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 2

September 11 – 12, 2025

Science and Technology Park Niš, Serbia

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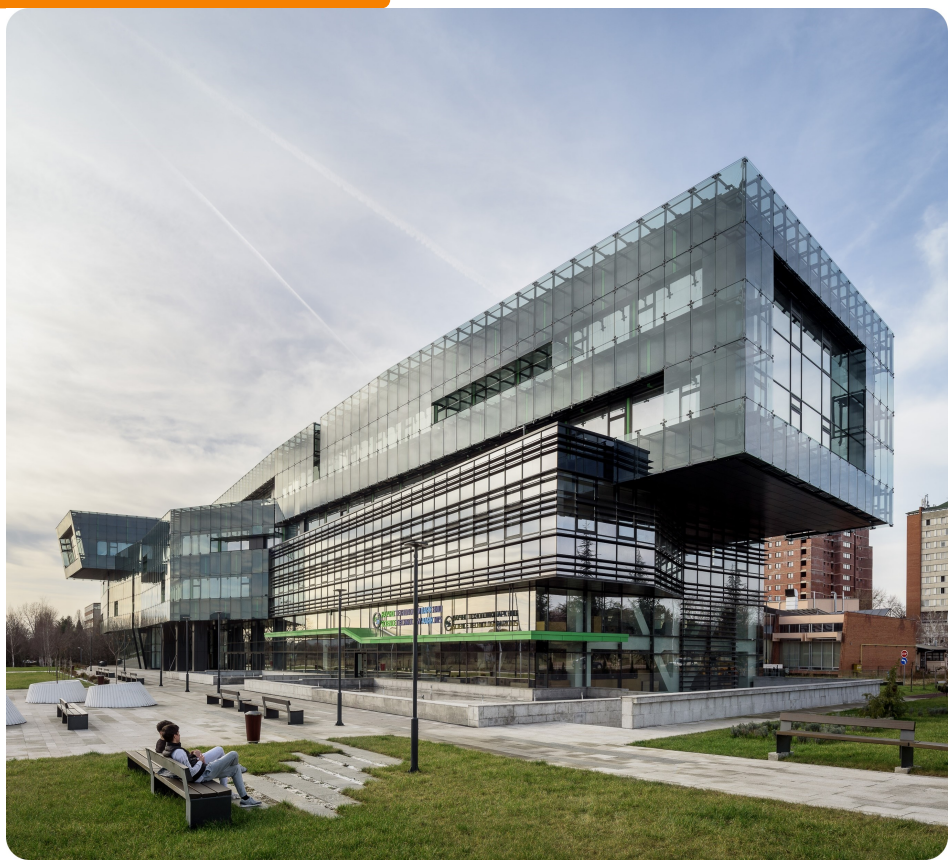
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PREFACE

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

TRANSFORMING TRADITIONAL FORMAL ELEMENTS: THE INTEGRATION OF SERBIAN RESIDENTIAL ARCHITECTURE INTO CONTEMPORARY PRACTICE

Petra Živadinović[1], Danica Stanković[2]

Abstract

In the context of contemporary architecture, there is a growing need for a critical reconsideration of tradition in response to the homogenization of global architectural expression. This paper explores the ways in which elements of traditional Serbian residential architecture are transformed within modern architectural design, with particular emphasis on the role of architectural form as a carrier of cultural meaning, spatial logic, and identity.

The research identifies key elements of traditional typologies: log houses, Morava houses, and Vojvodina houses and traces their formal and semantic transformation through strategies such as reinterpretation, stylization, abstraction, and reduction. Contemporary case studies show that the successful integration of traditional elements does not involve replication, but rather the critical translation of heritage into a new architectural context. The aim of this paper is to determine, through architectural analysis, transformation models that contribute to the preservation of local identity while forming a contemporary architectural language aligned with cultural, aesthetic, and technological demands.

Key words: *traditional elements, architectural form, interpretation, contemporary architecture, critical regionalism, local identity*

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1. INTRODUCTION

In contemporary architecture, integrating elements from traditional vernacular building practices has become increasingly relevant as a critical response to the uniformity of the international style, which often neglects climatic, ecological, and cultural specificities. Although technologically advanced, modern architectural expression frequently proves inadequate in addressing the particular conditions of the place [1]. As a reaction to such shortcomings, there is a growing tendency toward an architecture that recognizes and interprets the specificities of spatial context, materials, and tradition, thereby affirming local identity through a contemporary formal language [2].

However, the process of integrating traditional elements into contemporary architecture brings with it numerous challenges. The most significant among them is the emergence of formalism - the superficial adoption of stylistic features of tradition without understanding their cultural, spatial, and functional context. Such approaches often result in architectural solutions that resemble nostalgic quotations rather than an authentic dialogue with heritage. In this light, it becomes essential to understand how traditional elements can be interpreted critically and creatively, without reducing them to banality or decorative tokenism [3] [4].

The theoretical framework of this research is grounded in the principles of critical regionalism, which advocate for a contemporary architectural expression rooted in local context - where tradition is not imitated but transformed [2] [3] [4]. This study focuses on the analysis of traditional elements of Serbian vernacular residential architecture and investigates their transformative potential within contemporary architectural design. Various strategies of interpretation are identified - such as reinterpretation, abstraction, reduction, and stylization - that enable the preservation of the semantic value of tradition within the language of contemporary architecture. Special emphasis is also placed on the role of architectural form as a carrier of meaning, cultural memory, and spatial logic [5] [6] [7]. The aim of this paper is to identify models of contemporary transformation of traditional elements and to examine their role in preserving local identity and creating architecture that responds to current aesthetic, technological, and contextual demands.

1.1 Critical Regionalism as Theoretical Grounding

The concept of critical regionalism provides a valuable framework for understanding the integration of traditional elements into contemporary architectural expression. Initially introduced by Alexander Tzonis and Liane Lefaivre [8], and further elaborated by Kenneth Frampton in his essay Towards a Critical Regionalism: Six Points for an Architecture of Resistance, critical regionalism seeks to mediate between the universal aspirations of modernism and the specificities of place, climate, topography, and cultural identity [4]. Rather than replicating vernacular forms or indulging in decorative nostalgia, this approach promotes the reinterpretation of local traditions in ways that are innovative, site-specific, and materially authentic [9].

In the context of Serbian architectural practice, where traditional typologies reflect a deep connection to local materials, climate, and spatial organization, critical regionalism offers a theoretical grounding for the transformation of traditional elements into contemporary forms. By focusing on spatial experience, tectonics, and environmental responsiveness rather than stylistic citation, this approach enables architecture to preserve cultural memory while resisting global homogeneity [4][9]. As such, the analysis presented in this paper is positioned

within the broader framework of critical regionalism, viewing the reinterpretation of tradition not as a stylistic device, but as an architectural strategy that fosters continuity, authenticity, and contextual relevance.

2. METHODOLOGY

The methodological framework of this research is based on a qualitative, theoretical - analytical approach, grounded in a specific form of architectural reading - a comparative analysis of traditional and contemporary residential architecture. This form of analysis enables the identification of transformation patterns by juxtaposing original typological and formal characteristics of vernacular Serbian houses with selected examples from contemporary architectural practice.

In the initial phase of the study, key elements of traditional Serbian vernacular residential architecture are identified and analyzed in terms of their formal, functional, and symbolic values within their original context. These elements are regarded as having the potential for reinterpretation and transformation within the language of contemporary architecture.

The second segment draws upon insights from contemporary architectural theory in order to establish a critical framework for understanding how traditional elements can be integrated into modern design. The process of transformation is considered through four distinct interpretive strategies: *abstraction, stylization, reduction, and reinterpretation.* These strategies are synthesized into a recognizable analytical model named *ASTRRE* (from: **A**bstraction, **ST**ylization, **R**eduction, and **RE**interpretation), proposed as a conceptual framework for identifying and categorizing design approaches that engage with tradition in a meaningful way. This model ASTRRE may serve as a communicative and applicable tool in both academic and architectural design contexts.

The criteria for selecting the reference buildings include: residential function, realization in the 21st century, location in rural areas of Serbia, and an established relationship between traditional elements and contemporary expression. The selected examples are not analyzed as individual case studies; rather, they serve as representative illustrations of various interpretative strategies through which the formal and semantic aspects of traditional patterns are examined in a contemporary context.The aim of this methodological approach is to, through the synthesis of theoretical reflection and comparative practical analysis, identify models of successful integration of traditional forms into contemporary design, and to assess their contribution to the preservation of local identity within the conditions of modern life.

3. ELEMENTS OF TRADITIONAL ARCHITECTURE

Traditional Serbian residential architecture has been shaped according to climatic, geographical, and social conditions, where every spatial element held both functional and symbolic roles. The three main typologies - Morava house (in Serbian: "moravska kuća"), log cabin (in Serbian: "brvnara"), and Vojvodina house (in Serbian: "vojvođanska kuča"), - reflect regional differences in form, materials, and spatial organization [10]. The form of the traditional Serbian house is characterized by simplicity and clear geometry, most commonly cubic or rectangular in plan, with rational spatial organization adapted to local environmental

conditions. Regardless of regional differences, the basic design logic stems from the need for functionality, economical construction, and adaptation to local climatic and social factors.

In mountainous areas, where the log cabin typology prevails, houses are compact, and made of wood, with steep roofs that facilitate snow runoff and provide protection from cold and precipitation. Their form - simple and enclosed - responds to the harsh natural environment and the need for thermal insulation. The Morava house, typical of hilly and central parts of Serbia, features a tripartite organization with a porch (in Serbian: "trem") serving as an intermediary space between the interior and courtyard. Its spatial layout reflects a family-oriented lifestyle, the need for larger interior space, and a connection to the external environment. The Vojvodina house, developed in flatlands with narrow parcels, is elongated in the direction of the parcel's depth. It is characterized by a rectangular form, rational and linear room organization, and a long porch connecting the rooms, often serving a decorative purpose. Its form derives from parcel limitations as well as Austro-Hungarian construction regulations from the 18th and 19th centuries [11] [12].

A common thread linking all these typologies is the simplicity of form and spatial organization aimed at functionality, optimal use of available resources, and adaptation to the specificities of the natural environment. Elements of traditional Serbian residential architecture form, such as simple cubes, pitched roofs, porches, and the use of local materials, carry deep significance in Serbia's cultural history and are therefore elaborated in more detail [13].

The pitched roof is a significant architectural element of the past, recognizable in all types of Serbian houses. In traditional residential design, the pitched roof plays an important role not only functionally - as an adaptation to climatic conditions but also aesthetically, in shaping architectural expression and creating spatial visual dynamics. Two types of pitched roofs are recognized in domestic architecture: Vojvodina houses typically have gable roofs with lower pitches, prominent eaves, and decorative treatments, whereas Morava houses and log cabins have hipped roofs with steeper slopes, often with ridges, pronounced eaves, and greater pitch [10].

Porches represent an important typological and symbolic element of Morava and Vojvodina houses. This architectural element serves as a transitional space between the interior and exterior, contributing to the integration of the building with the natural environment. Functionally, porches served as spaces for relaxation and everyday outdoor activities, while aesthetically they contributed to the character and beauty of the house, often adorned with carved wooden columns and details reflecting regional stylistic features [12]. Characteristic arcade columns were typical in Morava houses, while in Pannonian houses (in Serbian: "panonska kuća/vojvođanska kuča"), porches often extended along the entire length of the facade [10].

The use of local materials is a fundamental principle of traditional architecture. Wood, stone, and ceramic products represent the primary building materials, whose processing depends on their natural properties [14]. **Wood** is the most common material in mountainous areas for building log cabins, used both structurally and as cladding. Wooden constructions are used for primary structural elements such as walls of log cabins, timber framing, construction of columns, floors, and roofs, as well as secondary elements such as windows and doors across all house types [12] [14]. **Soil**, was most commonly used in Vojvodina due to the scarcity of forests. Initially, the soil was used as rammed earth ("rammed earth houses"- in Serbian: "kuća od naboja"), later as adobe bricks (in Serbian: "ćerpič"), and

eventually as fired bricks [12]. **Stone** was used in traditional architecture for foundations, retaining walls, and basement walls, and its massiveness and texture contributed to the stability and protection of buildings against climatic conditions [11]. Stone construction was mostly present in hilly terrains. The combination of different materials is observed in all house types; for example, combining stone and wood in log cabins creates the two-story log cabin (in Serbian: "kuća na ćelici"), while the combination of wood and soil is characteristic of the Bundwerk construction of Morava houses (in Serbian: "bondručna konstrukcija") [12].

3.1. Interpretation Methods of Traditional Elements of Residential Architecture in Contemporary Expression

The architectural form has undergone continuous transformation throughout history - it reflects not only functional requirements but also formal and cultural innovations [15]. In contemporary architectural design, traditional elements are rarely transferred directly; instead, various design strategies are employed that enable the preservation of meaning while adapting the form to the spirit of the time and contemporary needs.

Marić, identifies two principal approaches: (1) *interpretation through an eclectic approach* (copying, formalism, citation, and stylization of traditional characteristics), and (2) *critical regionalism*, which relies on a deeper understanding of context and the integration of elements into a new architectural language without mimicking traditional forms [16].

Familiarity with the typological and morphological characteristics of vernacular architecture allows traditional elements to be transformed by contemporary lifestyles and modern construction techniques. While **stylization** is often used as one of the methods for interpreting traditional architecture, its value depends on the depth of understanding of the essence of the form being transformed. Stylization implies retaining the visual recognizability of an element but modifying its proportions, materials, or details in line with contemporary expression. However, if stylization is applied without a deeper spatial-functional rationale, it risks becoming superficial formalism - decorative use of motifs devoid of essential logic and meaning. In this regard, the boundary between meaningful stylization and inauthentic formalism lies in the project's capacity to preserve the spatial, cultural, or symbolic function of the traditional element through a contemporary architectural language [17].

In the project *"Log Houses - Holiday Homes for the Employees of the Branković Bakery" (Alterno)*, the classical form of the log cabin is retained as a starting point but is redefined through clean lines, a contemporary treatment of the facade using characteristic traditional materials such as wood and stone, along with asymmetrical roof slopes, the absence of eaves, and distinctive glazed openings *(Figure 1 and 2)* [18]. The use of stone for retaining walls and pathways aligns with traditional construction techniques on sloped terrain, where stone is used to create stable foundations and terraces. This approach enhances both the visual and tactile connection with the natural surroundings and evokes the stone ground floors typical of two-story log cabins *(Figure 2).*

The process of stylization in material expression is also evident in the project *"Rilak Family House"* in Alibunar, Serbia, *(Modelart Arhitekti)* where modern black facade brick can be contextually linked to the traditional use of brick (soil) in Vojvodina architecture *(Figures 3 and 4)* [17]. However, unlike classic terracotta brick, this example features a contemporary treatment of both material and color, clearly indicating a transformation within a stylized approach. Likewise, the use of white color in combination with stone in the project *"House in Popovica"* (*4Mind Architecture*) *(Figure 5)* can be interpreted as an allusion to "čatmara" (the

forerunner of the Moravian houses), which were characterized by white facades and natural materials. In both cases, traditional motifs are not directly replicated but instead appear in a refined, aesthetically balanced form that establishes a connection with local heritage - without resorting to literal citation *(Figure 6)* [17].

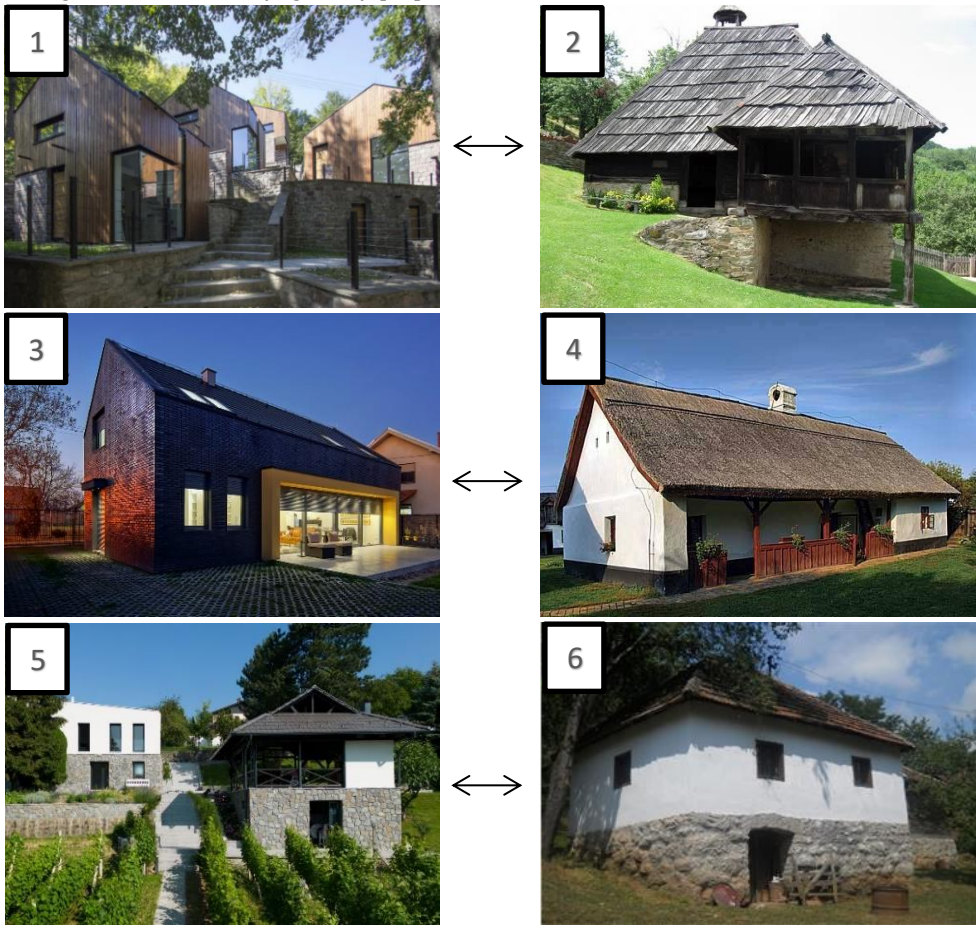


Figure 1. Log Houses - Holiday Homes for the Employees of the Branković Bakery, Alterno Inc., Vrelo, Stara Planina, Serbia, 2017, (Branković Mountain Resort | Alterno INC, 03. 05.2025.)

Figure 2. Traditional log cabin, Gornja Crnuća, Serbia, (Милошев конак у Горњој Црнући — Википедија, 03. 05.2025.)

Figure 3. Rilak Family House, Modelart Arhitekti, Alibunar, Serbia, 2017, (https://issuu.com/arhitektacasopis/docs/arhitekta_4_mejl/s/12440043 , 02. 05.2025.)

Figure 4.Traditional Vojvodina house, (https://terrabija.com/110/, 02. 05.2025.)

Figure 5. House in Popovica, 4MindArchitecture, Popovica, Fruška gora, Serbia, 2022, (https://www.4mind.rs/projects/residential-popovica, 02. 05.2025.)

Figure 6. Čatmara, Serbia, (https://lepotesrbije.alo.rs/turizam/vesti/43766/zlatiborska-osacanka-kako-su-izgledale-brvnare-i-crkve-posle-srpskih-ustanaka/vest , 01. 04.2025.)

On the other hand, regionalism as an architectural approach integrates historical transformations of forms with cultural and geographical specificities, allowing traditional forms and local elements to be adapted and developed within a contemporary expression. Thus, architectural space and form, through the lens of regionalism, become expressions of local culture and history, while simultaneously undergoing physical and semantic transformations in accordance with modern demands [2] [3]. Critical regionalism strives for a synergy between concepts of national culture and global influences, opposing universality by employing elements that evoke a sense of belonging and identity through associative meanings [4]. During the design of new solutions, architects start from a prototypical architectural model, which they transform through a series of discrete manipulations, integrating forms, proportions, and indigenous materials from traditional architecture, with the connection to folk heritage realized through the application of specific details, symbols, and constructive solutions [13].

Reinterpretation, as the deepest form of transmitting tradition into contemporary architectural creation, implies a departure from direct copying of visual forms and instead focuses on the essence - spatial logic, function, and cultural significance of certain elements. The architect investigates the reasons behind the existence of a traditional form, its context, and its role in daily life, then transfers its characteristics into a new form through contemporary expressions, materials, and technology. For example, the traditional porch, which served as a transitional space between interior and exterior, can be reinterpreted in contemporary architecture as a covered platform or terrace with large glazed surfaces, retaining its functional role but expressed in a modern form. In the project *"House in Popovica"* (*4Mind Architecture*), the spatial logic of the traditional porch is transformed into a cantilevered terrace with a glazed wall, functioning as a transition from inside to outside, preserving the role of occupancy and visual openness to the landscape, but within a contemporary formal and material interpretation [19]. The auxiliary summer kitchen structure represents an example of the reinterpretation of traditional architecture, where a contemporary approach retains the spatial logic and materiality characteristic of vernacular building - the ground floor is constructed in stone, while the upper level is designed as an open wooden terrace with a small kitchen, intended as a space for relaxation and gathering (Figure 5). *Modelart Architects*, in the project *"Rilak Family House"*, designed a simple concrete structure as a modern replica of the Vojvodina porch, which extends along the entire house, visually and spatially connected to the interior through large glass portals, maintaining the traditional function of relaxation and social gathering [20].

Abstraction in architectural design implies the reduction of traditional elements to basic spatial and geometric principles, omitting decorative and constructive details while preserving proportions and volume [21]. Space is defined through pure forms - wall, opening, roof - that are treated as simplified, geometrically articulated elements, thus conveying tradition through an archetypal form rather than stylistic reproduction. The *pitched roof*, as an archetypal element of traditional architecture, can be abstracted into a simple gabled volume without eaves or ornamentation, yet retaining its proportions and slope. The pitched roof, as a symbolic form of the house, receives an abstract expression in the *"Rilak Family House"*. The gabled roof, without eaves or ornaments but maintaining slope and relation to the ground, remains visually recognizable and simultaneously modern. A similar abstraction is observed in the *"House in Popovica"*, where the traditional roof volume is minimally interpreted through a diagonally oriented, low-pitched gabled roof, whose geometry fully integrates into the

overall form of the building without any ornamentation, while the facade remains clean and flat. In these solutions, elements are not copied, but their essence is translated into a new architectural language.

