17.82 °C in August. The highest amplitude is evident in the air temperature which indicates a seasonal forcing that is progressively decreased as depth increases.

In late fall, thermal regime shows signs of broken stratification as mean monthly averages begin to converge across all depths indicating the onset of vertical mixing. This pattern is typical for monomictic lakes that experience stratification during warmer seasons and fully mix during colder seasons. The clear layering of temperatures during summer, and convergence of monthly mean temperatures during winter is a strong visual representation to classify this reservoir, and show the reservoirs sensitivity to seasonal atmospheric variations.

The changes in temperature seen in Bovan Lake are very much in line with global patterns of lake warming and shifting mixing patterns. For example, increased stratification in the upper layers (T3 and T4) led to larger thermal gradients between the upper and bottom layers (T1 and T2) for a longer period of time during spring, summer, and early fall. In all cases, the continual stratification was similar to the patterns observed in temperate lakes where air temperatures increased and changes in solar radiation contributed to stronger and longer thermal stratification [7]. Additionally, the stable bottom layer (T1) temperatures during colder periods suggest reduced vertical mixing and decrease in total number of complete overturn events, similar to what occurs in warming conditions for monomictic reservoirs [8]. It is also noteworthy that the reasonable correlations between the air temperatures (T5) and the water

temperature in the upper water layers has suggest, atmosphere forcing is Likely the largest driver of the vertical thermal structure gradient, as would be expected. Similarly, it is likely that Bovan Lake is exhibiting signs of early warming driven climate changes, which supports the need to continue monitoring functions of adaptive management.

4. CONCLUSION

This study provides a detailed assessment of the thermal regime of Bovan Lake using one complete year of hourly temperature data collected at four different depths, as well as atmospheric temperatures. The results indicated a clear seasonal stratification pattern with thermally stable layers developed during the summer and vertical mixing suggested during the colder months. These results suggest an overall monomictic thermal regime; stratification developed during the warmer seasons and the lake completely mixed at some point during the year. In monomictic systems, the final peak mixing period occurs typically during winter or early spring. However, multi-year observations may be needed to clarify and confirm truly monomictic status.

The surface water layers (T3 and T4) had more variability, a stronger correlation, and a stronger response to the atmospheric temperature (T5). The deeper layers (T1 and T2) resisted more variability, suggesting they are thermally insulated from short-term variability at the surface. Visual and statistical summaries (e.g., boxplots, heatmaps, line plots, and correlation matrices) provided evidence of a strong vertical temperature gradient and dynamic stratification and mixing over the yearly time scale. These thermal assessments provided a clearer picture of the thermal structure of the lake, its sensitivity to climatic and environmental drivers.

From a wider climate perspective, these trends in Bovan Lake are consistent with recent Global changes indicating that warming air temperatures are causing longer and more intense thermal stratification in lakes. A lesser degree of mixing in the cooler months and a stronger atmospheric influence at the surface suggest Bovan Lake may already be changing its thermal regime due to climate influences. These results demonstrate the necessity of continuing high-frequency monitoring and that future reservoir management plans need to more explicitly consider hydrological and hydroclimatic changes.

The findings may serve to facilitate local water resource management decisions, assist reservoir operations, or provide additional information to conduct environmental studies. Ongoing monitoring and expanded modeling and validation will allow for better characterization of long-term and extreme thermal behavior and to predict lake responses under a changing hydroclimatic environment.

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