Similar to abstraction, **reduction** is an approach that simplifies traditional form to its fundamental elements by removing ornamentation, unnecessary layers, and structural complexities. Unlike abstraction, reduction often lacks semantic depth and is motivated by rational criteria: minimalism, budget constraints, technical feasibility, or aesthetic purity.The difference between abstraction and reduction can be observed in the following examples. In the holiday cabins for bakery workers designed by *Alterno Studio*, an abstraction process is evident: the traditional pitched roof of the cabin is preserved in its basic geometric shape, but without eaves or visible structural details. The volume is maintained, but the form is purified, resulting in a contemporary expression that references tradition through proportions and spatial logic rather than stylistic elements. On the other hand, alongside abstraction in the *"House in Popovica"*, the reduction of certain elements is noticeable - for instance, the complete removal of the eaves, and the roof and facade elements are merged into a unified surface without any ornamentation or roof emphasis. Although the building carries contextual logic (positioning on the slope, orientation towards the courtyard), the reduction of formal elements indicates a tendency toward minimalism and functional purity, without a direct semantic connection to tradition. Likewise, the removal of the eaves on the roof of the *"House in Popovica"*, creates a simplified roof appearance aiming for minimalism and integration of the roof and facade into a cohesive whole. A similar approach is present in the *"Rilak Family House"*, where the absence of decorative gable treatments typical of traditional Vojvodina houses shows a conscious reduction of ornamentation in favor of simplicity, clean lines, and modernism.

4. DISCUSSION

Through the analysis of selected architectural examples within the contemporary Serbian context, this study explored how traditional elements are formally and semantically transformed in present-day architectural practice. These transformations are most commonly achieved through the strategies of abstraction, reduction, stylization, and semantic reinterpretation. Rather than replicating historical forms, contemporary projects adopt traditional typological and formal elements in abstracted, symbolic, or purified expressions, enabling new architectural languages that retain recognizable local codes while addressing current aesthetic, functional, and technological demands.

4.1. Interpreting tradition through the ASTRRE model

In contemporary practice, the integration of traditional forms occurs not through direct replication but via interpretative strategies that enable meaningful transformation and contextual relevance. These approaches aim to preserve the cultural and spatial essence of tradition while adapting it to modern life. The ASTRRE model proposed in this study systematizes four key strategies of formal transformation and provides a structured framework for analyzing contemporary projects that engage with heritage. When critically applied, each strategy offers a distinct mode of engaging with tradition and supports the creation of identity-conscious, contextually grounded architecture.

The most common patterns of formal transformation include:

- **Abstraction and reduction of the object's form** - Traditional pitched roofs and porches are transformed into geometrically simplified shapes, stripped of decorative details, as seen in the “Rilak Family House” and the “House in Popovica.” Here, the roof becomes a continuous flat surface, the eaves are reduced, and elements such as porches are simplified into platforms and covered terraces. Abstraction preserves the volumetric essence of a traditional form but expresses it in a minimalist, often tectonically reduced language. This process is particularly effective in creating continuity with tradition while aligning with contemporary aesthetic tendencies toward minimalism. However, while reduction can contribute to sustainability and clarity of form, it must be applied with caution, as excessive simplification can lead to the loss of cultural meaning. For this reason, reduction should aim to refine form and construction while preserving those features that embody local identity.
- **Reinterpretation of the function of elements** - Elements such as porches, which once served as transitional and leisure spaces, acquire new roles. Instead of classic wooden porches, glazed loggias, semi-covered entrances, or spaces open to the courtyard now appear. In the *“House in Popovica,”* the auxiliary structure reminiscent of traditional Serbian buildings acquires a new function as a storage facility, while the upper-floor terrace functions as a summer kitchen. On the same object, the main house’s large terrace serves a dual purpose: it provides access to the house and functions as a leisure area. In contrast, the porch in the *“Rilak Family House”* functions as a contemporary veranda - an extension of the living zone and a mediator between the interior and the landscape. These examples show how reinterpretation maintains continuity with tradition while fully embracing contemporary design principles. Reinterpretation avoids direct visual reference with tradition and instead focuses on transforming the logic, function, and cultural role of traditional elements into new architectural configurations.
- **Use of traditional materials in contemporary design** - Wood and stone, as dominant traditional materials, are used in new technological contexts. In the projects *“House in Popovica”* and *“Log Houses – Holiday Homes for the Employees of the Branković Bakery*”, these materials are processed and applied according to contemporary construction standards while retaining their symbolic association with the local context. Traditional materials are not used literally, but placed in a new constructive and aesthetic context; through reinterpretation, their symbolic value is preserved, while their expression is transformed and stylized through a contemporary visual interpretation. *“*The Rilak Family House” is entirely clad in black facade brick, giving the house a modern appearance while simultaneously evoking a connection with heritage, as brick is the dominant building material in Pannonian houses.
- **Critical regionalism as a framework for the sustainable development of identity**

The ASTRRE model closely aligns with the principles of critical regionalism, offering a framework for resisting architectural homogenization through context-sensitive design. When applied reflectively, its strategies support an architecture that is both contemporary and rooted in local identity. This is evident in examples like the *“Log Houses*” on Stara Planina and *“The family complex*” on Fruška Gora, where the buildings follow the terrain, use local materials, and engage with the climate. Such an approach reflects Frampton’s concept of tactile, place-based architecture, grounded in memory, material, and landscape. Rather than treating critical regionalism as a style, the study adopts it as a methodological and ethical

lens, confirming that thoughtful reinterpretation of tradition can preserve cultural identity without slipping into formalism or pastiche.

4.2. Between Identity and Representation: Balancing Authenticity in Contemporary Practice

One of the most complex challenges in the integration of traditional elements into contemporary architecture is maintaining a balance between authentic expression and superficial representation. This issue is particularly present in rural contexts, where traditional styles are often uncritically replicated through pitched roofs, decorative wooden elements, or covered porches without adaptation to the realities of contemporary life and without understanding their functional or symbolic roles. As a result, many buildings that visually evoke the past lack a genuine connection to their place and context [2]. As Antešević points out, “to emulate tradition does not mean to copy and transfer its morphological, spatial, or constructive elements, but rather to understand its broader axiological significance within social and cultural contexts” [17]. In this sense, the challenge is not in preserving the form itself, but in translating its semantic value into an architectural language that reflects both cultural continuity and contemporary relevance. On the other hand, the misuse of traditional elements for the sake of purely aesthetic effect leads to a disconnection between form and content, resulting in an impoverished architectural experience.

The projects analyzed in this study demonstrate that traditional elements can be meaningfully integrated into contemporary architecture through a careful understanding of context - topography, climate, material culture, and social patterns - in combination with thoughtful design strategies. Within the proposed ASTRRE model, four interpretive approaches serve as tools for the critical transformation of tradition without resorting to imitation. For example, *abstraction* allows for the transformation of the pitched roof into a clean, minimalist volume that preserves its geometric logic, free of decoration, as seen in the *Rilak Family House project. Stylization*, when grounded in spatial reasoning, enables the modernization of traditional forms while preserving their recognizability. *Reinterpretation*, as in the *House in Popovica* project, transforms the typological essence of the porch into a cantilevered glazed terrace - retaining its function in a completely new form - while reduction is often present across other strategies as a way of achieving a contemporary, often minimalist, design language in relation to recognizable traditional styles.These examples show that traditional architectural elements - formal simplicity, pitched roofs, porches, local materials can be reimagined not as visual symbols, but as active spatial agents that respond to the site and program. Their success lies not in how closely they resemble the past visually, but in how meaningfully they reinterpret its essence. This critical approach aligns with the principles of *critical regionalism*, which advocates for architecture rooted in place sensitive to natural conditions, cultural memory, and material specificity, while also resisting the homogenization imposed by the global architectural discourse [4] [9]. In this sense, the ASTRRE model represents not just a classification of design strategies, but a practical framework for navigating the space between heritage and innovation. Through subtle formal transformation, material sensitivity, and contextual awareness, contemporary architecture can achieve a balance in which tradition is not imitated, but evolved - where identity is not preserved as a static image, but sustained through dynamic reinterpretation.

5. CONCLUSION

This paper presents a comprehensive analysis of the integration of traditional elements of Serbian vernacular residential architecture into contemporary architectural expression and investigates how these elements are transformed within modern design practices. The research first identifies the key formal, functional, and semantic characteristics of traditional typologies as a foundation for further interpretation. The focus then shifts to the strategies of interpreting these elements in contemporary design, analyzing approaches such as reinterpretation, stylization, abstraction, and reduction.

The aim of the study - to identify models of transformation of traditional elements and to examine their role in preserving local identity and shaping contemporary architecture that responds to current aesthetic, technological, and contextual demands - has been successfully achieved. The research has demonstrated that architectural form, as a bearer of cultural meaning, memory, and spatial logic, is a key medium through which tradition can be preserved and translated into a contemporary language. Findings indicate that the successful transformation of traditional elements is not a matter of stylistic citation, but rather of deep understanding of their meaning and context. Projects that apply the approach of critical regionalism - focusing not on mimicking the form, but on capturing the essence - show the greatest potential for creating architecture that is both innovative and authentic. The use of local materials, preservation of spatial logic, and reinterpretation of culturally significant elements such as the roof, porch, or building proportions have proven to be effective mechanisms in the process of preserving cultural identity. The research confirms that critical regionalism offers a sustainable architectural strategy by fostering dialogue between global trends and local values, supporting contextual design and efficient resource use. This approach affirms cultural heritage while also opening the way for high-quality architectural solutions, with the ASTRRE model offering a valuable methodological framework for identifying and systematizing strategies for meaningful reinterpretation of tradition in contemporary practice. The model offers a structured yet flexible tool for future research and design experimentation, supporting a critical and creative engagement with heritage. These findings provide a basis for future research into the relationship between tradition, innovation, and context, and for expanding the ASTRRE model toward developing design methodologies that strengthen cultural identity in a globalized era.

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Review paper

INVESTOR DECISION-MAKING IN CONSTRUCTION DEVELOPMENT: DATA-DRIVEN STRATEGIES FOR OPTIMAL INVESTMENT CHOICES

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Abstract

Investment decision-making in construction development is a multi-layered process shaped by market dynamics, financial risk assessments, regulatory frameworks, and emerging industry trends. In an era of rapid urbanization, digital transformation, and increasing sustainability concerns, investors must integrate diverse data sources and analytical methods to optimize their decisions. This study explores the key factors influencing investor choices, emphasizing the role of structured feasibility assessments, technological advancements, and environmental considerations in shaping investment strategies.

To investigate these aspects, this research will employ a combined narrative and thematic literature review approach. The narrative review will provide a broad exploration of key investment factors, tracing the evolution of decision-making frameworks in construction, including traditional investment principles, financial assessment models, and the impact of regulatory and economic shifts. The thematic review will categorize findings into structured decision-making components, aligning with key investment phases such as market analysis, risk assessment, financial modeling, and stakeholder engagement. This dual approach ensures both flexibility in exploring diverse literature and a structured synthesis of key themes, offering a comprehensive understanding of how investors evaluate construction opportunities.

The findings of this study highlight the increasing reliance on financial modeling, regulatory compliance mechanisms, and sustainability-driven investment criteria in modern construction decision-making. By integrating traditional feasibility assessments with modern investment analytics, this paper provides an updated, structured framework for evaluating construction investment opportunities. The study will equip investors, developers, and policymakers with insights to navigate complex and volatile markets, optimize decision-making processes, and enhance long-term project viability.

Key words: *Construction Investment, Market Analysis, Risk Assessment, Financial Modeling, Sustainability, Stakeholder Engagement.*

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1. INTRODUCTION

Construction investment decisions critically influence urban development, economic expansion, and the sustainable evolution of the built environment. As global urbanization accelerates, investors must navigate increasingly complex environments shaped by regulatory frameworks, technological innovations, and sustainability imperatives [1]. The ability to make structured, data-driven investment decisions has thus become essential to achieving project resilience and success.

Recent global trends have intensified these complexities. Urban densification and the growing prominence of environmental sustainability are redefining construction standards and investor expectations [2]. Additionally, the digital transformation, characterized by the adoption of big data analytics, Building Information Modeling (BIM), and decision-support systems, is revolutionizing how construction investments are evaluated and managed [3]. In parallel, heightened economic volatility and regulatory shifts have made traditional static investment models less reliable for modern project appraisal.

Historical approaches to construction investment, heavily reliant on financial feasibility studies and intuitive judgment, increasingly fall short in adequately capturing the multifaceted risks and opportunities present today [4]. Modern investment frameworks now demand the integration of comprehensive market analytics, dynamic risk assessments, sustainability criteria, and digital tools to ensure informed decision-making. This shift reflects a broader trend toward structured, adaptive strategies in construction project evaluation and execution.

The purpose of this paper is to explore how investor decision-making processes have evolved under the pressures of urbanization, sustainability, and technological advancement. It aims to identify the key factors shaping optimal investment strategies and to propose a structured, updated framework for decision-making in construction development.

To achieve this, the study employs a dual literature review approach. A narrative review will trace the historical evolution of construction investment frameworks, outlining how economic, technological, and regulatory forces have transformed traditional models. A thematic review will then categorize and synthesize contemporary decision-making factors, focusing on critical domains such as market analysis, risk management, financial modeling, sustainability integration, and stakeholder engagement [5]. This methodology ensures a comprehensive and structured exploration of the literature.

Ultimately, the findings of this research aim to provide investors, developers, and policymakers with an actionable, data-driven framework capable of navigating the volatility, complexity, and sustainability challenges inherent in contemporary construction development.

2. METHODOLOGY

This study adopts a dual literature review methodology, combining a narrative review and a thematic synthesis to develop a comprehensive understanding of the factors influencing investor decision-making in construction development. This approach provides both a historical grounding and a contemporary lens through which evolving investment priorities, strategies, and risks can be critically examined. The narrative review traces the historical evolution of construction investment frameworks, highlighting how urbanization, regulatory reform, sustainability imperatives, and digital transformation have reshaped traditional

decision models. This contextual analysis explores macroeconomic influences, policy transitions, and sectoral innovations that have contributed to the shifting priorities of construction investors over the past decade. To complement this, a thematic review organizes and evaluates the literature across five critical domains identified as central to construction investment decision-making: Market Analysis, Risk Assessment, Financial Modeling, Sustainability Integration and Stakeholder Engagement. Each theme was derived from observed frequency and analytical depth in recent academic and industry literature, and reflects the multifaceted nature of investment evaluation in modern construction contexts. To identify relevant literature, a structured search strategy was employed using AI-enhanced scholarly databases. Search queries were tailored for each thematic domain using targeted keywords such as “construction investment,” “ESG metrics,” “PPP,” “financial modeling,” and “cost-benefit analysis.” The following inclusion criteria guided the selection:

- peer-reviewed journal articles, conference proceedings, or institutional reports;
- publication year from 2018 to 2025 to ensure relevance;
- full-text accessibility, with preference for open-access publications;
- direct topical relevance to construction investment.

Initial queries yielded approximately 110 documents. Following two rounds of screening, first for topical scope and then for methodological quality and sector relevance. Total of 25 publications were selected for detailed review. Studies that focused on non-construction sectors or were not freely accessible were excluded. Sources were retrieved from platforms such as ResearchGate, MDPI, Springer, Frontiers, and institutional repositories. This methodological approach ensures that both historical context and current research priorities are integrated into the analysis, providing a robust foundation for evaluating construction investment decision frameworks.

3. LITERATURE REVIEW

3.1. Narrative Review

Traditional approaches to investment decision-making in the construction sector have long centered on financial feasibility studies. These models typically emphasized static economic indicators such as Return on Investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR) to evaluate project viability. While adequate in relatively stable markets, such techniques often excluded dynamic risk factors, long-term sustainability impacts, and non-financial variables. Historically, construction investors relied heavily on intuition, personal experience, and narrow financial models to guide decisions, often overlooking broader market indicators or environmental constraints.

Over time, several macro-environmental factors began to challenge this traditional framework. The rapid pace of urbanization created new spatial, social, and regulatory complexities that conventional models failed to account for. Digital transformation introduced advanced technologies such as Building Information Modeling (BIM), data analytics, and geospatial forecasting, revolutionizing how construction planning and investment forecasting were conducted. In parallel, increasing regulatory scrutiny and international sustainability commitments placed environmental performance and ESG (Environmental, Social, and Governance) criteria at the forefront of investment evaluation. These shifts exposed the

limitations of purely financial assessments and highlighted the need for a more holistic, integrated investment framework.

In response, a transition began toward structured and multi-dimensional investment evaluation methods. Investors began incorporating dynamic risk analysis, lifecycle costing, stakeholder analysis, and sustainability metrics into decision models. The integration of probabilistic modeling techniques such as Monte Carlo simulations and Bayesian Networks further enhanced the predictive power of investment evaluations in uncertain environments. These methods allowed for better quantification of risk and improved the adaptability of investment decisions in fast-changing markets [1][2]. In particular, ESG-specific adaptations for the construction industry emerged, framing sustainability as not only a regulatory obligation but also a value-generating investment principle [3].

This evolution from traditional feasibility models to integrated, data-informed frameworks sets the foundation for analyzing today's key investment decision factors. The thematic review that follows will explore how modern investors assess market potential, evaluate financial and operational risk, model returns, incorporate sustainability objectives, and engage with a wide range of project stakeholders.

3.2 Thematic review

3.2.1. Market Analysis

Market analysis forms the foundation of early-stage construction investment evaluation. Traditionally, this process focused on macroeconomic trends and general demand assumptions, often using outdated or static demographic data. However, modern approaches emphasize data-driven methods that account for spatial, economic, and urban development dynamics specific to the investment region.

Ekemode and Ogunba [1] highlight a significant weakness in feasibility appraisals of property development projects in Lagos, Nigeria namely, the inadequate use of localized market data and the failure to account for neighborhood-level demand patterns. Their study demonstrates how insufficient market scoping contributes to poor investment outcomes, suggesting that incorporating detailed, real-time indicators is essential for more accurate feasibility forecasting.

Similarly, Zhang [2] demonstrates the influence of urban land-use planning on the success of real estate development projects. The study outlines how zoning laws, transportation planning, and neighborhood typologies critically impact the viability of proposed developments. The integration of urban spatial logic into market feasibility represents a key advancement in aligning investment targets with local socioeconomic realities.

Together, these studies support the evolution of market analysis in construction from a generic economic indicator exercise to a precise, contextualized assessment using granular planning, demographic, and behavioral data. Modern investors are increasingly incorporating geospatial analysis, competitor benchmarking, and demand elasticity modeling into feasibility studies, moving toward a multidimensional framework for market evaluation.

3.2.2 Risk Assessment

Risk assessment is a central pillar in construction investment decision-making, given the sector's high exposure to financial, operational, regulatory, and environmental uncertainty.

Historically, investors relied on deterministic models or subjective assessments, often underestimating the compound effects of project delays, cost overruns, and external shocks. Today's methodologies prioritize quantitative modeling, scenario simulation, and multi-criteria decision analysis to navigate risk in volatile project environments.

Fischer et al. [5] demonstrate how probabilistic climate forecasting and actionable risk data can inform infrastructure investment planning under long-term environmental uncertainty. While not specific to real estate alone, the framework they propose is highly adaptable to construction projects, particularly those facing climate sensitivity or weather-dependent performance metrics. It illustrates the growing importance of integrating external, climate-related risks into standard investment risk portfolios.

From a methodological standpoint, Xiao et al. [3] offer a powerful construction-specific approach by combining Bayesian Networks with Analytic Hierarchy Process (AHP). This hybrid model allows for both qualitative and quantitative factors to be assessed simultaneously and is particularly useful in projects with uncertain labor conditions, complex site logistics, or layered contractor dependencies. The probabilistic output of such models enables better contingency planning and stakeholder confidence.

Namazian et al. [4] further advance probabilistic modeling in construction by integrating Monte Carlo simulation with Bayesian Networks to assess project completion time risk. This approach supports financial forecasting and contract structuring by generating a spectrum of potential completion dates, rather than relying on a single fixed timeline. The method is especially useful for megaprojects or PPPs, where time delays can critically erode returns.

Collectively, these studies illustrate how modern risk assessment in construction investment has shifted from reactive contingency planning to proactive, data-informed modeling. Investors now seek to quantify not only the likelihood of adverse events but also their cascading impact on financial feasibility and stakeholder trust, making probabilistic risk assessment essential in high-stakes construction environments.

3.2.3 Financial Modeling

Financial modeling serves as the quantitative backbone of construction investment decisions. It involves assessing the expected return on investment by projecting cash flows, evaluating life-cycle costs, and incorporating financing strategies and sensitivity analyses. While traditional models relied on static projections, contemporary methods account for variable risk profiles, environmental costs, and long-term asset performance under different economic scenarios.

Vagdatli and Petroutsatou [6] review a range of life cycle cost–benefit analysis (LCCBA) approaches applied to road infrastructure, emphasizing the growing use of net present value (NPV), internal rate of return (IRR), and cost-efficiency indicators in infrastructure investment appraisal. Their analysis highlights that model accuracy increases when operation, maintenance, and end-of-life disposal costs are internalized into investment evaluation, a practice becoming increasingly relevant to private and public developers alike.

Henke et al. [7] apply a mixed-method financial evaluation framework to transport sector investments, combining traditional cost-benefit analysis (CBA) with multi-criteria analysis (MCA) to account for social and environmental impacts. Their methodology is particularly relevant for large-scale urban projects and public-private partnerships (PPPs), where financial metrics alone cannot capture full project value. This integrative approach strengthens decision-making under political, economic, and environmental complexity.

Aroquipa and Hurtado [8] contribute a domain-specific model addressing probabilistic seismic risk in building portfolio investments. Their work bridges risk modeling with financial planning by simulating the social and market costs of seismic disruptions. The model's ability to incorporate spatial risk distribution into financial evaluation enhances the resilience of investment decisions in vulnerable urban environments.

Together, these studies reinforce the transition of financial modeling from a narrow accounting tool into a dynamic, risk-sensitive, and socially informed decision support mechanism. Investors are increasingly using these hybrid models to ensure projects are both profitable and adaptable to long-term changes in regulation, climate, and infrastructure use.

3.2.4 Sustainability Considerations

The integration of sustainability considerations into construction investment decision-making has moved from a fringe concern to a central evaluation criterion. Investors are increasingly expected to consider long-term environmental performance, resource efficiency, and societal impact alongside financial return. This shift is largely driven by regulatory developments, ESG (Environmental, Social, and Governance) reporting mandates, and the recognition that sustainable buildings yield long-term operational and reputational benefits.

Kim and Chang [9] propose a construction-specific adaptation of ESG known as C-ESG. Their review identifies critical sustainability indicators at the project level, including carbon emissions, energy intensity, water usage, and community impact. Importantly, they argue for dynamic ESG scoring mechanisms that adjust throughout the project lifecycle, improving transparency and aligning investor priorities with global sustainability standards. This framework helps quantify sustainability in ways that are compatible with financial models and investor decision tools.

Debrah [10] explores the economic feasibility of green buildings using life cycle costing (LCC) in the context of Ghana. The study demonstrates that although upfront costs for green buildings tend to be higher, their life cycle operational savings often exceed conventional designs. This cost-benefit framing strengthens the argument for green construction investment and underscores the importance of considering whole-life performance in the financial appraisal phase.

Liang [11] expands the discussion to financing, exploring instruments such as green bonds and sustainability-linked loans. These financing vehicles are increasingly used to support infrastructure and building projects that meet ESG benchmarks. Liang emphasizes that the credibility of these instruments relies on robust project evaluation frameworks that include measurable sustainability criteria, thus tying sustainability compliance directly to capital market access and investor risk appetite.

Collectively, these works demonstrate that sustainability in construction is no longer a passive label, but an active design and financing principle. Investment decisions that ignore sustainability criteria now risk not only environmental backlash but also financial underperformance in increasingly ESG-conscious capital markets.

3.2.5 Stakeholder Engagement

Effective stakeholder engagement has become a defining factor in the success or failure of construction investment projects. As construction increasingly intersects with public infrastructure, urban development, and community identity, investors must navigate complex networks of actors, including local authorities, private partners, end-users, and civil society

organizations. Modern investment models view stakeholder alignment not only as a risk mitigation strategy but also as a means of generating long-term value, trust, and social license to operate.

Węgrzyn and Wojewnik-Filipkowska [12] examine stakeholder attitudes toward success in public-private partnership (PPP) construction projects. Their findings indicate that clear role definition, shared financial expectations, and early-phase involvement significantly influence project viability and investor confidence. The study demonstrates that misaligned objectives between public authorities and private investors can lead to project delays, contractual disputes, and funding shortfalls.

Hamdan et al. [13] extend this conversation to sustainable urban neighborhood projects, where stakeholder collaboration is essential for balancing ecological goals, economic development, and social inclusion. The authors propose a framework for participatory governance, emphasizing mechanisms such as stakeholder mapping, transparency protocols, and deliberative planning. These collaborative models increase the legitimacy of construction investments and are particularly valuable in contexts where environmental or zoning conflicts might arise.

Together, these studies reinforce the notion that stakeholder engagement is not a peripheral concern but a strategic pillar in construction investment decision-making. Investors now evaluate stakeholder dynamics through structured tools such as influence-interest matrices, engagement audits, and benefit-distribution analyses. Incorporating these techniques improves risk forecasting, accelerates project approvals, and enhances reputational performance in ESG-sensitive environments.

4.SYNTHESIS OF THEMATIC DOMAINS: STRATEGIC INTERACTIONS IN INVESTMENT DECISIONS

Building upon the thematic review in Section 3.2, this section presents a synthesis of how the core domains of construction investment, market analysis, risk assessment, financial modeling, sustainability integration, and stakeholder engagement, interact in shaping investor strategies. Rather than functioning in isolation, these dimensions form a dynamic and interdependent framework, where decisions in one area influence and condition choices in others. Recognizing these interconnections is critical for developing robust, forward-looking investment strategies in an increasingly complex and uncertain built environment.

4.1 Interdependence of Market, Risk, and Finance

Shifts in urban form, land use policy, and demographic dynamics directly shape investment opportunities while introducing new layers of uncertainty. Market volatility, inflationary pressures, and supply chain disruptions now demand that risk assessment is not a secondary phase but integral to early-stage feasibility. Investors must employ dynamic financial modeling tools, such as scenario-based cash flow simulations and probabilistic forecasting to account for the cascading effects of market risks on projected returns. In this interconnected context, static financial models are inadequate; adaptability and continuous recalibration are key to sound investment evaluation.

4.2 Embedding Sustainability and Technology into Financial Logic

Sustainability has become a core determinant of investment viability, not merely a compliance obligation. ESG performance influences not only approval timelines and public perception but also access to financing instruments like green bonds and sustainability-linked loans. Likewise, digital technologies, such as BIM, geospatial intelligence, and AI-enabled risk tools, enable real-time responsiveness to project complexity. When integrated into financial projections, sustainability indicators transform from external benchmarks into measurable, project-critical variables. This fusion of environmental and technological factors enhances both financial viability and long-term strategic value.

4.3 Stakeholder Alignment as Strategic Infrastructure

Investor decisions are increasingly influenced by the alignment, or misalignment, of stakeholder priorities. Regulatory authorities, community actors, and project partners impose expectations that extend beyond financial deliverables. Early and structured stakeholder engagement enhances project credibility, reduces friction in permitting or land acquisition, and mitigates reputational risk. By embedding stakeholder governance into the risk and financial planning processes, investors ensure that social license, institutional alignment, and public acceptance are strategically addressed alongside profitability and sustainability.

5. PROPOSED STRUCTURED FRAMEWORK FOR INVESTOR DECISION-MAKING

5.1 Process Flow and Key Components

The proposed framework for construction investment decision-making is organized as a sequential process integrating critical evaluation domains to enhance decision quality and project resilience. Each step of the process corresponds to a vital component, ensuring that investment decisions are comprehensive, data-driven, and adaptable to evolving project contexts.

The process begins with Market Analysis, where investors define a clear project vision aligned with broader strategic goals such as profitability, sustainability, or social impact. This phase includes identifying target markets, clarifying building function suitability (e.g., residential, commercial, mixed-use), and performing a competitor landscape analysis to highlight market gaps and differentiation opportunities. Detailed geospatial analysis, demographic studies, customer behavior trends, and policy reviews form the foundation of this stage, ensuring that project concepts align with actual market needs rather than relying on generalized assumptions [1][2].

Following market evaluation, the process advances to Risk Profiling and Scenario Planning. Here, probabilistic models, such as Monte Carlo simulations and Bayesian networks, are employed to simulate potential disruptions affecting timelines, costs, or regulatory approvals [3][4]. Risk assessment is not limited to internal project factors but extends to macroeconomic volatility, supply chain instability, and climate resilience [5]. By quantifying the likelihood and impact of risks, investors establish contingency measures early in the project cycle.

The third stage, Financial Feasibility and Flexibility Analysis, builds on market and risk insights to conduct a dynamic appraisal of expected returns, lifecycle costs, and financial

sustainability. Preliminary business model screening, including analysis of potential revenue streams such as rental income, sales proceeds, or mixed-use models, is incorporated early to refine financial expectations. This phase integrates traditional metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR) alongside scenario-based cash flow simulations. Investors also evaluate funding structures, such as the use of green bonds or mixed-financing strategies, to maximize capital efficiency and resilience [6].

Subsequently, Sustainability Integration is performed, embedding ESG (Environmental, Social, Governance) criteria into both project design and operational planning [9]. At this stage, environmental impacts, energy efficiency, social inclusivity, and governance mechanisms are evaluated against recognized frameworks such as LEED, BREEAM, and the EU Taxonomy. Sustainability considerations are treated not as externalities but as core investment value drivers, directly influencing project approval rates, financing costs, and long-term profitability [10][11].

The final critical step involves Stakeholder Engagement Strategy Development. Investors map key stakeholders, assess their influence and interests, and design targeted engagement strategies. Active management of stakeholder relationships, ranging from regulatory authorities and community groups to financial partners and end-users, ensures smoother project delivery and stronger risk mitigation [12][13]. Transparent communication channels, benefit-sharing mechanisms, and adaptive governance structures are prioritized to maintain alignment and trust across all project phases.

The sequential but interconnected nature of this process enables iterative refinement; insights from later stages can prompt recalibration of earlier analyses, fostering a dynamic and responsive investment strategy.

5.2 Implementation Considerations

Successful application of the proposed framework depends on access to high-quality, up-to-date data and the integration of advanced decision-support tools. Geographic Information Systems (GIS) for market analysis, Building Information Modeling (BIM) for design coordination and progress monitoring, and AI-based risk analytics are recommended to enhance decision accuracy and responsiveness [6]. Scenario simulation platforms further enable investors to model project behavior under a variety of macroeconomic and environmental conditions [5].

Flexibility is another critical consideration. Although the framework provides a structured sequence, it must be adapted to the specific scale, location, and type of project. Smaller projects may streamline certain analyses, while larger, more complex developments will require full integration of all components. Investors must also remain vigilant regarding regulatory changes, technological innovations, and shifting stakeholder expectations, updating their assessments accordingly throughout the project lifecycle.

Ultimately, the strength of the proposed framework lies in its ability to combine structured discipline with adaptive capacity, enabling construction investment decisions that are both robust and resilient in the face of growing complexity and uncertainty.

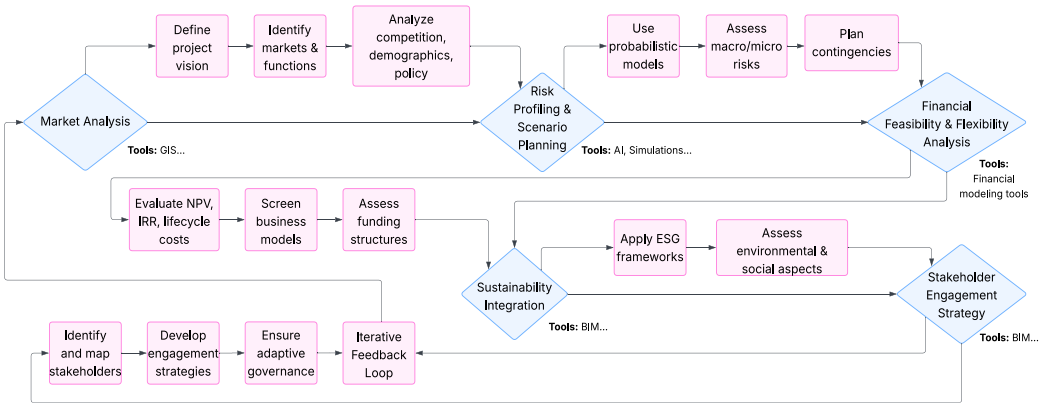


Figure 1. Structured Framework for Construction Investment Decision-Making, drawn by Authors

6. DISCUSSION

The structured investment decision-making framework proposed in this paper addresses a significant gap in contemporary construction project evaluation, namely the lack of integrated models that account for market, financial, risk, sustainability, and stakeholder dimensions in a unified process. By aligning feasibility analysis with evolving technological and regulatory landscapes, this model offers a multidimensional alternative to traditional linear or finance-centric appraisal tools.

In contrast to conventional industry practices, which often isolate financial viability from social, environmental, or stakeholder considerations, the proposed framework emphasizes a holistic, anticipatory approach. Early-stage investment evaluations typically rely on static financial indicators and past benchmarks, with limited integration of dynamic risk modeling, ESG factors, or stakeholder mapping. This narrow focus can lead to underestimation of long-term uncertainties and misalignment with regulatory or community expectations. The framework seeks to overcome these limitations by embedding probabilistic analysis, sustainability metrics, and stakeholder engagement into the core of pre-investment planning.

However, several limitations must be acknowledged. First, the framework assumes a relatively high degree of data availability and investor sophistication. Tools like Monte Carlo simulation or ESG scoring may be unrealistic for smaller developers, public bodies in emerging markets, or informal construction ecosystems. This presents an access barrier that could reinforce disparities in investment quality. Second, the model relies on digital tools (BIM, geospatial forecasting, AI analytics) whose outputs are only as reliable as the input data, raising concerns about transparency and false precision.

Additionally, the framework could be criticized for being normatively optimistic, it presumes stakeholders act rationally and that sustainability and profitability objectives are always reconcilable. In reality, conflict between financial and ESG performance often arises, particularly in time-constrained projects or politically sensitive zones. While ESG scoring provides a valuable structure, it can be gamed or inconsistently applied, leading to greenwashing or unintended exclusions.

To increase utility and inclusivity, future versions should consider a modular scaling system, with simplified templates for resource-constrained investors. Integrating real-time data streams, through IoT sensors, satellite data, or municipal dashboards, could enable more dynamic feedback during decision execution. Finally, to validate the model empirically, it should be piloted in real-world contexts across diverse geographies and project types (e.g., social housing, greenfield infrastructure, or brownfield redevelopment).

Despite these caveats, the framework represents a meaningful advance in how construction investments are conceptualized and assessed. Its structured, adaptive design enables decision-makers to synthesize fragmented insights into a coherent strategy aligned with modern challenges such as climate adaptation, digital transformation, and stakeholder accountability.

7. CONCLUSION

This study presents a structured framework for investment decision-making in construction, grounded in an integrated review of market, financial, risk, sustainability, and stakeholder dimensions. By moving beyond traditional single-focus evaluations, the framework responds to the increasing complexity and interdependence of factors shaping modern development projects.

A key strength lies in its ability to bridge conceptual domains often treated in isolation. Rather than prescribing rigid criteria, the framework offers a flexible architecture investors can adapt based on project scale, regulatory context, or sustainability priorities. This integrative logic positions the model as a forward-looking tool aligning investment strategy with both immediate feasibility and long-term resilience.

Nevertheless, the study is not without methodological constraints. The dual literature review approach, while effective for mapping broad thematic landscapes, is limited by source selection subjectivity and lack of empirical validation. Reliance on secondary data means emergent or context-specific practices may be underrepresented, particularly in under-researched regions or non-English literature. Excluding real-world testing also limits applicability beyond conceptual planning.

Looking ahead, further validation is essential. Future research should focus on field-based applications involving active construction projects to evaluate how the framework performs under real constraints and decision timelines. Mixed-methods studies, combining case implementation with stakeholder interviews, could refine the tool's adaptability and identify operational barriers. Comparative analyses across investment contexts (e.g., public infrastructure vs. private development) would also offer insight into scalability and generalizability.

Ultimately, this paper contributes not a definitive model, but a structured foundation from which more evidence-based, integrated, and context-sensitive investment tools can be developed. As demands on the built environment evolve, so too must the frameworks that guide the decisions shaping it.

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Research paper

URBAN TRANSFORMATION AND RETROMANIA: SUBCULTURES RESHAPING THE AESTHETIC OF SPACE

Damjan Trifunović[1], Jovana Stefanović[2]

Abstract

Contemporary aesthetics is facing an identity issue with being truly original and rather reviving trends from the past. This nostalgia-forward approach to style has made its way to every aspect of human culture, including music, fashion, and ultimately, space. Increasingly, we are witnessing a growing trend of transforming abandoned urban spaces and former industrial sites into aesthetically curated venues, where layers of historical patina merge with contemporary design interventions, creating spaces that are perceived as highly desirable, particularly among young people belonging to specific subcultures. This paper examines this phenomenon, exploring why these groups are drawn to such aesthetics and identifying the key spatial and atmospheric elements that contribute to their appeal. The methodological framework begins with spatial mapping of selected zones across the city, identifying venues that embody specific aesthetic and atmospheric qualities associated with nostalgia and subcultural appeal. This mapping is guided by the principles of affect theory and the concept of retromania, providing a theoretical lens through which spatial and emotional dynamics are interpreted. Following this, a survey is conducted among users and visitors, examining why these spaces are perceived as attractive — whether due to branding, location, physical structure, or other symbolic and experiential factors. Special attention is given to how these elements contribute to emotional attachment and the formation of a sense of belonging within specific social groups. The expected results suggest that distinct patterns or characteristics that define the "vibe" of these spaces will emerge, explaining why young people feel a sense of attachment and belonging in these environments. These elements contribute to the creation of communal spaces where users not only engage with the physical environment but also form emotional connections, reinforcing a sense of collective identity.

Key words: *urban identity, urban regeneration, retro aesthetics, youth, subculture*

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1. INTRODUCTION

Contemporary aesthetics is facing an identity issue with being truly original and rather reviving trends from the past. This nostalgia-forward approach to style has made its way to every aspect of human culture, including music, fashion, and ultimately, space. The term nostalgia, first coined by Johannes Hofer in 1688, derives from the Greek nostos (return) and algos (pain), reflecting a deep emotional yearning for the past [1]. It typically emerges when individuals develop a sentimental longing for previously experienced times, often triggered by both tangible elements (e.g., social groups, possessions) and intangible cues (e.g., olfactory stimuli, music) [2]. In recent studies, it is noted that nostalgia is not merely a psychological phenomenon but also a powerful marketing strategy. It has been demonstrated that nostalgic branding can significantly influence consumer engagement [3]. It is increasingly evident that retro aesthetic tendencies are permeating all aspects of contemporary consumer culture, including the spatial domain—extending even to the branding and identity of places. Notably, we are witnessing a growing trend in which elements of retro aesthetics are employed to transform abandoned urban areas and former industrial sites into intentionally curated venues. These spaces are particularly appealing to younger populations, especially those connected by similar educational backgrounds, cultural interests, social circles, or even subcultural affiliations.

This paper examines this phenomenon, exploring why this specific group of people is drawn to such aesthetics where layers of historical patina merge with contemporary design interventions, creating spaces that they perceive as highly desirable. In the context of urban youth subcultures, it can be posited that individuals belonging to these groups tend to frequent the same urban zones, particularly those outlined earlier. These zones will be systematically identified and catalogued in the initial section of the paper to clarify and structure the subsequent analysis. Through a survey of the target population, the study aims to delineate the key spatial and atmospheric elements that contribute to the appeal of these spaces where young people spend a considerable amount of their time. The expected results suggest that distinct patterns or characteristics that define the "vibe" of these spaces will emerge, explaining why young people feel a sense of attachment and belonging in these environments. The central question extends beyond the visual cues that characterize specific locations, delving into how these spaces evoke emotional attachment among young people. The spatial and atmospheric elements at play facilitate the creation of communal environments where users engage with the physical space while simultaneously establishing emotional connections. This interaction not only reinforces a sense of belonging but also fosters a deeper connection to the urban fabric, contributing to the formation of a collective identity within these spaces. By examining the nuances of these spaces, this study aims to understand the underlying factors that shape youth engagement and attachment in such environments.

The goal of this paper is to give an insight into why, and on what basis, these places are attractive to certain demographics and social groups, along with questioning whether these people belong to a subculture. The presumption was, and will be proven during this research, that these types of places are commonly associated with being visited almost exclusively by young people, and those belonging to some subcultural demographic.

2. RESEARCH METHODOLOGY

The methodological framework begins with spatial mapping of selected zones across the city, identifying venues that embody specific aesthetic and atmospheric qualities, mostly associated with nostalgia and subcultural appeal. The mapping of these urban zones is structured to clearly define spatial entities, particularly those that align with a theoretical lens through which spatial and emotional dynamics will be interpreted [4]. Within these most frequented zones by young people, venues are precisely categorized according to specific qualities.

Following this, a survey is conducted among users and visitors, examining why these spaces are perceived as attractive — whether due to branding, location, physical structure, or other symbolic and experiential factors. Through the analysis of visiting habits, aesthetic preferences, and the level of sense of belonging, the survey explores how these spaces contribute to the formation of identity, collective values, and emotional bonds among youth, particularly in the context of contemporary subcultural patterns. The survey is completely anonymous and consists of 27 questions divided into three sections: visiting habits related to zones, visiting habits related to individual venues, and the general perception of the spaces. This phenomenon can be understood best through the lens of place attachment theory, which emphasizes how personal experiences, social interactions and the physical elements of a place shape one's sense of connection to it.

3. THEORETIC BACKGROUND

As previously stated, one of the key theoretical grounds of this paper is the place attachment theory, also reffered to as The PPP model [5]. It is a theory which refers to the attachment relationship between people and places based on emotion, cognition and practice. The theory has widely shown there are common factors associated behind the reasoning of this phenomenon accuring. Its main arguments are that there are three dimensions crucial to explaining place attachment. Person, which refers to the construct of an individual or group that experienses the attachment, place, which defines the characteristics of places, also by figuring out the ties with people who visit them, and proccess, which deals with the specific interactions of the persons happening in the places. This PPP model was particularly relevant in forming the survey, as it highlights the importance of individuality, the ambience of the place itself, and the interactions that occur in it, all of which are covered within the survey's focus areas.

The way this theory intertwines with the hypothesis of this research is in discovering the motives of people, individuals or groups, to visit certain places or in this case, bars and/or caffees across the city of Belgrade. Few things all of these catering facilities (listed in the survey) have in commmon are their placement across the city (all of the bars/caffees are grouped by location and thereby divided up into zones) and the type of objects which they are located in. Most, if not all of them, are not part of a newly built, standalone building but rather situated inside run down industrial objects or historical buildings, which gives the space a certain aesthetic appeal. In this paper, the elements which cater to space recognition will be systematized and presented through the questions of the distributed survey. As noted before, the main goal was to unravel which elements of these catering facilities resonate the most with its frequent visitors by applying the framework locally.

Therefore, the survey focuses on the emotional aspect in particular, or how people develop a sense of belonging (i.e. feeling at home) in these spaces, which is central to the place attachment theory. It thus served as a means of testing whether the theoretical assumptions about the connections formed between people (identifying with some subcultural values) and places they choose to spend time in, actually held up in practice.

4. SPATIAL ANALYSIS

The study examined the most frequented spaces in Belgrade by young individuals, aiming to identify patterns of spatial preference. Six key zones were defined, each named after prominent spatial landmarks: Zone 1 (Upper Dorćol), Zone 2 (Cetinjska), Zone 3 (National Assembly), Zone 4 (Savamala), Zone 5 (Vračar), and Zone 6 (Gastrošor). Within these zones, a predefined list of venues was established under the assumption that they represent the most frequently visited locations. Notably, the use of open-ended response was minimal, suggesting a clear and defined preference for the listed venues.

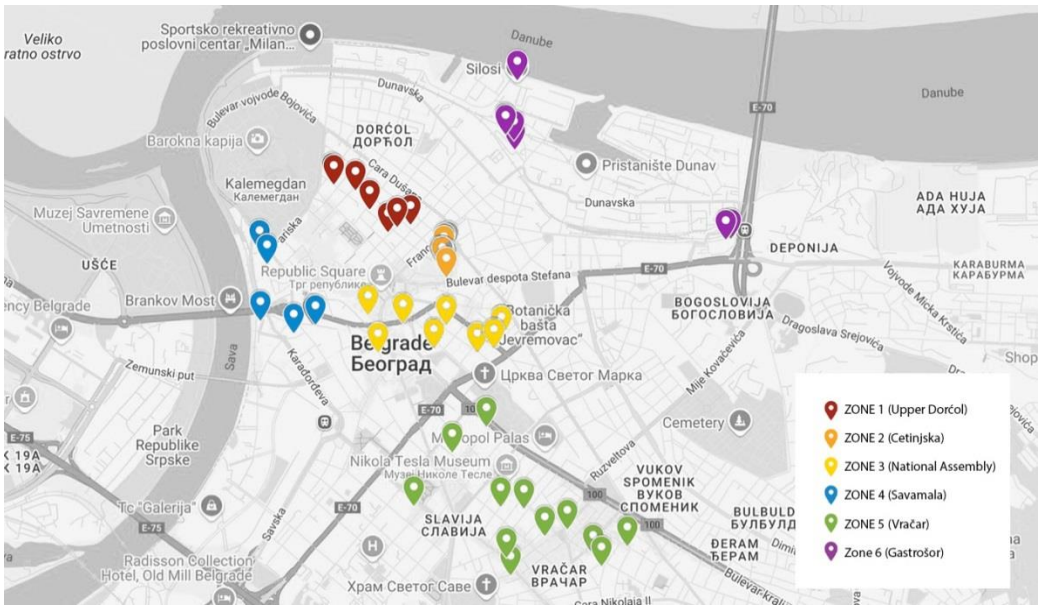


Figure 1. Map of characteristic zones in Belgrade (author: Trifunović, D. 2025)

Within the defined zones, the venues are organised according to spatial units as follows:

- Zone 1: *Meduza, Leila Records, Kuća umetnica, Shsh bar, D59B, Saće, Blaznavac*
- Zone 2: *Dim, Kula, Sprat bar, Zaokret, Polet, Ljubimac, LIFT bar, April bar, Kutijica se za sad zove*
- Zone 3: *Vjeran pas, Ljutić, Bar Vukosava, Restoran tri, Jašta bar, Štrik kafe knjižara, Kafe strip, Guvernanta drinks & decadence, Bife bar*
- Zone 4: *Leposava bar, KC Grad, Čistilište bar, Kafe Šupa, Paradajz Radio*
- Zone 5: *Monks bar, Pržionica, Bistro tri, Chillton bar, Vilidž Bar, Robusta, Single Origin, Kafe Kozmetičar, Liquid Bar&Bistro, Sonder Vračar, Bar Svetozar, Telma*
- Zone 6: *Silosi, Doker Pivara i bašta, Ruke, Dragstor, PolaPola bar, 8 Bar*

It is important to note that these bars and cafés serve as focal points of Belgrade's evolving cultural landscape, where industrial heritage and innovative design converge. Together, through urban revival, they form a network of social and aesthetic hotspots that reflect both the city's storied past and its vibrant, youth-driven present.



Figure 2. Characteristic interior shots photo collage (author: Trifunović, D. 2025)

5. SURVEY RESULTS

Focusing on six defined zones and their catering venues that blend nostalgic aesthetics with contemporary design, this survey examines how young people perceive and relate to these spaces [6]. The contextualisation of the findings within broader social context, was done through examination of the demographic profile of respondents, their professional engagement and subcultural affiliations. This was crucial for interpreting how various groups experience and value retro-inspired environments.

The survey participants represented various genders (31% male, 65% female, and 4% other) and age groups. The largest proportion of respondents was within the 24-30 age range (71%), followed by the 18-23 group (23%), and the smallest group was from 31-35 years old (6%). Half of the respondents (50%) were professionally engaged in creative, artistic, or creative fields, while 23% pursued these activities as hobbies, and 17% did so occasionally or on an amateur basis. The largest proportion of respondents (46%) worked in architecture, urbanism, or design, while 34% were involved in visual arts. Other fields represented included: academia (19%), IT (13%), activism (13%), marketing (11%), craftsmanship or manual work (10%), performing arts (9%), music (8%), retail (8%), law, and administration (4%).

In terms of subcultural affiliation, 48% of respondents stated they did not feel a connection to any particular subculture, while a significant portion expressed a strong sense of belonging (20%) or a partial connection (32%). Some of the most prominent social groups among respondents included: the LGBTQ+ and queer community, alternative scenes (rock, metal, punk), skateboarders, as well as the theatre community, hipster culture, and the clubbing scene.

5.1 Visiting habits evaluation by zone

The survey is structured to progressively unpack spatial engagement, beginning with broad evaluative criteria and narrowing to venue-specific dynamics. This dual analysis of macro and micro scales places comprehensive patterns of spatial use alongside recognized local specificities. The second segment of the survey quantifies visit frequency, duration and underlying motivations across each of the six predefined urban areas, enabling a meso-level analysis of spatial engagement.

The results show that the zones most frequently visited by respondents were Zone 1 (Gornji Dorćol) (57%) and Zone 2 (Cetinjska) (49%). The least frequently visited zones were Zone 6 (Gastrošor) (49%) and Zone 4 (Savamala) (42%). Zone 5 (Vračar) showed mixed responses, with 51% of respondents considering it one of the most visited zones, while 21% stated it was one of the least visited. Regarding the frequency of visits to spaces within these six zones, respondents visit them multiple times a week (57%), once a week (16%), multiple times a month (16%), or once a month (10%). The responses indicate a range of interrelated reasons for frequent visits to these specific urban zones.

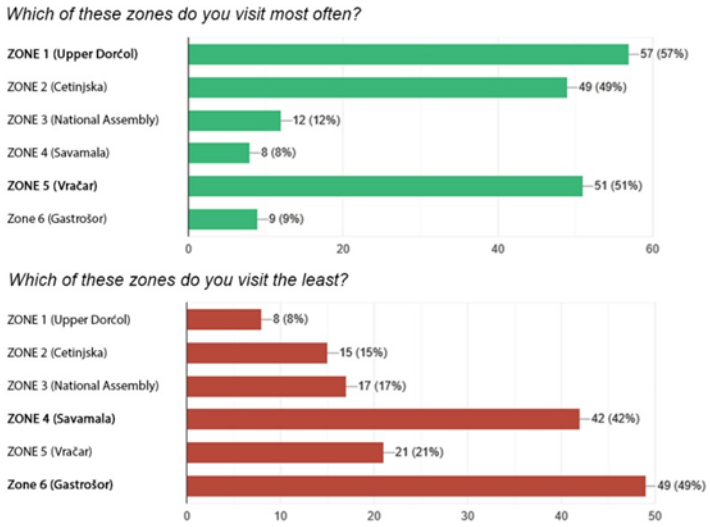


Figure 3. Visiting habits defined by zones, survey results (2025)

Qualitative analysis identified several thematic categories explaining the frequent visits. The most prominent category relates to the atmosphere and ambiance (36%), with respondents highlighting the relaxed, pleasant, homely warmth, and overall "chill" vibe of the spaces. Spaces were often described as unobtrusive and familiar, fostering a sense of belonging and comfort, with some participants even comparing them to the atmosphere of home. Proximity and accessibility (19%) were another significant factor, with respondents choosing spaces based on their physical proximity to everyday routines—such as home, university, or work—and ease of access through public transport. The third category, aesthetic appeal (17%), reflects respondents' preferences for spatial expression and coherence, particularly in the context of alternative and retro aesthetics. There was positive feedback regarding spaces that avoid dominant gentrification patterns and maintain a consistent interior identity. In the category of social factors and sense of belonging (21%), responses emphasized the importance of social identification with other visitors. There was a clear tendency to seek environments where like-minded individuals gather, contributing to a sense of community and social security. Finally, the programmatic and functional offer (15%) included elements such as quality coffee, a variety of drinks, music, as well as spaces suitable for work (e.g., laptop-friendly), gardens, and terraces. These features make the spaces attractive for longer stays and spontaneous social gatherings.

The top 3 most visited venues per zone are as follows:

- Zone 1 – Blaznavac (49%), Meduza (35%) i Leila (23%)
- Zone 2 – Zaokret (59%), Lift (43%), Ljubimac (40%)
- Zone 3 - Vjeran pas (49%), Restoran Tri (34%) i Bife bar (15%)
- Zone 4 – KC Grad (61%), Leposava bar (37%), Kafe Šupa (25%)
- Zone 5- Monks bar (46%), Bistro Tri (27%), Vilidž bar (22%)
- Zone 6 – Silosi (53%), Dragstor (42%) i Ruke (36%)

5.2 Visiting habits evaluation by individual venues

The third segment examines venue-specific patronage criteria, probing how factors such as spatial layout, nostalgic cues and social ambience drive micro-scale patterns of use and attachment. Regarding the habits of using these spaces for leisure or work, 48% of respondents use these spaces for socializing and going out multiple times a week, while only 9% of respondents use these spaces for work multiple times a week. Based on the analysis of the responses, the three most frequently mentioned venues that respondents use or would use as workspaces are Zaokret (13%), Bistro Tri (10%), and Leposava (9%).

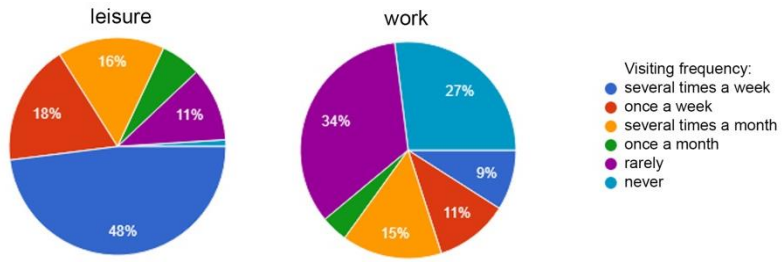


Figure 4. How often do you use these spaces for leisure or work?, survey results (2025)

For other purposes, such as personal artistic or creative activities, only 16% of respondents have occasionally used these spaces, while only 4% do so regularly. The most frequently mentioned contexts are exhibitions, performances, or workshops/courses. Venues such as Polet and KC Grad stand out as the most frequently mentioned in this regard. A significant 51% of respondents stated that the appearance of the spaces they visit is very important or moderately important (48%). For 82% of respondents, the most important criterion when choosing a venue for going out or staying is the ambiance/interior design, followed by location and accessibility (66%) and the type of clientele visiting the venue (62%).

5.3 Place attachment

The expected result was confirmed by the survey, with 75% of respondents indicating an emotional connection to one or more of the spaces. The main reasons for this connection include events and experiences in these spaces (72%), the atmosphere and ambiance (63%), and the people they have met (44%). A noteworthy proportion of respondents also emphasized a sense of belonging to a particular social group (30%) and shared ideological or cultural values (24%).

Furthermore, 84% of respondents strongly believe that these spaces contribute to the formation of a collective identity among specific youth groups [7]. In order to qualitatively examine a deeper articulation of place attachment, the survey included a set of questions that aimed to provide a more precise insight into the duration, intensity, and complexity of the emotional bond with these spaces. Respondents were asked, *"To what extent do the following statements apply to the spaces you frequently visit?"*

The statements were designed to measure various aspects of the respondents' feelings of closeness to these spaces:

A. *I feel relaxed and "at home" in this space* (Intimacy and emotional comfort);
B. *I feel that this space is familiar and close to me* (Recognition and continuity – spatial familiarity);
C. *This space gives me a sense of security and acceptance* (Social security and emotional stability);
D. *When I am here, I feel that I belong to this environment* (Sense of belonging and identification with the community)

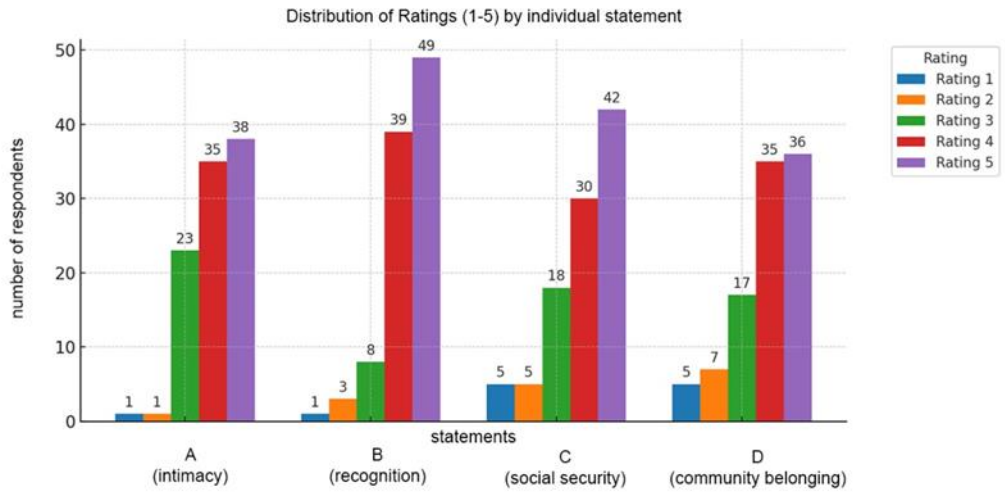


Figure 5. Distribution of ratings (1–5) for place attachment statements, survey results (2025)

Although these statements may appear similar, each one touches upon slightly different aspects of attachment to the space. On a scale of 1 to 5, where 5 represents the most positive rating, the most common responses were as follows:

- *I feel relaxed and "at home" in this space* (average rating: 4.06, rating 5 by 38% of respondents);
- *I feel that this space is familiar and close to me* (average rating: 4.32, rating 5 by 49% of respondents);
- *This space gives me a sense of security and acceptance* (average rating: 3.99, rating 5 by 42% of respondents);
- *When I am here, I feel that I belong to this environment* (average rating: 3.90, rating 5 by 36% of respondents)

6. CONCLUSION

Based on the questionnaire and theoretical analysis, it can be concluded that emotional attachment constitutes a significant determinant in the selection of urban spaces for both work and casual social gatherings. Equally critical, however, are the aesthetic qualities of these environments and the sense of belonging they foster. This effect is particularly visible among subcultural communities, for whom spatial identity and affective resonance are inseparable from venue choice. The concensus states that young people care deeply about the ambient properties of the physical enviroment they socialise, create or work in. In fact, the results speak strongly about the importance they see in the spatial elements of these places, and how specific ambients are what they seek, especially those found in the proposed physical structure and city zones.

The connection between individuals and the spaces they frequent plays a crucial role in shaping their perception and experience of the urban environment. Emotional connections are formed through repeated interactions with these spaces [8], contributing to a sense of community and collective identity. Additionally, the aesthetic qualities, ambiance, and functionality of the space were found to influence the degree of attachment, with factors such as interior design, atmosphere, and social dynamics playing significant roles.

This study contributes by applying the PPP model to retro-inspired urban spaces in Belgrade, demonstrating that nostalgic atmospheres actively shape youth subcultural identity. Practically, these findings suggest that designers can enhance social cohesion and cultural vitality by integrating carefully curated nostalgic elements (such as lighting schemes, material textures and thematic décor). By fostering environments that resonate emotionally and support vibrant social networks, cities can sustain subcultural vitality and enrich the collective urban experience.

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Research paper

TROPOSPHERIC INFLUENCE IN GNSS POSITIONING

Sanja Tucikešić[1], Tanja Đukanović[2], Ankica Milinković[3], Branko Božić[4]

Abstract

Atmospheric influences, mainly caused by ionospheric and tropospheric conditions, lead to delays and distortions of GNSS signals that travel from satellites to receivers on Earth. This impact must be considered for projects that require high positioning and navigation accuracy. The troposphere dominates in areas with a large amount of water vapour and can also cause measurement errors due to changes in signal propagation speed. In this work, the tropospheric influence on GNSS positioning was analysed. The focus is on their cause, how they affect the accuracy of GNSS measurements, and the methods and technologies used to reduce or eliminate this influence. A 3D geodetic network of permanent stations was levelled using different empirical tropospheric models. Understanding and correcting these factors are important for improving GNSS technology's accuracy, reliability and practical use in modern geodetic and scientific research. The tropospheric delay is usually modelled in the zenith direction and is called the zenith tropospheric delay. As the zenith angle increases, the delay itself increases. So-called reduction functions obtain the relationship between the zenith and oblique delays. The GNSS-Lab Tool software and data collection and processing methods were used to calculate and obtain the zenith tropospheric delay (ZTK) value.

Keywords: *global navigation satellite system, the network of permanent stations, atmosphere, troposphere, tropospheric models, mapping functions*

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1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are a collective name for all systems that deal with positioning and navigation using artificial satellites. GNSS are based on a technique called trilateration, which is the determination of the position of an unknown point based on measuring its distance to points with known positions, or coordinates. The atmosphere is defined as the region that surrounds the Earth from sea level to about 1000 km in altitude, with different physical and chemical properties. The atmosphere has various effects on our planet: on the shape, rotation and gravitational field of the Earth [1]. When considering the influence of the atmosphere on the measurement results in satellite geodesy, the atmosphere is divided into two basic layers, the troposphere and the ionosphere. The troposphere is the lower part of the Earth's atmosphere, which extends to a height of about 15 km (depending on geographical location). This part of the atmosphere consists of dry gases and water vapour [2], which can cause measurement errors due to changes in signal propagation speed. The stratosphere is much more stable and less turbulent, and therefore, the electromagnetic waves of GNSS signals experience practically no significant delays or changes as they pass through this layer of the atmosphere [3-5].

Among the many sources of errors affecting and reducing GNSS measurements' accuracy, tropospheric refraction is considered one of the most significant. GNSS signal propagation errors occurred amid ionospheric influences, eliminating the use of dual-frequency transmissions. Being a refractive layer, the troposphere delays the GNSS signal. Its temperature decreases with altitude, its thickness also varies with latitude, and it contains 90% of the atmospheric mass. The troposphere is an environment that is not dispersive for the frequencies used in the GNSS system (<30 GHz) and is made up of neutral atoms and molecules [6], which is why tropospheric refraction, unlike ionospheric influences, cannot be eliminated using dual-frequency receivers. The delay value caused by the troposphere during signal propagation is identical at all frequencies and all types of measurement. Tropospheric delay is characterised by a refractive index that can be divided into two parts, i.e. are a dry and a wet component.

Many studies have been carried out to create and test tropospheric refraction models for calculating the refractivity along the signal propagation path. Saastamoinen (Saastamoinen, 1972), Hopfield (Hopfield, 1969), Goud and Goodman (1974) and Black (1978) stand out as the most significant researchers and originators of the theory of empirical tropospheric modelling, of which the Saastamoinen and Hopfield model stands out as the most commonly used in practice. These models typically calculate the zenith delay (for elevation angle = 0) and then use a mapping function to obtain the total tilt delay, depending on the satellite elevation angle [7].

The permanent GNSS network of Bosnia and Herzegovina, BiHPOS, consists of two subnetworks: SRPOS (managed by the Republic Administration for Geodetic and Property-Legal Affairs of the Republic of Srpska) and FBiHPOS (managed by the Federal Administration for Geodetic and Property-Legal Affairs of the Federation of BiH). Both permanent GNSS networks of BiHPOS have been active and available to users since 27.09.2011. They are based on the same hardware and software solutions, which enable full system compatibility and data exchange. The networks of permanent GNSS stations enable fast and reliable determination of point coordinates for geodetic positioning, surveying, establishment and reflection of the real estate cadastre, and other applications in engineering geodesy [8].

The subject of the work is to perform an analysis of a levelled 3D geodetic network of permanent stations using different empirical tropospheric models. Despite the well-documented impact of the troposphere on GNSS signals and the existence of various correction models, there is a research gap regarding a comprehensive comparison of different empirical models (Hopfield, modified Hopfield, and Saastamoinen) and their specific influence on the levelling of a 3D geodetic network of permanent stations in a particular geographical area like Bosnia and Herzegovina's BiHPOS network. Furthermore, a detailed analysis of how geographical location and altitude directly affect the values of the zenith tropospheric delay (ZTD) using data from local networks such as SRPOS has not been sufficiently explored. Based on these considerations, the main hypothesis of this work is that the application of empirical tropospheric models significantly improves the accuracy of coordinates, especially the height component, compared to levelling without any model, with the greatest differences observed over longer baselines. The secondary hypothesis is that the value of the zenith tropospheric delay (ZTD) is directly dependent on the altitude of the permanent station: with increasing altitude, the ZTD values decrease proportionally.

Alignment will be done in the global WGS84 system, with subsequent transformation of the aligned coordinates into the national coordinate system (DKS) with special emphasis on applying the same observation plan when processing vectors with different tropospheric models.

The tropospheric delay is usually modelled in the direction of the zenith and is called the zenith tropospheric delay. As the zenith angle increases, the delay itself increases. The Niell Mapping reduction function is used to obtain the relationship between the zenith delay and the slant delay. The paper will also calculate the zenith tropospheric delay for three stations of the SRPOS network of permanent stations for a multi-day observation period, with the help of the appropriate gLAB software.

2. MATERIALS AND METHODOLOGY

2.1. Study of the area

In the Republic of Srpska, the SRPOS network of permanent stations is active, consisting of 23 permanent stations, evenly distributed at distances of 35-50 km from each other. To ensure better network geometry, the SRPOS network also receives data from 12 stations of the FBiHPOS network and 9 stations from surrounding countries (Croatia, Serbia and Montenegro). Also, in addition to SRPOS, there is the newly established GiCORS network of permanent stations, which was installed in 2022. Three permanent stations of the SRPOS network were used in the work: Banja Luka, Teslić and Derventa (Figure 1) and three stations of the GiCORS network: GIBL (Banja Luka), GIDE (Derventa) and GITE (Teslić).

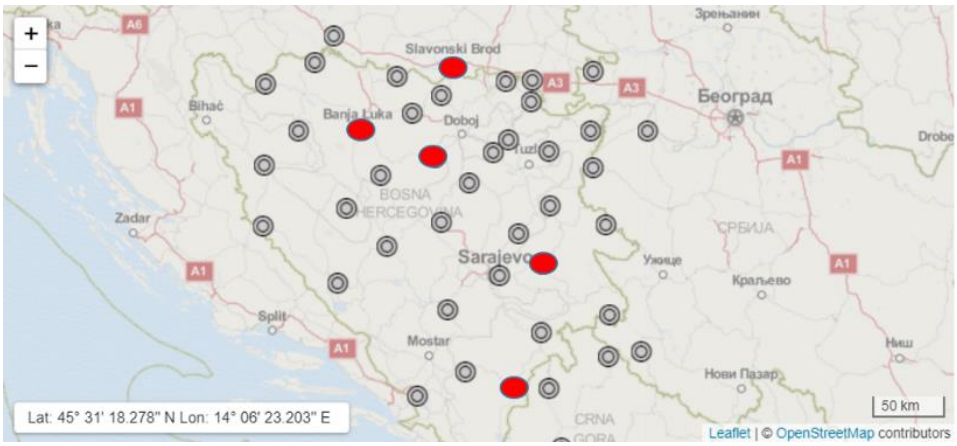


Figure 1. Locations of SRPOS permanent stations within the BiHPOS network [9]

2.2. Input data

The precise positioning method (PPP) was used for data processing. RINEX raw observations for individual stations, SP3 files with precise ephemeris for the corresponding day and ANTEX files with data on the deviations of the phase centres of receiver and satellite antennas are used as input data for the mentioned type of processing.

RINEX raw observations were taken from the Republic Administration for Geodetic and Property Legal Affairs in Banja Luka, for SRPOS permanent stations Banja Luka, Derventa and Teslić. The data referred to the measurement period of five consecutive days, from August 8, 2020, to August 12, 2020. The length of the measurement session at the mentioned stations was 24 hours, for a data registration interval of 15" and a limiting vertical angle of 10°. Observations were also taken from the stations of the GiCORS network, i.e. GIBL (Banja Luka), GIDE (Derventa) and GITE (Teslić). The observations refer to a twenty-four-hour period, from 00:59:45 hours on August 9 until 00:59:30 on August 10, 2020.

To examine the influence of geographical location and altitude, raw data were downloaded for SRPOS permanent stations Banja Luka (214 m a.s.l.), Teslić (270 m a.s.l.), Brod (150 m a.s.l.), Gacko (1016 m a.s.l.) and Sokolac (944 m a.s.l.). Data were taken for one measurement day, April 23, 2015.

Precise ephemerides are downloaded in standard SP3 format. The download was made from the official website of the International GNSS Service (IGS) for the necessary periods for which the observations are analysed. A separate, corresponding SP3 file is loaded for each measurement day.

ANTEX files provide data on antennas, that is, on deviations of the phase centres of receiver and satellite antennas, and were downloaded from the official website of the National Geodetic Survey (NGS) belonging to the American National Oceanic and Atmospheric Administration (NOAA).

For the given task, 5 independent vectors were formed between six permanent stations (Figure 2).

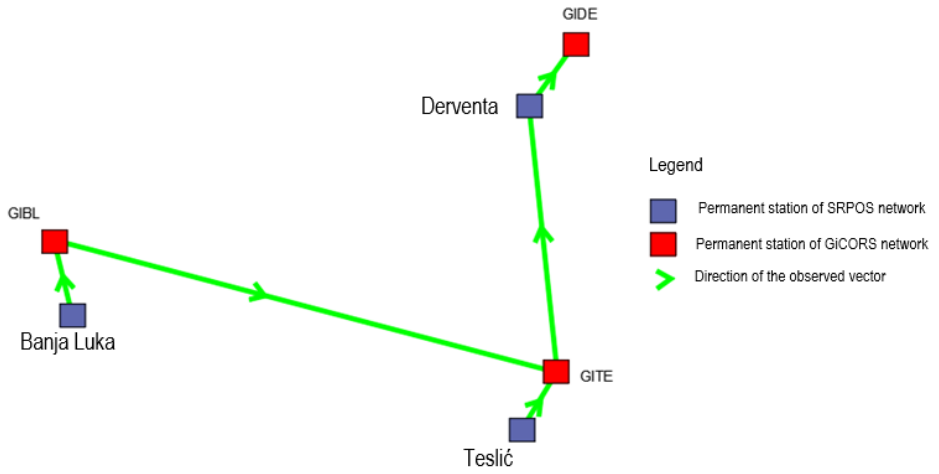


Figure 2. Representation of GNSS vectors selected for basic mathematical processing

2.3. Tropospheric refraction of GNSS signals

Tropospheric refraction parameters are evaluated during GPS positioning according to:

$$\mathrm{ZTD}=\mathrm{ZHD}+\mathrm{ZWD} \tag{1}$$

which contains the following members: ZTD is Zenith Total Delay, ZHD is Zenith Hydrostatic Delay, and ZWD is Zenith Wet Delay. The dry component or hydrostatic part has a slow time variation, so it is modelled and used as an a-priori value while the wet component or ZWD is evaluated in the parameter estimation procedure. The most commonly used models for the ZHD component are the ECMWF (European Centre for Medium-Range Weather Forecasts) or the GPT (Global Pressure Temperature) model [10].

2.3.1. Models for correcting hydrostatic tropospheric delay

The hydrostatic (dry) zenith delay can be accurately calculated a priori from the surface pressure and the station latitude and altitude [11], using the Saastamoinen and Hopfield model [4, 5]. If meteorological data are not available, values derived from the standard atmosphere are used instead. The hydrostatic component of the delay accounts for about 90% of the total delay. For smaller wet zenith delays, there is no exact model to obtain an a priori value. Therefore, this component is usually included as an unknown parameter in the observation equations and is estimated as such in the PPP processing. This parameterisation can be further improved by including horizontal gradients [12-15], which primarily improves the latitudinal component at the millimetre level [16].

Saastamoinen developed a model based on surface pressure measurements and the latitude and altitude of the station. In his model, he adopts the Essen and Froome (1951) refractive constant. The expression for calculating the hydrostatic zenith delay is:

$$ZHD_{[m]} = \frac{0.0022768 * \rho_{0[mbar]}}{1 - 0.00266 * cos\varphi - 0.00028 * H_{[km]}} \tag{2}$$

where: ρ_0, total pressure at the station; φ, latitude of the station, and и H, orthometric height of the station.

Hopfield uses a quartic model based on temperature and altitude, representing the hydrostatic refractivity by a fourth-degree curve, and the Smith and Weintraub (1953) refractive constant:

$$ZHD = \frac{10^{-6}}{5} N_H h_H \quad (3)$$

where: N_H, hydrostatic refractivity and h_H, temperature-dependent hydrostatic height (h_H=40082-0.14898*(T -273.16)).

In addition to the basic Hopfield model, there is a modified version of it, where the lengths of the position vectors are introduced instead of heights, and the expression is obtained:

$$N_d(r) = N_{ds} * \left(\frac{r_d - r}{r_d - Rz}\right)^4 \quad (4)$$

where: Rz is the radius of the Earth, and the lengths r_d and r can be obtained as the sum of the radius and the corresponding heights, *H* (the height corresponding to the humid part of the atmosphere) and *Hd* (the height corresponding to the dry part of the atmosphere):

$$r_d = Rz + Hd \quad (5)$$

$$r = Rz + H \quad (6)$$

2.3.2. Models for correcting wet tropospheric delay

Moist delay models have lower accuracy than hydrostatic delay models. This is since the characteristics of water vapour vary greatly in time and space, which significantly complicates the modelling of the moist component of refraction. Therefore, detailed research has been conducted to define an a-priori value of the moist zenith delay, but it has been determined that an accuracy of determination better than a few centimetres cannot be achieved. [17].

Saastamoinen's model assumes that temperature and water vapour decrease linearly with increasing altitude. He uses the same refractive constant as in the hydrostatic delay model. Therefore, Saastamoinen's expression for calculating the wet delay model is:

$$ZWD = 0.002277 * \left(\frac{1255}{T_s} + 0.05\right) * e_s \quad (7)$$

where: T_s, the temperature at the Earth's surface and e_s, the water vapour pressure at the Earth's surface.

Hopfield gives an expression using the wet component Nws from Smith and Weintraub (1953):

$$d_w^z = 10^{-6} N_{ws} \frac{H_w^e}{5} \quad (8)$$

2.4. Neill mapping reduction function (NMF) for tropospheric modelling

Tropospheric delay is the smallest in the zenith direction. With increasing zenith angle, the tropospheric delay itself increases. Reduction functions serve to give the relationship between zenith delay and oblique delay.

Due to the lower accuracy of determining a-priori wet delay models compared to dry delay models, the same principle is applied to reduction functions. That is, determining the total reduction function would not satisfy the needs of precise positioning, and therefore, the wet delay reduction functions and the hydrostatic delay reduction functions are most often studied

separately. The Niell reduction function was used in the paper. Although it was defined in 1996, the Niell reduction function is still used today in many GNSS software because it is independent of atmospheric parameter measurements. The advantage of this function over others is that it provides accurate positioning results for receivers located between 43° and 75° north latitude, for a minimum elevation angle of 3°.

The Niell reduction function is [18]:

$$m(E) = \frac{1+\frac{a_i}{1+\frac{b_i}{1+c_i}}}{sinE+\frac{a_i}{sinE+\frac{b_i}{sinE+c_i}}} + \left(\frac{1}{sinE} - \frac{1+\frac{a_{ht}}{1+\frac{b_{ht}}{1+c_{ht}}}}{sinE+\frac{a_{ht}}{sinE+\frac{b_{ht}}{sinE+c_{ht}}}} \right) * \frac{H}{1000} \quad (9)$$

where a_i, b_i and c_i are the parameters of the hydrostatic or wet reduction function. a_{ht}, b_{ht} and c_{ht} are the constant values of the height correction, and are $a_{ht} = 2{,}53 * 10^{-5}$, $b_{ht} = 5{,}49 * 10^{-3}$ and $c_{ht} = 1{,}14 * 10^{-3}$. *H* is the orthometric height of the receiver in meters. The height correction is applied only to the hydrostatic NMF, and the values of the coefficients a_i, b_i and c_i are shown in Tables 1 and 2 [18].

Table 1. Coefficients of the hydrostatic mapping function

Coefficient	Latitude				
	15°	30°	45°	60°	75°
a	0	$1.271*10^{-5}$	$2.652*10^{-5}$	$3.400*10^{-5}$	$4.120*10^{-5}$
b	0	$2.142*10^{-5}$	$3.016*10^{-5}$	$7.256*10^{-5}$	$11.723*10^{-5}$
c	0	$9.013*10^{-5}$	$4.350*10^{-5}$	$84.795*10^{-5}$	$170.372*10^{-5}$

Table 2. Coefficients of the wet mapping function

Coefficient	Latitude				
	15°	30°	45°	60°	75°
a	$5.802*10^{-4}$	$5.679*10^{-4}$	$5.812*10^{-4}$	$5.973*10^{-4}$	$6.164*10^{-4}$
b	$1.428*10^{-3}$	$1.514*10^{-3}$	$1.457*10^{-3}$	$1.457*10^{-3}$	$1.457*10^{-3}$
c	$4.347*10^{-2}$	$4.347*10^{-2}$	$4.391*10^{-2}$	$4.453*10^{-2}$	$5.474*10^{-2}$

3. RESULTS

3.1. 3D levelling using various tropospheric models

In the first practical part of the work, data from six permanent stations were processed using the commercial software package Leica Geo Office (LGO). Three permanent stations are related to the SRPOS network of permanent stations, and three to the GiCORS network. The adjustment is performed using the least squares method using a mathematical model that implies a functional and stochastic model and a network datum. The network datum is defined by the coordinates of the SRPOS permanent station Banja Luka, fixing its given values.

The adjustment of the appropriate tropospheric model, without a tropospheric model, the Hopfield model, the modified Hopfield model and the Saastamoinen model, is performed before the processing of each vector. To ensure the validity of the obtained results, 3D

adjustment was performed for all tropospheric models according to the same observation plan.

As a result of processing, individual reports are obtained for each vector. The reports include basic data on the processing performed, such as data on observed points, processing parameters, observation quality ratings, approximate coordinates, etc. After alignment, the final coordinates were transformed from the WGS84 system to the State Coordinate System (DKS), i.e. the sixth zone of the Gauss-Krüger projection, using the seven-parameter Helmert transformation model (Tables 3, 4, 5, and 6). Given that the subject permanent stations are located at three separate "microlocations" (the city of Banja Luka, the municipality of Teslić, and Derventa), transformation parameters were created for each of these locations.

Table 3. Coordinates of permanent stations without an applied tropospheric model

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.537	4961077.384	175.015
Derventa	6493077.446	4981380.852	171.753
GIDE	6493110.139	4981501.583	158.070
GITE	6489304.095	4939854.012	217.911
Teslic	6489078.093	4939593.253	224.797

Table 4. Coordinates of permanent stations with the applied Hopfield model

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.025
Derventa	6493077.388	4981380.818	171.771
GIDE	6493110.081	4981501.549	158.077
GITE	6489304.040	4939854.034	217.981
Teslic	6489078.039	4939593.274	224.874

Table 5. Coordinates of permanent stations with the modified Hopfield model applied

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.026
Derventa	6493077.389	4981380.818	171.770
GIDE	6493110.082	4981501.549	158.074
GITE	6489304.041	4939854.033	217.988
Teslic	6489078.040	4939593.273	224.881

Table 6. Coordinates of permanent stations with the Saastamoinen model applied

Station	Y [m]	X [m]	H [m]
Banja Luka	6438923.345	4959040.676	168.936
GIBL	6437304.540	4961077.382	175.025
Derventa	6493077.389	4981380.818	171.771
GIDE	6493110.082	4981501.549	158.077
GITE	6489304.040	4939854.034	217.981
Teslic	6489078.039	4939593.274	224.874

The values obtained with the different tropospheric models applied were first compared with those obtained without using the tropospheric model, and then a mutual comparison of the results obtained from the different models was performed (Tables 7 and 8).

Table 7. Differences in coordinates obtained by comparing coordinates without models with different models

	Without troposphere-Hopfield			Without troposphere-modified Hopfield			Without troposphere-Saastamoinen		
Station	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]
Banja Luka	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GIBL	-0.3	0.2	-1.0	-0.3	0.2	-1.1	-0.3	0.2	-1.0
Derventa	5.7	3.4	-1.8	5.7	3.4	-1.8	5.7	3.4	-1.8
GIDE	5.7	3.4	-0.6	5.7	3.4	-0.4	5.7	3.4	-0.6
GITE	5.5	-2.2	-6.9	5.5	-2.2	-7.6	5.5	-2.2	-7.0
Teslic	5.4	-2.1	-7.7	5.3	-2.0	-8.3	5.4	-2.1	-7.7

Table 8. Differences in coordinates obtained by comparing the coordinates different models

	Hopfield - modified Hopfield			Hopfield - Saastamoinen			Saastamoinen - modified Hopfield		
Station	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]	Y [cm]	X [cm]	H [cm]
Banja Luka	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GIBL	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	-0.1
Derventa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
GIDE	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2
GITE	0.0	0.1	-0.7	0.0	0.0	-0.1	0.0	0.1	-0.6
Teslic	-0.1	0.1	-0.7	0.0	0.0	-0.1	-0.1	0.1	-0.6

3.2. Determination of zenith tropospheric delay

In the second part of the paper, the zenith tropospheric delay (ZTD) was calculated for the permanent stations of Banja Luka, Teslić and Derventa, during a measurement period of 5 days. The dependence of ZTD on the geographical position, i.e. the altitude of the measuring station, was also examined. ZTD was determined for the permanent stations of Banja Luka (214 m a.s.l.), Teslić (270 m a.s.l.), Brod (150 m a.s.l.), Gacko (1016 m a.s.l.) and Sokolac (944 m a.s.l.). The calculation was performed using the specialised GNSS-Lab Tool, abbreviated as gLAB.

This software package is used for precise modelling of GNSS observations. Observations of the SRPOS network stations were performed using the PPP method. The software used consists of five basic modules that are passed through to obtain the desired final results: Input, Preprocess, Modelling, Filter and Output. The corresponding RINEX, SP3 and ANTEX files are imported. The loading is done separately for each measurement day, with the selection of the appropriate precise ephemeris, while ANTEX is the same for all permanent stations in question.

In the Modelling module, the Simple Nominal option with the Niell reduction function is selected because, in this case, the tropospheric correction is significant. The Simple Nominal model is a global tropospheric model that does not require meteorological data for modelling.

Table 9 shows the averaged values of the tropospheric zenith delay for the permanent stations Banja Luka, Teslić and Derventa.

Table 9. ZTD values for the period 08.08.2020-12.08.2020. year

Date →	08.08.2020.	09.08.2020.	10.08.2020.	11.08.2020.	12.08.2020.
Station	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]	Average ZTD [m]
Banja Luka	2.494	2.465	2.461	2.506	2.476
Derventa	2.486	2.455	2.459	2.495	2.461
Teslic	2.480	2.453	2.453	2.447	2.472

To determine the dependence of ZTD and altitude, the same methods described above were used to calculate ZTD for the lowest permanent station in the SRPOS network (Brod – 150 m a.s.l.), as well as the two highest permanent stations (Sokolac – 944 m a.s.l. and Gacko 1016 m a.s.l.). Given that, based on previous data, it was determined that there were no significant deviations in determining ZTD on consecutive measurement days, the data were taken and the analysis was carried out for one measurement day, 23.04.2015. Table 10 presents the obtained results of determining ZTD for the permanent stations Banja Luka, Teslić, Gacko, Brod and Sokolac. There are no measurement data for the permanent station Derventa for the specified day.

Table 10. ZTD values on April 23, 2015. year

Station	Station altitude [m]	Average ZTD [m]
Banja Luka	214	2.408
Brod	150	2.418
Teslic	270	2.367
Gacko	1016	2.145
Sokolac	944	2.187

4. DISCUSSION

The GNSS network consisted of six permanent stations, three belonging to the SRPOS network of permanent stations of the Republic of Srpska and three belonging to the private GiCors network of permanent stations. Raw observations in RINEX format were downloaded for the above stations. The downloaded observations refer to a twenty-four-hour period during August 8 and 9, 2020.

Based on the results in Table 7, it is visible that there is a significant difference in the calculation of coordinates without tropospheric corrections and using tropospheric models. The application of tropospheric models led to a significant improvement in the accuracy of coordinates, especially for the height component, compared to processing without a model. For longer baselines (over 50 km from the reference station), these differences reached up to 5.7 cm along the positional axes and 8.3 cm for the height component. In contrast, for the GIBL station, located only 2.6 km from the Banja Luka station, the differences were minimal,

measuring up to 0.3 cm on the positional axes and 1.1 cm in height. The difference is especially pronounced for permanent stations located at greater distances from the permanent station Banja Luka, whose values were taken as known (fixed) in the smoothing. The permanent station GIBL, located 2.6 km from the Banja Luka station, did not show significant deviations with and without the use of tropospheric corrections (up to 0.3 cm along the positional coordinate axes and up to 1.1 cm along the height). The remaining permanent stations are located at distances greater than 50 km from the Banja Luka station, and their coordinates change significantly with the use of tropospheric models, in the range of 2.2 cm - 5.7 cm along the coordinate axes and from 0.6 cm - 8.3 cm along the height. The values in Table 8 show the mutual relationships of the coordinates obtained by using different tropospheric models. From the obtained results, it is evident that all models give approximately the same results, with special emphasis on the Hopfield and Saastamoinen models, where differences were obtained only for two permanent stations, in the value of 0.1 cm. On the other hand, the modified Hopfield model shows slightly larger deviations than the other two models, especially in terms of height for the permanent stations Teslic and GITE, where differences of 0.6 cm and 0.7 cm were obtained.

From the results presented in Table 9, it can be seen that the ZTD values for all stations vary in the range from 2,447 m to 2,507 m, with a maximum change of 4.5 cm for an individual station. The similarity of the ZTD values can be associated with a similar geographical location and altitude (the lowest station is Banja Luka with 214 m a.s.l., and the highest is Teslić with 270 m a.s.l.).

From Table 10, it is visible that the zenith tropospheric delay is noticeably different for permanent stations located at altitudes of approximately 1000 m and those located in lower areas. Our results unambiguously indicate a direct dependence of the zenith tropospheric delay (ZTD) values on the geographical location and altitude of the station, with ZTD values decreasing proportionally as altitude increases. For example, the average ZTD for the highest stations (Gacko at 1016 m a.s.l. and Sokolac at 944 m a.s.l.) were 2.145 m and 2.187 m, respectively. In comparison, lower-altitude stations like Brod (150 m a.s.l.) and Banja Luka (214 m a.s.l.) had higher average ZTD values of 2.418 m and 2.408 m, respectively.

First, the altitude of the permanent stations is compared with the lowest (Brod) and then the obtained ZTD values are compared in the same way. There is a clear direct connection and proportionality between the geographical location, i.e. the altitude of the permanent station, and the values of the zenith tropospheric delay for the same. With increasing altitude, the ZTD decreases and vice versa.

5. CONCLUSION

In GNSS receivers for civil use, tropospheric delay is determined using developed models that estimate the delay based on surface meteorological parameters. In the last few decades, models have been developed in such a way that models for zenith tropospheric delay (the satellite is at an elevation angle of 90˚) and models for a functional delay function that judges the delay at a certain angle have been developed. The most famous model of the function that maps the zenith tropospheric delay to the angular delay is the Niell function. A. Niell in 1996, in his work, gave an expression for the Niell function and showed that it gives satisfactory accuracy for elevation angles greater than or equal to 3˚. The Niell function is written in the form of continued fractions. J. V. Marini, in 1972, first expressed the function

that maps the zenith delay to the angular delay in the form of continued fractions. Since then, it has been most commonly used because it has proven to be better than the others for small elevation angles.

The research presented in this paper aimed to address a specific research gap by comparing the effectiveness of various empirical tropospheric models on GNSS network adjustment and by analyzing the relationship between station altitude and Zenith Tropospheric Delay (ZTD) values within the context of the BiHPOS network. The findings confirmed our initial hypothesis that the application of tropospheric models leads to a significant improvement in the accuracy of coordinates.

The analysis of the obtained results showed that, depending on the length of the baselines, the application of tropospheric models yields time coordinates of grid points that differ significantly from those obtained without the model in tropical models. These differences reach values of up to 5.7 cm along the position axes and 8.3 cm along the height. For this reason, the permanent station GIBL, located 2.6 km from the Banja Luka station, shows only 0.3 cm along the position coordinate axes and 1.1 cm along the height. The modified Hopfield model does not take into account the station's sea level in its calculation, which shows slightly larger deviations than the other two models, especially in terms of altitude for the permanent stations Teslić and GITE, where 06 cm were obtained.

The second task in the work was related to the calculation of the values of the zenith tropospheric delay (ZTD) and the examination of the dependence of the station altitude on these values. For the first measurement period of five consecutive days (08.08.2020 - 12.08.2020), the obtained ZTD values for the SRPOS permanent stations Banja Luka, Derventa and Teslić were in the interval from 2447 m to 2507 m, with a maximum daily change of 4.5 cm for an individual station. Given that the obtained results showed similar values, both for different permanent stations and for different measurement days, a similar procedure was repeated for the one-day measurement period. For the second measurement period, data were taken for the Banja Luka and Teslić stations as common stations with the previous procedure, as well as Gacko and Sokolac as stations located at a significantly higher altitude, and the Brod station, which is located at a significantly lower altitude than all stations from the SRPOS network.

The average ZTD values for the stations Brod, Banja Luka, Teslić, Sokolac and Gacko were 2418 m, 2408 m, 2467 m, 2187 m and 2145 m, respectively, which confirmed the above assumptions.

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Research paper

GEOTECHNICAL PROPERTIES OF DREDGED SEDIMENT FROM VOJVODINA FOR USE IN ROAD CONSTRUCTION

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Abstract

Deposited river sediment represents a mixture of fine clay, silt, and sand particles that accumulate at the bottom of aquatic ecosystems due to erosion of riverbanks and soil within the river basin, decomposition of plant and animal matter, as well as the accumulation of industrial and municipal waste. This process leads to large amounts of sediment forming in canals, rivers, and lakes, which can reduce water flow, decrease water quality, and disrupt waterway traffic. Disposal sites formed after regular dredging operations occupy significant land areas, making the management of this material a challenge both globally and in the region of Vojvodina. One potential reuse of this material lies in its stabilization and application as a construction material in road construction. This study analyzes a sample of dredged river sediment from the Begej River near Zrenjanin, categorizing it according to domestic standards. The application of this material is planned alone and in combination with lime binder ViaCalco F90 at a proportion of 5 and 7% relative to the dry sample mass. Afterwards, physical and mechanical tests were conducted, including the determination of maximum dry density (MDD) at optimal moisture content (Proctor test), unconfined compressive strength (UCS) test after 7 days of curing and CBR index test of the stabilized and non-stabilized samples. The results were compared with the relevant technical requirements and standards to draw a final conclusion regarding its suitability for use in pavement construction.

Key words: *dredged sediment, stabilization, pavement, waste management*

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1. INTRODUCTION

Over time, due to the process of sedimentation, large amounts of sediment accumulate at the bottom of channels, rivers, lakes, and seas. The formation of this material is associated both with the weathering of rocks or surrounding soil into finer particles, as well as with the decomposition of plant and animal matter and human activities such as the discharge of industrial or municipal wastewater. The deposited material generally consists of a mixture of sand, silt, and clay—of both organic and inorganic origin—as well as pollutants such as heavy metals and other toxic substances [1], [2]. Therefore, the regular removal of accumulated sediment is necessary to prevent potential flooding, ensure the proper functioning of waterway traffic, preserve existing ecosystems, and prevent water contamination in rivers and lakes.

In general, removing sediment from the bottom of aquatic ecosystems involves the excavation of deposited material, its transport, and, if necessary, treatment and disposal at designated landfill sites [3]. This procedure results in large quantities of dredged sediment, the further management of which can pose a challenge due to high costs, excessive land use for landfill formation, and potential pollution. Data from 2023 indicate that 160 million tons of dredged sediment were generated in Europe alone, with a rising trend [4]. In the Republic of Serbia, an average of 300,000 to 600,000 m³ of sediment is dredged annually, primarily in the Autonomous Province of Vojvodina, within the Danube–Tisa–Danube (DTD) hydro system [5]. Recently, there has been growing interest in more sustainable and cost-effective management of this material and its reuse. This type of sediment has been used worldwide in construction, agriculture, and for restoring endangered aquatic and terrestrial habitats or eroded shorelines [6].

Several analyzed studies have reported that dredged sediment is a material with low shear strength, often increased natural moisture content, a high proportion of organic matter, and high compressibility [1], [3], [7]. However, sediments cannot be considered uniform, as their physical and chemical properties depend on the specific location and their formation mechanism. Dredged sediment with a low level of contaminants and adequate physical properties, even in its raw form, can be used in concrete production—as a partial replacement for cement or fine aggregate, in the manufacturing of tiles, bricks, or blocks, as well as in road construction [3], [8]. An overview of beneficial sediment reuse is provided in *Figure 1*.

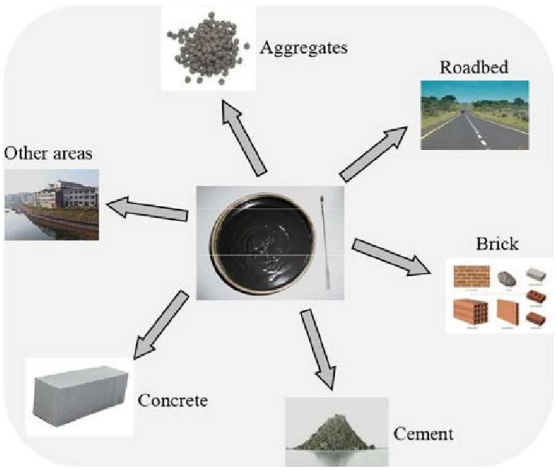


Figure 1. Beneficial reuse of dredged sediment for various purposes [8]

Since roadways are structures exposed to intensive and repetitive traffic loads, the use of raw sediment is mostly limited. In the case of contaminated and low-strength sediment, chemical stabilization can improve the material's strength while reducing its contamination level and environmental hazard [7]. Typical binders used for soil stabilization include cement, quicklime and hydrated lime, fly ash, and their combinations, and these can also be successfully applied in stabilizing dredged sediment. Sediment stabilization opens up possibilities for directly applying this material in the construction of road embankments, subbase and subgrade layers. The beneficial use of dredged sediment in infrastructure objects is presented in *Figure 2*.

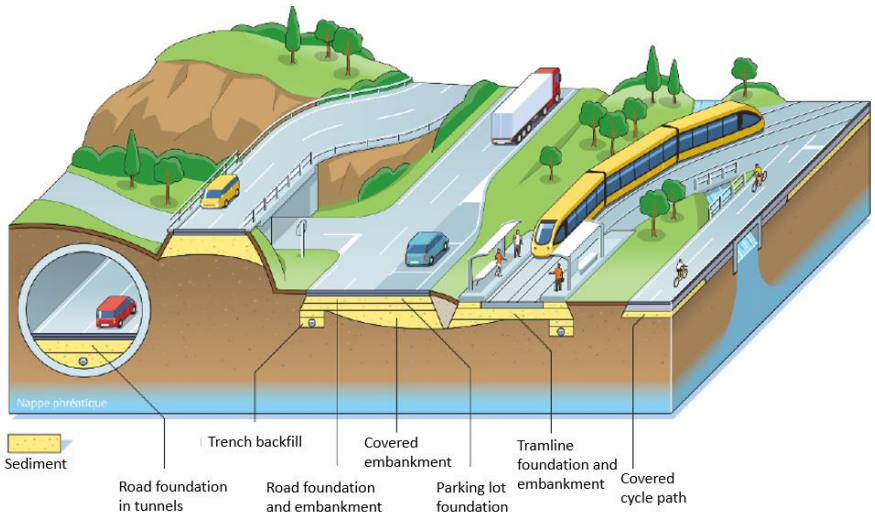


Figure 2. Beneficial reuse of dredged sediment in infrastructure objects, according to [9]

Research conducted by authors from France, India, and the USA has shown that the stabilization of dredged sediment using hydrated and quicklime significantly improves the material's physical and mechanical properties. Athira et al. [10] investigated the properties of dredged sediment stabilized with hydrated lime ($Ca(OH)_2$), fly ash, calcium lignosulfonate, and their combinations. Based on unconfined compressive strength (UCS) and California Bearing Ratio (CBR) tests, it was concluded that the optimal percentage of $Ca(OH)_2$ for achieving maximum strength was 4% by dry weight of the sample. Wang et al. [11] tested the UCS, CBR value, and indirect tensile strength of marine sediment stabilized with 3%, 6% and 9% of cement and quicklime (CaO) by dry sample mass. A significant improvement in the sediment's physical and mechanical characteristics was noticed. Minh Nguyen et al. [12] analyzed the physical and mechanical properties of dredged sediment from the Texas region that was previously stabilized with 6% $Ca(OH)_2$ and 12% CaO by dry weight. Adding binders led to a significant reduction in the plasticity index, therefore opening the possibility of using this material in embankment construction.

As part of this research, laboratory testing of the physical and mechanical properties of sediment collected from a disposal site formed after the dredging of the Begej River near Zrenjanin will be conducted. The study will focus on the analysis and comparison of the geotechnical characteristics of stabilized and non-stabilized sediment samples, as well as the assessment of whether the resulting material complies with relevant technical standards for use in pavement construction. For sediment stabilization, the binder ViaCalco F90, based on

CaO, will be used in proportions of 5% and 7% by dry weight of the sample. Additionally, the influence of the applied binder content on the physical and mechanical properties of the material will be analyzed.

2. MATHERIALS AND METHODS

Before starting the laboratory testing phase, a certain amount of the material in question was collected from a dredged sediment disposal site near Zrenjanin. The material is dried, has a brown colour, and has a very fine, silt and sandy-like texture when touched. The disposal site from which the material was collected, along with a sample of the material, is shown in *Figure 3*.



Figure 3. Landfill location and material sample

The use of the lime-based binder ViaCalco F90, produced by Carmeuse, is planned. This binder is used for soil drying, modification, and stabilization. According to the manufacturer's specifications, the binder contains more than 80% CaO [13]. By applying the binder in proportions of 5% and 7% by dry weight of the sample, long-term improvements in material strength and a reduction in natural plasticity are expected. The experimental part of the research is planned for stabilized and non-stabilized samples in order to monitor changes in the geotechnical properties of the material resulting from stabilization.

The experimental phase includes tests for determining the physical characteristics and classification of the material, specifically:

1. Determination of the particle size distribution, in accordance with SRPS EN ISO 17892-4:2017 [14];
2. Determination of bulk density and natural moisture content, in accordance with SRPS EN ISO 17892-1:2015 [15] and SRPS EN ISO 17892-2:2015 [16];
3. Determination of Atterberg limits (plastic limit, liquid limit, plasticity index), in accordance with SRPS EN ISO 17892-12:2018 [17]
4. Classification of the soil material according to the Unified Soil Classification System (USCS), in accordance with ASTM D2487 [18].

The following tests are necessary for determining the mechanical characteristics of the sediment:

1. Determination of maximum dry density and optimum moisture content using the standard Proctor test, in accordance with SRPS EN 13286-2:2012 [19];
2. Determination of the California Bearing Ratio (CBR), in accordance with SRPS EN 13286-47:2022 [20];

3. Determination of unconfined compressive strength after 7 days, in accordance with SRPS EN ISO 17892-7:2018 [21].

The described testing procedure aligns with the standard methodology for determining soil material characteristics. Particle size distribution analysis is performed by separating the soil sample into fractions of different sizes (sieving) based on a series of sieves defined by the referent standard. For particles smaller than 0.063 mm, the hydrometer method was applied. The liquid limit was determined using the Casagrande apparatus, while the plastic limit was defined as the water content at which a 3 mm diameter soil thread begins to crack during rolling. The procedure for determining the Atterberg consistency limits is shown in *Figure 4*.



Figure 4. Laboratory determination of the liquid (left) and plasticity limit (right)

The mechanical property tests presented in this study are basic test commonly performed in practice to assess the bearing capacity of materials and their potential use in pavement structures. The laboratory test used to determine the optimum moisture content (W_{opt}) and maximum compaction of the samples is the Proctor test. The standard Proctor test was conducted on both stabilized and non-stabilized samples at various moisture contents. Cylindrical samples with a diameter of Ø100 mm and height H = 120 mm were prepared, with a compaction energy of 600 kN/m³ applied. Following the Proctor test, CBR and UCS tests were performed at the W_{opt} and maximum dry density (MDD), in accordance with relevant standards. For the CBR test, cylindrical samples with a diameter of Ø200 mm and height H = 214 mm were prepared, while for the UCS test, cylindrical samples with a diameter of Ø100 mm and height H = 120 mm were used. Penetration tests in the CBR procedure were performed after 96 hours of sample submersion in water, with monitoring of linear swelling. UCS tests were carried out using a universal hydraulic press, and the results shown represent average values based on three tested samples. The measurement of sample dimensions and the UCS testing on the hydraulic press are presented in *Figure 5*.

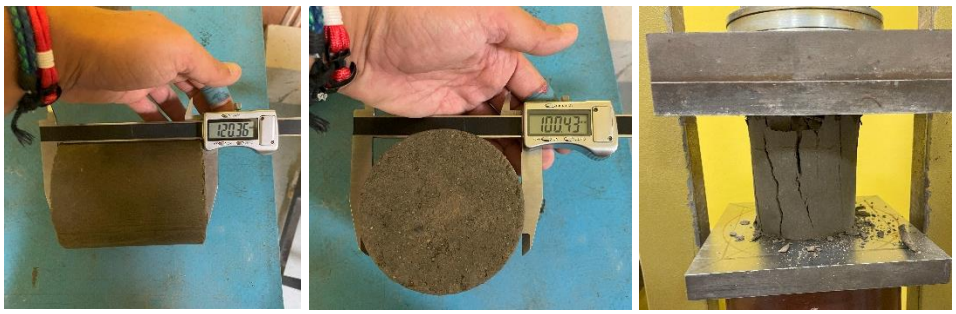


Figure 5. Laboratory investigation of UCS after 7 days of curing

3. RESULTS

3.1. Material characterization

The results of the physical characterization of the dredged sediment are presented in *Table 1*. Granulometric analysis showed that the material predominantly consists of silty fractions, over 40%. The natural moisture content of the sample was recorded at 1.98%, and the natural bulk density was 1.34 Mg/m³. The Atterberg liquid and plastic limits were 27.44% and 17.32%, respectively. Based on these values, it was concluded that the plasticity index is 10.12%, indicating that the material is moderately plastic. Based on the granulometric analysis and defined consistency limits, the material was classified as low plasticity clay (CL) according to the USCS classification.

Table 1. Geotechnical properties of non-stabilized dredged sediment

Material property	**Value**
Granulometric composition (%)	
Clay (<0.002 mm)	22.55
Silt (0.002 - 0.06 mm)	41.40
Sand (0.06 - 2 mm)	32.55
Gravel (2 - 6 mm)	3.50
Boulder (>60mm)	0
Initial moisture content (%)	1.98
Natural bulk density (Mg/m³)	1.34
Liquid limit (%)	27.44
Plasticity limit (%)	17.32
Plasticity index (%)	10.12
Soil classification (according to USCS)	CL (Low plasticity clay)

The Atterberg limits were also determined for the stabilized samples in order to adequately track the changes in plasticity of the samples upon the addition of the binder. The obtained plasticity indexes did not significantly deviate from the values obtained while testing the non-stabilized sediment. This can be explained by the type of material itself. The material in question naturally has lower plasticity, so the applied lime binder loses its primary role in reducing plasticity, as is the case with highly plastic clays [22]. The consistency limits for the stabilized samples are presented in *Table 2*.

Table 2. Atterberg consistency limits of stabilized dredged sediment

Material property	**Value**	
	5% of binder	**7% of binder**
Liquid limit (%)	27.64	27.60
Plasticity limit (%)	17.04	17.00
Plasticity index (%)	10.60	10.60

3.2 Mechanical properties

The MDD and W_{opt} of the material were determined based on the bulk densities of samples prepared with different moisture contents and the corresponding diagrams formed according to the reference standard. MDD and W_{opt} were determined for both stabilized and non-stabilized samples. The recorded W_{opt} was 12.5% for the non-stabilized sediment and

the MDD was 1.62 Mg/m³. The Proctor curve for the non-stabilized sediment is presented in *Figure 6*.

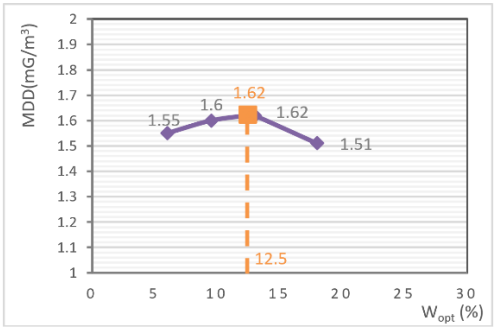


Figure 6. Proctor compaction curve of non-stabilized samples

For the samples stabilized with 5% binder based on dry mass, the MDD obtained was 1.70 Mg/m³ and the W_{opt} was 16.9%. When 7% binder was added, the MDD was recorded as 1.73 Mg/m³ and the W_{opt} as 19.4%. The increase in W_{opt} was expected due to the higher binder content and the chemical reactions occurring during stabilization. No significant changes in MDD were observed with the increase in binder percentage. The graphical representation of MDD and W_{opt} for the samples stabilized with 5% and 7% binder, based on the dry mass of the sample, is presented in *Figure 7*.

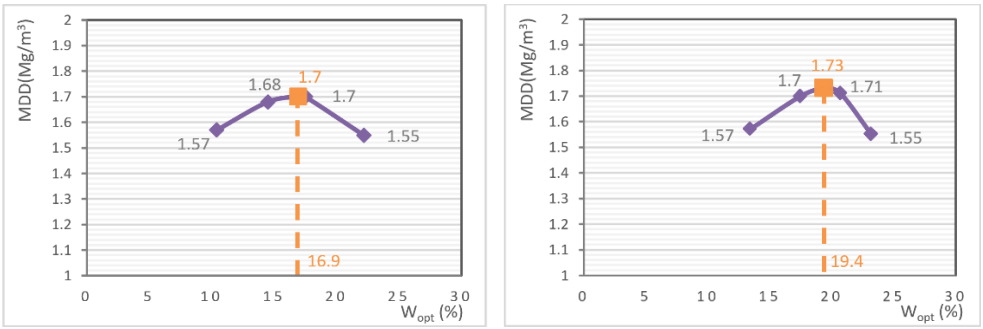


Figure 7. Proctor compaction curves of samples stabilized with 5% (left) and 7% of binder (right)

The recorded CBR index value for the non-stabilized samples was 9.70%, indicating the potential for direct application of the sediment (without prior stabilization) in the subgrade of the pavement structure. By adding lime binder, or stabilization, a significant increase in the CBR value was observed, which can be associated with the hardening of the material due to the formation of C-S-H products during the stabilization process [11]. As the binder percentage increased, a significant increase in the measured CBR value of the sample was also observed. When 7% lime binder was applied for stabilization, the CBR index reached 49.75%. The variations in the CBR values in relation to the applied binder content are presented in *Figure 8*.

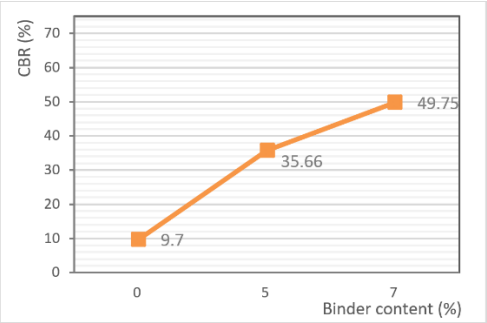


Figure 8. CBR values of sediment samples depending on binder content

Determining the UCS is an integral part of testing samples during soil stabilization and the construction of pavement structure. The UCS after 7 days could not be determined for the non-stabilized samples, nor for the sample stabilized with 5% lime binder. With the application of 7% lime binder, the strength of the samples was recorded as 0.32 MPa.

4. DISCUSSION

To assess the suitability of the material for use in the construction of embankments or subgrade, it is necessary to compare the obtained geotechnical parameters with the referent technical conditions and relevant national standards. *Table 3* provides the summarized required values of geotechnical parameters for embankment and road subgrade construction based on the valid standards SRPS U.E1.010 [23] and SRPS U.E8.010 [24].

Table 3. Technical requirements for embankment and subgrade construction and results of laboratory examination for non-stabilized sediment [23], [24]

Laboratory examination	**Required value**		**Obtained values**
	Embankment	**Subgrade**	
MDD of soil (Mg/m^3)	≥ 1.50 (*up to 3m of height*) ≥ 1.55 (*over 3m*)	≥ 1.60	1.62
W_{opt} (%)	< 25	-	12.5
Liquid limit (%)	< 65	< 50	27.44
Plasticity index (%)	< 30	< 20	10.12
Coefficient of uniformity	> 9	> 9	-
Organic matter (%)	< 6	< 6	-
CBR (%)	-	> 3	9.7

By comparing the values obtained from laboratory testing with the required values, it can be concluded that this material can be used in both the subgrade and embankment of the pavement structure, even without stabilization. The obtained CBR values, liquid limit, plasticity index, and MDD meet all the criteria prescribed by the technical conditions. The testing not covered in this study is the determination of organic matter content, which should be conducted in future research to eliminate concerns about the long-term durability of the road structure.

When it comes to sediment stabilized with lime binder, the obtained CBR values are significantly higher compared to the non-stabilized sediment. Additionally, the values of MDD, liquid limit, and plasticity index meet the requirements for use in the embankment and subgrade of the pavement structure.

Regarding the property of compressive strength, the *Technical Conditions for Earthworks* of PE Roads of Serbia from 2012 [25] require a minimum UCS of 0.5 MPa for stabilized soil after 7 days. Samples stabilized with lime binder do not meet this requirement, which may seem illogical bearing in mind the achieved CBR values of 35.66% and 49.75% for samples stabilized with 5% and 7% of binder, respectively. The reason for this inconsistency may be that the stated conditions do not differentiate between the type of binder used, nor the mechanism of strength development during stabilization with cement, lime, or fly ash. The development of strength when stabilizing with lime and fly ash can be much slower, so it would be more reasonable to test the strength of samples after a longer period [22].

5. CONCLUSION

Common materials that have been used for decades in the construction of road base, subbase and subgrade include sand, gravel, and crushed stone. Standard processes for producing these aggregates can generate large emissions of pollutant gases. Also, the distance between the sources of material and the construction site can drastically increase the cost of the roadway. Therefore, it is essential to stimulate the recycling of existing natural or artificial materials, which helps preserve existing resources, protect the environment, and reduce construction costs. Dredged sediment is one of the materials with great potential for use in these purposes, as increasing deposits of this material are forming near our rivers, and managing this waste will represent an increasing challenge in the future.

The results of this study indicate that raw river sediment originating from the Begej River can be utilized for the construction of road embankments or subgrade. The material examined in this research is a material with moderate to low plasticity, with a low content of particles smaller than 0.002 mm. It demonstrates adequate strength in terms of MDD and CBR index. Further research should include determining the organic matter content in the sediment to prevent potential negative effects on the development of material strength.

When stabilizing this material with CaO-based lime binders, additional improvement of the mechanical properties was observed, most notably through a significant increase in CBR values. A considerable rise in the W_{opt} was also recorded, attributed to lime hydration. However, stabilization with lime did not achieve the required UCS values after 7 days. This may be due to the longer curing time typically needed for strength development in lime-stabilized soils and the relatively low clay content in the material itself. Therefore, to achieve higher strength values, the use of cement-based binders for stabilization should be considered.

ACKNOWLEDGMENTS

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Review paper

MICROBIAL SELF-HEALING CONCRETE: A SUSTAINABLE SOLUTION FOR CRACK REPAIR

Jelena Mirjanić[1], Tiana Milović[2], Vesna Bulatović[3], Olja Šovljanski[4], Igor Džolev[5]

Abstract

Concrete is the most commonly used material in the construction sector after water, with an annual production of approximately two tons per person worldwide. Crack formation is a significant issue in concrete structures, leading to reduced service life, increased repair costs, and increased maintenance. Although it is impossible to completely prevent cracks formation, various repair techniques have been developed. Traditional methods pose environmental and health risks. Consequently, there is a growing demand for sustainable solutions such as microbial self-healing techniques that have emerged as a promising alternative, offering rapid, autonomous crack repair while maintaining environmental compatibility. The self-healing effect of bacteria-based concrete acts as a self-sufficient repair mechanism, where bacterial cells initiate the healing process independently, without external monitoring or human intervention. This process is driven by bacterial metabolic activities that produce carbonate ions, which then interact with calcium ions present in the material, resulting in the formation of $CaCO_3$ crystals. This phenomenon, known as microbiologically or bacterially induced carbonate precipitation, plays a key role in enhancing the durability and longevity of concrete structures.

Key words: *self-healing concrete, crack repair, autonomous materials, supplementary cementitious materials, bacteria, microbiologically induced carbonate precipitation*

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1. INTRODUCTION

A small skin cut heals with the protection of a bandage, which allows the body to self-heal. This natural repair process is common in living organisms but rare in man-made materials. In engineering disciplines, material improvement efforts are most often directed toward increasing strength and stiffness, enabling materials to bear higher loads without damage. Over time, these damages can develop into larger cracks that compromise the material's structure and functionality [1]. To increase the service life of engineering structures and reduce maintenance costs, the development of self-healing materials attracts increasing interest from researchers. Concrete, as the most widely used composite material, has proven to be particularly well-suited for the development of self-healing technology. Its multiphase microstructure, porosity, and presence of unreacted particles of cement enable autogenous healing, even without additional interventions. However, natural autogenous processes are generally effective only in sealing microcracks up to 150 μm in width, while larger cracks require application of specially designed autonomous methods, such as shape memory alloys, electrodeposition, capsules, vascular networks, and microbial technologies [2].

Among all available autonomous methods, the use of microbial technologies has shown exceptional potential due to its sustainability, adaptability, and environmental friendliness. Microbial self-healing relies on certain bacteria, primarily bacilli, to induce precipitation of calcium carbonate ($CaCO_3$) via metabolic processes such as ureolysis or nitrate reduction. This biomineralization effectively seals cracks and restores material integrity. This paper analyzes this innovative self-healing approach based on bacterial contribution, focusing on the conditions for cells survival in cement-based composites, methods of bacterial incorporation, their impact on the properties of concrete, and challenges associated with their practical application [3].

2. MECHANISM OF MICROBIAL SELF-HEALING

One of the most widespread natural phenomena present in living organisms is the process of biomineralization. It is a natural process in which living organisms create solid mineral structures, such as the formation of shells and pearls in shellfish, formation of shells in turtles, and formation of bones and teeth in mammals. Biomineralization occurs through a biologically induced mineralization process, in which living organisms trigger the formation of minerals in their surroundings either as an adaptation to environmental conditions or as a product of metabolic activities, such as respiration or digestion [4].

Biomineralization by microorganisms is a process in which microorganisms, most commonly bacteria, unintentionally create mineral structures because of their metabolic activities. In bacteria, the most well-known form of biomineralization is the precipitation of calcium carbonate ($CaCO_3$) through metabolic processes such as ureolysis or nitrate reduction. Metabolic degradation of urea at specific types of bacteria, primarily bacilli (rod-shaped bacteria, usually sporogenic), releases dissolved carbon ions (DIC) and ammonia (AMM) in the microenvironment of cells (Figure 1a). Negatively charged bacterial cell walls attract calcium cations (Ca^{2+}) from the surrounding environment and react with inorganic carbon ions (CO_3^{2-}). As a result of their chemical reaction shown in equation (1), insoluble $CaCO_3$ crystals are formed and deposited on the bacterial cell walls (Figure 1b).

$$CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3 \quad (1)$$

This process can occur within the cementitious matrix, as it contains positively charged calcium ions required for the described precipitation reaction. Over time, the bacterial cell becomes fully immobilized by the precipitated material (Figure 1c), which can seal cracks and strengthen the structure of concrete material. Figure 1d shows the imprints of bacterial cells involved in carbonate precipitation. $CaCO_3$ is considered one of the most suitable fillers for concrete due to its high compatibility with cement compounds [3]. This principle forms the basis for the development of microbial self-healing concrete, and this autonomous approach has shown its effectiveness in repairing cracks of larger widths. The maximum crack width healed in the specimens by bacteria was 970 μm [5].

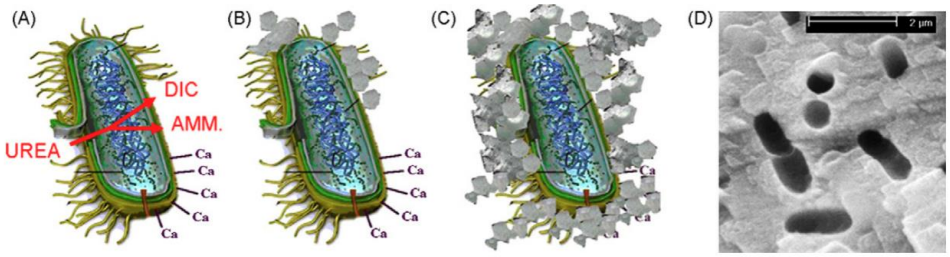


Figure 1. Simplified representation of the events occurring during the ureolytic induced $CaCO_3$ precipitation [3]

When cracks appear, the bacteria, initially in a dormant state, are activated by the ingress of water, multiply and initiate the self-healing process by rapidly producing $CaCO_3$ to seal the crack (Figure 2). Once the crack is filled and the healing process is completed, the bacteria return to a dormant state, remaining inactive until new cracks form and favorable environmental conditions reactivate them [3].

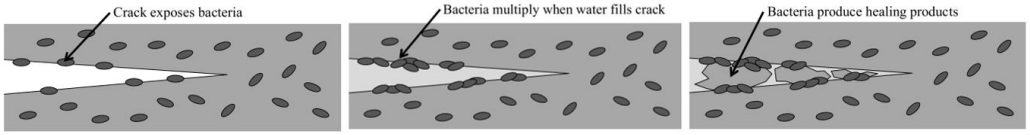


Figure 2. Schematic illustration of bacterial contribution through self-healing approach [6]

3. CONDITIONS AFFECTING BACTERIAL VIABILITY

The efficiency of bacterial self-healing in concrete depends on the production of $CaCO_3$, which is influenced by environmental factors such as pH and temperature. Temperature affects the activity of the urease enzyme, a key catalyst in the hydrolysis of urea, while pH levels also play a crucial role in controlling the availability and efficiency of urease activity. Urea hydrolysis is fundamental to producing carbonate ions, but this process also releases ammonia, which increases the alkalinity of the environment and may inhibit bacterial growth [7]. Any variation in pH or temperature directly affects the rate and extent of $CaCO_3$ precipitation, as illustrated in Figure 3. Given that concrete presents an extremely challenging microenvironment due to its high alkalinity, whose pH values are 12-13 [8], caused by the presence of calcium hydroxide, and elevated temperatures resulting from cement hydration reactions and may reach 70°C [9], bacteria must be able to survive in highly alkaline and thermally unstable conditions to maintain their self-healing function. Elevated pH levels in concrete can cause bacteria to enter a dormant state - spores, which can allow them to

survive for up to 200 years, depending on the bacterial strain [10][11]. Dormant cells can return to an active state through a process called germination, which is stimulated by changes in the surrounding environment [12]. However, studies by Šovljanski et al. [13] and Milović et al. [14] have shown that certain bacterial species can perform well and survive extreme conditions in the cement-based matrix, making them particularly suitable for use in self-healing concrete.

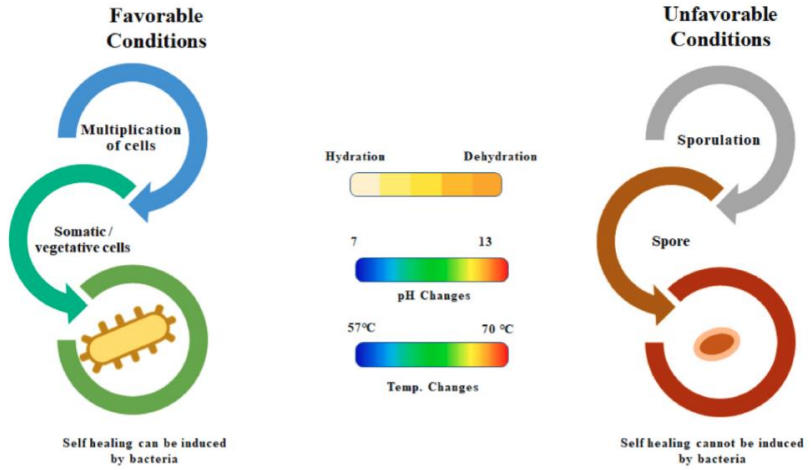


Figure 3. Behavior of bacteria under favorable and unfavorable conditions [15]

Several bacterial species have been identified as suitable for surviving in the highly alkaline environment of self-healing concrete (Table 1). Their optimal growth generally occurs between 30°C and 40°C. It is important to note that, in addition to testing individual bacterial strains, combining strains into co-cultures has also shown significantly improved bacterial growth under high pH and temperature conditions making them particularly valuable for use in bacterial-based self-healing concrete [13][14].

Table 1. The optimum bacterial growth at various pH and temperature levels

Bacteria	pH	Temperature (°C)	References
Sporosarcina pasteurii	11.6	30	[16][17]
Bacillus cereus	7-10	40	[8][18]
B. licheniformis	8-11	37	[18][19]
B. halodurans	12-14	37	[13][18][19]
B. muralis	9	20	[13]
B. simplex	11	37	[13]

4. BACTERIA IMPLEMENTATION

4.1. Direct method

Direct method represents a simple approach for bacteria implementation into self-healing concrete, involving techniques such as surface spraying, injecting bacteria into the crack or directly mixing bacteria with concrete mixture [15].

Despite the simplicity and cost-effectiveness of this method, several challenges can reduce the ability of bacteria to effectively heal cracks:

- Immediate exposure of bacteria to the highly alkaline environment inside concrete leads to a reduction in bacterial viability, and prolonged exposure can impair the germination ability of bacterial spores.
- Shear forces during the concrete mixing process can seriously harm bacterial spores.
- Nutrient availability is often limited within the dense cementitious matrix.
- Cement hydration reduces the diameter of cement matrix pores to 0.5 μm, while bacterial cells are larger in size, 0.5 μm wide and 2-3 μm long.
- Thermal effects during the process of cement hydration can damage active bacterial cells if they are not in spore form [11].

Recent studies by Šovljanski et al. [13] and Milović et al. [14] have shown that direct incorporation can be effective, especially when using robust, alkaliphilic, and sporogenic bacterial strains, such as *Bacillus licheniformis*, *B. muralis* and their co-cultures. These bacteria can survive the highly alkaline environment of fresh cement paste and can remain viable through spore formation over extended periods, even under limited nutrient and moisture conditions. By selecting highly resistant bacterial strains and optimizing initial conditions (such as controlling curing temperature and applying nutrients at later stages), direct incorporation remains a promising and practical method for the application in microbial self-healing concrete.

4.2. Indirect method

Indirect implementation was developed to overcome the challenges associated with the direct implementation method and involves encapsulating bacteria within protective carriers before their introduction into the cement matrix [15]. These carriers provide both physical and chemical barriers, shielding the bacteria from harsh environmental conditions such as high alkalinity, mechanical stresses during mixing, thermal effects during hydration, and limited nutrient availability. Common types of carriers include:

1. **Special Cement Aggregates** – Porous aggregates (e.g., expanded clay, zeolites, lightweight aggregates) for immobilization of bacterial spores and nutrients [20].
2. **Polymer and Special Mineral Compounds** – Microcapsules containing bacterial suspensions or spores immobilized within polymeric shells, as well as silica-based carriers or diatomaceous earth, which offer additional protection (Figure 4) [21].
3. **Special Additives in the Cement Matrix** – Hydrogels, which can serve as reservoirs for bacterial cells and nutrient solutions [22].

Encapsulation allows bacteria to survive the mixing and early curing stages and remain dormant until cracks form and water ingress triggers their activation. However, indirect incorporation increases the complexity of bacterial carrier production and integration, thus also raising the overall cost of material preparation. Based on the above, it can be concluded that both methods, direct and indirect implementation, have their respective advantages and limitations.

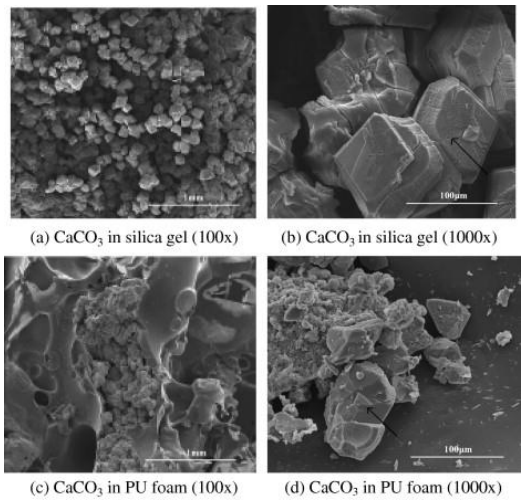


Figure 4. Scanning electron micrographs of $CaCO_3$ precipitation in the silica gel and polyurethane foam [21]

5. KEY FACTORS AFFECTING THE EFFICIENCY OF BACTERIAL SELF-HEALING

The potential of bacteria-based self-healing concrete is influenced by several different factors. Among them, the availability of a calcium source, crack width, crack age, and curing conditions play a dominant role in determining the success and rate of healing.

1. **Calcium source** - the presence of an adequate calcium source is essential for the calcification process to occur. Insufficient calcium availability can limit the extent of healing even if bacterial activity is high. Various calcium salts have been used in research as precursors for mineral precipitation. Initially, calcium chloride was widely used due to its high solubility. However, since chloride ions are detrimental to reinforcement and the long-term durability of concrete, alternative calcium compounds have been explored to ensure a continuous supply of calcium, such as calcium acetate, calcium nitrate, calcium lactate, and calcium di-glutamate [7].
2. **Crack width** - when cracks are wider, the self-healing products may be insufficient to seal them fully. Studies have shown that the effectiveness of bacterial crack healing is limited when the crack width exceeds 970 μm [5]. Figure 5 shows surface images of samples with different crack widths, 300 μm and 800 μm, after various healing periods.
3. **Crack age** - Luo et al. [23] observed that the degree of healing decreased as the crack aged, primarily due to a reduction in bacterial viability within the harsh concrete environment. Newly formed cracks offer more favorable conditions for bacterial activation and precipitation due to better water ingress and nutrient availability. In contrast, older cracks may accumulate dust, contaminants, or undergo carbonation, all of which can inhibit bacterial growth and reduce healing efficiency.
4. **Curing conditions** - especially moisture availability and temperature, are essential for activating bacterial metabolism. A moist environment is critical to

trigger bacterial activity and maintain favorable conditions for ureolytic or nitrate-reducing pathways. Dry curing environments can severely limit bacterial viability and halt the healing process. Similarly, extreme temperatures may negatively impact bacterial survival and enzymatic reactions essential for healing [8].

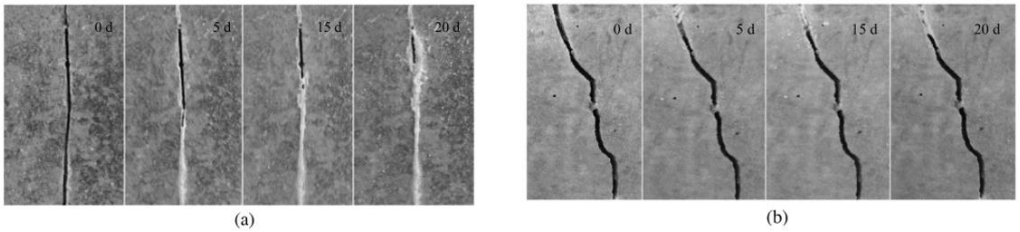


Figure 5. Surface images of specimens with different crack width after different repair time: (a) specimen with an average crack width of 300 μm; (b) specimen with an average crack width of 800 μm [23]

5.1. Efficiency evaluation

The efficiency of the self-healing process in concrete is most directly reflected through the extent of crack closure and the associated recovery of microstructural integrity, durability, and mechanical performance. Cracks that are effectively filled with healing products typically exhibit restored water tightness, enhanced resistance to aggressive environmental agents, and partial or full recovery of load-bearing capacity. Therefore, the evaluation of self-healing efficiency largely depends on the reliable characterization of the crack healing process. Key parameters used to assess crack healing include crack width, length, depth, and number, with crack width being the most critical indicator due to its strong correlation with healing potential. These parameters are commonly measured through optical methods (visual observation) such as high-resolution cameras or optical microscopes [2]. In addition to these efficiency visual assessment techniques, it is important to mention other techniques such as microstructural assessment techniques (SEM, XRD, EDS, TGA), strength recovery and improved durability. Thus, efficiency assessment techniques can generally be divided into four areas: microscopic observation, composition analysis, resistance and durability, and mechanical properties [24].

6. MECHANICAL PROPERTIES OF MICROBIAL SELF-HEALING CONCRETE

Yaveed et al. [15] provided a general overview of the mechanical properties of bacterial concrete, focusing on compressive strength, splitting tensile strength and flexural strength. Different types of bacteria were implemented using the direct method, and a series of samples with varying bacterial cell concentrations were considered for each type. After 28 days of curing, the mechanical properties of the bacterial concrete specimens were compared to those of the control specimens.

6.1. Compressive Strength

Two types of examined specimens, one containing *Bacillus acetophenoni* and the other *Deinococcus radiodurans*, exhibited the highest increase in compressive strength, reaching

up to 40.9% at a concentration of 5×10^7 CFU/ml [25] and 42.8% at a concentration of 10^5 CFU/ml [26], respectively. The observed specimens with other bacterial strains showed significant variation depending on cell concentration, highlighting the importance of evaluating not only the optimal concentration but also the selection of a specific bacterial strain to achieve maximum compressive strength in self-healing concrete.

6.2. Splitting Tensile Strength

After 28 days, the splitting tensile strength generally showed an increasing trend compared to the control mix across all tested specimen types, with improvements ranging from approximately 10% to 30%. Notably, the specimen containing *Bacillus sphaericus* at a concentration of 10^5 CFU/ml exhibited a remarkable 32.3% increase in splitting tensile strength after 28 days [16]. A similar effect was observed in specimens with *B. licheniformis*, which, when directly incorporated into the concrete mixture at a concentration of 10^7 CFU/ml, demonstrated a 32% increase in splitting tensile strength [27]. It is worth noting that in some mixtures, greater recovery in splitting tensile strength was observed at early curing stages compared to the 28-day results, likely due to the availability of sufficient pore space [28].

6.3. Flexural Strength

In self-healing concrete, the filling of voids with calcification products reduces porosity and results in a denser concrete matrix, which in turn positively affects the improvement of flexural strength [29]. The highest increase was observed in specimens containing *Bacillus subtilis* at a concentration of 10^7 CFU/mL, where the flexural strength after 28 days increased by 45%. Research has shown that, in addition to calcium carbonate precipitation within pores, the acceleration effect of available nutrients - such as calcium lactate, calcium nitrate, and urea—also plays a significant role in enhancing flexural strength [30]. Furthermore, mixtures containing *Sporosarcina sphaericus* within the cell concentration range of 10^0 to 10^7 CFU/mL demonstrated the best results at a concentration of 10^5 cells/mL, with a recorded increase of up to 48% [31]. Based on these findings, it can be concluded that both the choice of bacterial strain and the adjustment of its cell concentration are equally important factors in achieving improvements in the flexural strength of concrete.

7. PRACTICAL APPLICATION IN CONSTRUCTION SECTOR

Developing microbial self-healing technologies has led to an increasing number of real-world applications in the construction industry. Since 2015, several countries, including China, the Netherlands, Belgium, and the United Kingdom, have implemented demonstration projects utilizing bacterial self-healing concrete [15]. Table 2 summarizes notable examples of microbial self-healing concrete applications.

Table 2. Practical application of bacterial self-healing concrete, modified from [15]

Structures	Self- healing agents	Effects
Roof slab of drainage pipe [32]	Anaerobic granular bacteria and mixed ureolytic culture	There were no signs of cracks, but conditions were good for healing.
Retaining wall panel, Highway project [33]	*Bacillus pseudofirmus* spores with calcium acetate and yeast extract	Substantial improvement in panel self-healing after six months.
Mangdao river ship lock [34]	Bacteria spore in powder form with calcium source	No water leakage after 65days, complete healing of cracks.
Irrigation canal [35][36]	Alkali resistant bacterial spores along with yeast extract and calcium lactate	After a year, there were no visible signs of cracks on the lining surface.

8. CONCLUSIONS

Integration of microbial self-healing technologies into cementitious materials represents an innovative and sustainable approach to enhancing the durability and mechanical properties of concrete structures. Through the metabolic activity of specific bacterial strains, primarily of the *Bacillus* genus, calcium carbonate is precipitated and deposited within cracks, effectively restoring structural integrity. This study has provided a general overview of the conditions necessary for bacterial viability, including pH, temperature, nutrient availability and curing conditions, as well as the methods for incorporating bacteria into concrete. Examples of practical applications confirm the potential of these methods for use in the construction industry. However, despite the significant progress achieved in the field of self-healing concrete, there are still certain limitations and challenges in the application of this method, which are outlined below. These include the resistance of certain bacterial species to extreme environmental conditions, such as the high alkalinity and elevated temperatures present in concrete, the long-term stability and reactivation potential of the bacteria, as well as the high cost of producing and preparing bacterial carriers which remains one of the main barriers to broader application in conventional construction. Furthermore, there is a limited number of studies addressing resistance to carbonation, sulfate attack, frost and salt exposure, and there is currently no unified criterion for evaluating self-healing efficiency, as most tests are confined to small-scale material samples, resulting in limited and often inconclusive outcomes. Therefore, future research should focus on further investigation into healing efficiency and mechanisms, as well as exploring alternatives derived from waste materials. Additional focus is needed on selecting and genetically modifying bacterial strains with improved resistance to extreme conditions within the cement matrix, developing new encapsulation technologies that would allow simpler and more cost-effective implementation, and engineering-based modeling of healing kinetics and performance prediction under various service conditions in combination with other smart materials, techniques, and sensors for automated monitoring of damage and the self-healing process. Although various researchers have studied the use of microorganisms in self-healing concrete and investigated their performance, most of these studies have been conducted under laboratory conditions or on small-scale experimental models, meaning that the findings are often based on a limited dataset. These studies rarely consider real-world field conditions, such as geographical and climatic variations, which can significantly influence the effectiveness of microorganisms in practice. This represents one of the major limitations in bioconcrete

research and more thorough life cycle assessment (LCA) studies and outdoor applications with enhanced durability are required.

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Research paper

APPLICATION OF SEISMIC REFRACTION FOR DETERMINING GEOMECHANICAL PARAMETERS IN THE EXCAVATION ZONE OF THE VRANDUK TUNNEL ON THE CORRIDOR Vc ROUTE

Ekrem Bektašević[1], Ahmed Mušija[2], Kemal Gutić[3], Noris Sakić[4]

Abstract

The seismic refraction method belongs to the group of non-destructive testing techniques and represents an efficient geophysical approach for determining the propagation velocity of seismic waves through different geological environments. This allows for the assessment of key geomechanical parameters of the terrain. In this study, measurements were conducted along three profiles in the excavation zone of the Vranduk tunnel, located on the Corridor Vc route, with the aim of characterizing the rock mass and determining its condition before the commencement of construction work. Analysis of the obtained data defined the velocities of seismic waves, which were used to assess rock mass quality, classify materials, and identify potential discontinuities and weakened zones. The results indicated that in the upper zone, at a depth of 6–8 meters, the rock mass is weathered, whereas in deeper layers, the rock mass is more intact and only slightly fragmented. Since this method is entirely non-destructive, it enables rapid and reliable terrain investigation without disturbing its structure. The results were compared with in-situ geotechnical investigations, confirming the method's reliability in determining the mechanical properties of rocks. The obtained data served as a foundation for optimizing design solutions, adjusting excavation techniques, and improving the stability of the tunnel structure.

Keywords: *Seismic refraction, Geomechanical parameters, Vranduk tunnel, Corridor Vc route, Longitudinal wave velocity*

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1. INTRODUCTION

Geophysical methods play a key role in geotechnical investigations and the design of infrastructure projects [1]. When comparing the advantages of geophysical surveys to conventional underground or rock mass investigations, geophysics provides a larger volume of data over a greater area and depth while also offering significant savings in time and financial resources. This is because the instruments are relatively inexpensive, and the survey process is faster and simpler [2].

In addition to geophysics, conventional engineering investigations, such as borehole drilling, are also used. However, borehole investigations are costly. To develop an optimal investigation program, shallow seismic refraction was applied in the preliminary phase of research in the tunnel excavation zone of Vranduk. This method provided a general overview of the underground conditions and helped determine the optimal number and placement of boreholes based on the collected data.

The "Vranduk" tunnel is part of the motorway on Corridor Vc, specifically the section from the northern administrative border of the Municipality of Zenica (Nemila) to Zenica North (Donja Gračanica), within the Vranduk–Ponirak subsection [3].

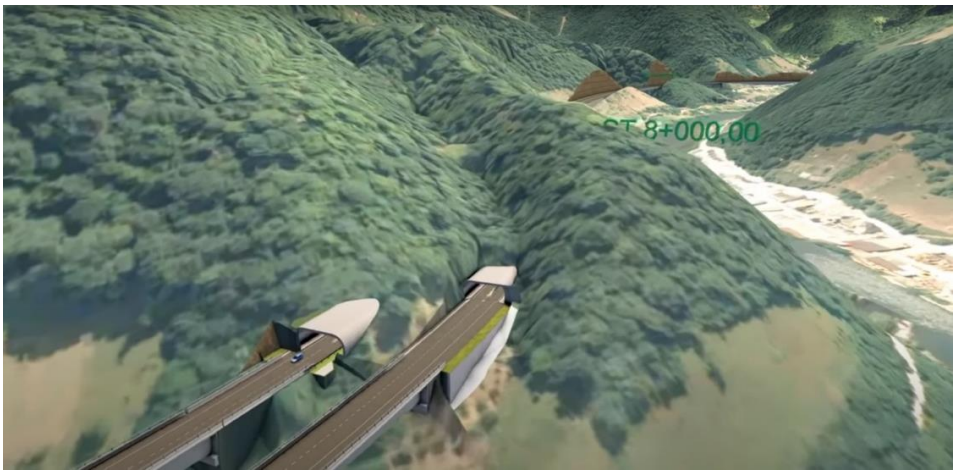


Figure 1. Satellite view of the Vranduk tunnel location

Shallow seismic refraction was developed more than 80 years ago [4,5,6]. The ASTM D5777-18 standard of the American Society for Testing and Materials (ASTM) outlines the methodological and equipment requirements for refraction measurements [7]. Seismic refraction is used to determine the velocities of longitudinal (P) and transverse (S) seismic waves, enabling the identification of the mechanical properties of rock and pressure formations [8,9,10,11].

This method provides a non-invasive approach to characterizing subsurface layers, which is particularly important for planning and optimizing engineering works [12,13,14]. The selection of a tunnel construction method for larger cross-sections is primarily based on the rock conditions through which the tunnel is being excavated [15,16].

Previous studies have shown that the application of seismic refraction allows for a reliable assessment of elasticity modulus, rock and soil resistance coefficients, and the identification of discontinuities in geological structures [17,18]. The method has been widely used in geotechnical analyses worldwide, including in complex geological environments where faults and zones of reduced strength have been documented [19,20].

2. RESEARCH METHODOLOGY

2.1. Seismic Refraction – General Overview

Seismic refraction is a geophysical exploration method based on measuring the first arrivals of a known signal source (artificially generated), while all later arrivals are disregarded due to complex reflection and interference processes. To generate mechanical force in shallow refraction surveys, a hammer weighing 5–10 kg, a dropped weight, or another impulsive source is used. For deeper investigations, reaching several hundred meters, explosives or heavy vibrators are typically employed [21].

When subjected to an external impulse, subsurface material particles temporarily shift from their initial positions, collide and transmit mechanical motion through the ground. This process enables the propagation of seismic waves from one point to another. If the waves are longitudinal (P-waves), the particles oscillate in the same direction as the wave propagation. In the case of transverse (S-waves), the particles move perpendicular to the direction of wave travel. During this motion, the particles do not permanently change their positions but merely oscillate around their equilibrium points, while elastic waves transmit mechanical energy through the subsurface medium [22]. The time elapsed from the emission to the reception of a seismic wave depends on the depth of the studied structures and the wave propagation velocities [23]. The fundamental principle of seismic refraction is illustrated in Figure 2**.**

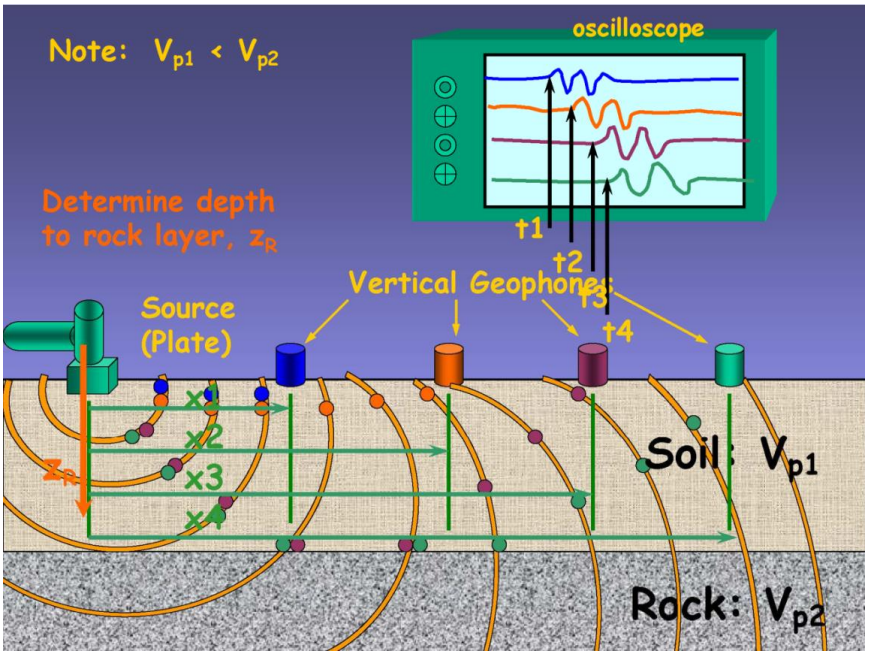


Figure 2. Principle of seismic refraction

The fundamental principle of this method is based on the fact that elastic waves, generated at the surface, begin to propagate at the velocity of the first medium (V1). The most important wave for this method is the one that reaches the boundary between two media at the critical angle or the angle of total refraction. This wave then propagates along the boundary at the velocity of the lower medium (V2) and returns to the surface, where it is detected by the placed geophones [24, 25].

Based on the arrangement of geophones and shot points, as well as the recorded first arrival times of the elastic wave, an x-t diagram (x-distance, t-time) is created, as illustrated in Figure 3.

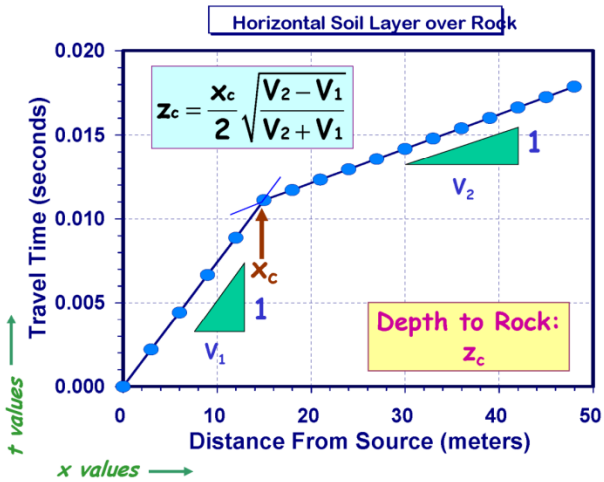


Figure 3. Representation of the x-t diagram

The coordinate system (x-t) in Figure 3 shows the first arrival times of waves [26] at individual geophones, starting from the moment the wave is generated. The points in the diagram are connected, ideally as shown in Figure 3, and represent two lines. The first line intersects the x-axis at the origin and has the equation [22]:

$$t = \left(\frac{1}{V_1}\right) \cdot x \tag{1}$$

While the second line has the equation:

$$t = \left(\frac{1}{V_2}\right) \cdot x + I_O \tag{2}$$

$\mathbf{I_0}$ is the intercept of the second branch of the dromochron on the ordinate through the shot point. From these equations, we determine the velocities $\mathbf{V_1}$ and $\mathbf{V_2}$ of the upper and lower seismic media, and calculate the depth to the first seismic discontinuity. The thickness of the upper layer can be calculated using the following equation [27]:

$$z_c = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \tag{3}$$

When excitation occurs in an elastic material, waves are immediately generated from the point of excitation and propagate with decreasing oscillation amplitude of the disturbance. Each of these waves behaves in a characteristic manner, and these characteristics depend on the elastic properties of the material. The obtained and processed velocities of the elastic waves, which depend on the elastic properties of the material through which the wave propagates, as shown in the equations for the velocity of P and S waves, are used to calculate the dynamic elastic constants [28]:

$$v_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \tag{4}$$

$$v_S = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}} \tag{5}$$

where:
v_p - velocity of primary (longitudinal) P – waves (m/s),
v_s - velocity of secondary (transverse) S – waves (m/s),
ρ - density (10^3 kg/m³),
E - Young's modulus (GPa),
G - shear modulus (GPa),
K - bulk modulus (GPa).

By knowing the propagation velocities of elastic waves through the rock mass and the density, it is possible to solve two equations with two unknowns to calculate two dynamic constants, which can then be used to determine and calculate the other constants [29].

$$a = \frac{v_p}{v_s} = \sqrt{\frac{2-2v}{1-2v}} \tag{6}$$

$$v = \frac{\left(\frac{v_p}{v_s}\right)^2 - 2}{2\left\{\left(\frac{v_p}{v_s}\right)^2 - 1\right\}} = \frac{a^2-2}{2(a^2-1)} \tag{7}$$

$$E = \rho v_p^2 \left(\frac{(1+v)(1-2v)}{1-v}\right) \tag{8}$$

$$G = \rho v_s^2 \qquad K = \rho v_p^2 \frac{1+v}{3(1-v)} \tag{9}$$

where:
v - Poisson's ratio,
ρ - density of the rock (kg/m³).

Using the above formulas, it is possible to calculate the dynamic elastic constants for each measurement position, and the density is calculated from the longitudinal wave velocity (v_p) using the known Anstey relation, as shown in the equation [30].

$$\rho = 0{,}31\sqrt[4]{v_p} \tag{10}$$

Based on the known velocities of longitudinal (V_p) and transverse (V_s) seismic waves according to the classification by Novosel and colleagues [31], it is possible to determine the engineering geological characteristics of soils and rocks, including the assessment of their seismic classification and deformability (Table 1). By analyzing these parameters, key shear strength parameters, such as cohesion and the angle of internal friction, can also be derived, allowing for a more accurate characterization of the mechanical behavior of geological materials. These data are essential for geotechnical calculations, assessing the stability of structures, and optimizing design solutions in engineering practice [32].

Table 1. Classification according to Novosel et al.

Category number	Description of Engineering-Geological Characteristics	The geophysical properties			Type of piozometric curve	RQD	Axial strenght	Shear strenght parameters	
		Seismic wave velocity		Magnitude of electrical resistance				Angle of friction	Choesion
		longitudinal	transverse						
		m/s	m/s	m		%	MPa		kPa
I	The rock is fresh the blocks are massive, and the frequency of fractures is very low. If fractures are present, they have very large surfaces, and the fracture width is very small. Fractures are either unfilled or filled with crystalline substances.	>4300	>2200	>1000	F	90-100	>100	>45	>500
II	The rock is weakly weathered, the blocks are large, and the frequency of fractures is low. Fractures are infrequent and large, with narrow widths. The fractures are rarely coated with a clay film on the fracture planes..	3000-4300	1600-2200	>1000	F	75-90	75-100	>45	>500
III	The rock is moderately weathered, the blocks are medium-sized, and the frequency of fractures is moderate. The fracture surfaces are of medium size, the fractures have a medium width, and the fractures are partially filled with clay.	2000-3000	1000-1600	300-1000	E	50-75	50-75	40-45	300-500
IV	The rock is highly weathered, the blocks are small, and the frequency of fractures is high. The fracture surfaces are mostly small, but the occurrence of medium-sized fractures is frequent. The fractures are filled with a mixture of rock fragments and clay or semi-consolidated breccias.	1400-2000	650-1000	300-1000	D	25-50	25-50	35-40	200-300
V	The rock is very highly weathered, with the frequent occurrence of very small blocks. The fracture surfaces are very small, and milonitized zones are observed. Large-width fractures filled with clay and rock fragments or semi-consolidated breccias are present.	900-1400	400-650	150-300	C	10-25	10-25	30-35	150-200
VI	The rock is extremely weathered, with the predominance of extremely small blocks and mylonitized zones. The fracture surfaces are extremely small, and the frequency of fractures is extremely high. Extremely wide fractures are observed, filled with clay, rock fragments, and semi-consolidated breccias.	600-900	250-400	150-300	B	0-10	3-10	<30	100-150
VII	Voids and depressions filled with clay or a mixture of clay and rock fragments.	300-600	150-250	35-200	A	0	0-1	<30	<100

2.2. Application of the Method in the Vranduk Tunnel Excavation Zone

The investigation was conducted on the section of Corridor Vc, where the excavation of the Vranduk Tunnel was carried out. The seismic refraction method was performed on three test profiles (17-17', 18-18', and 19-19'). Profiles 18-18' and 19-19' were positioned in the zone of the entrance profile excavation, while profile 17-17' was positioned in the zone of the exit profile excavation. This arrangement was chosen to cover the area with the smallest overburden thickness. The profile arrangement is shown in Figure 4.

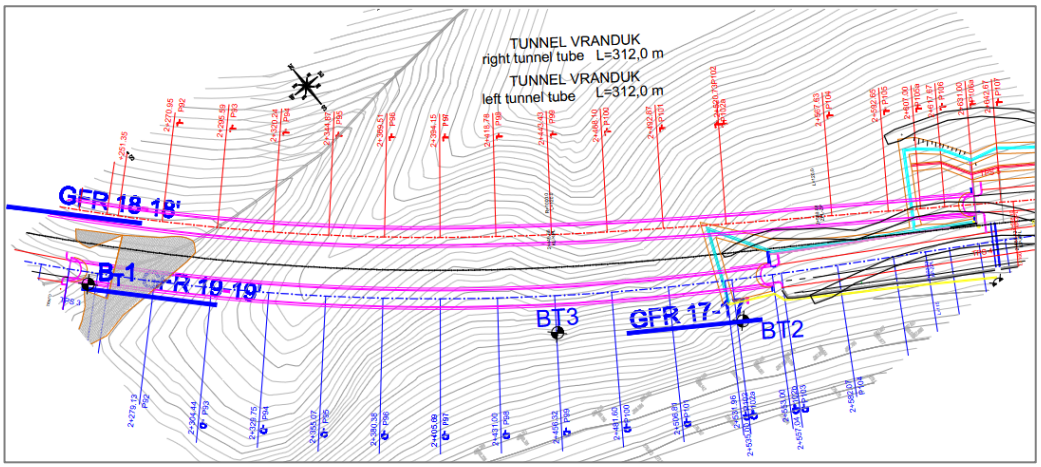


Figure 4. Arrangement of test profiles in the Vranduk Tunnel excavation zone

Seismic waves were generated using impulsive impact sources, and the data were recorded with a series of geophones placed at defined intervals. The recordings were made using a digital seismograph, which enabled precise registration of wave arrival times.

All measurements were carried out using OYO equipment with twelve channels, with seismic wave initiation by hammer and electronic trigger. The profile length was 60 meters, with seismic Vp and Vs wave reception intervals of 5 meters. Data processing was done using the SeisREFA program [33]. The processed results are shown in Figures 5, 6, and 7.

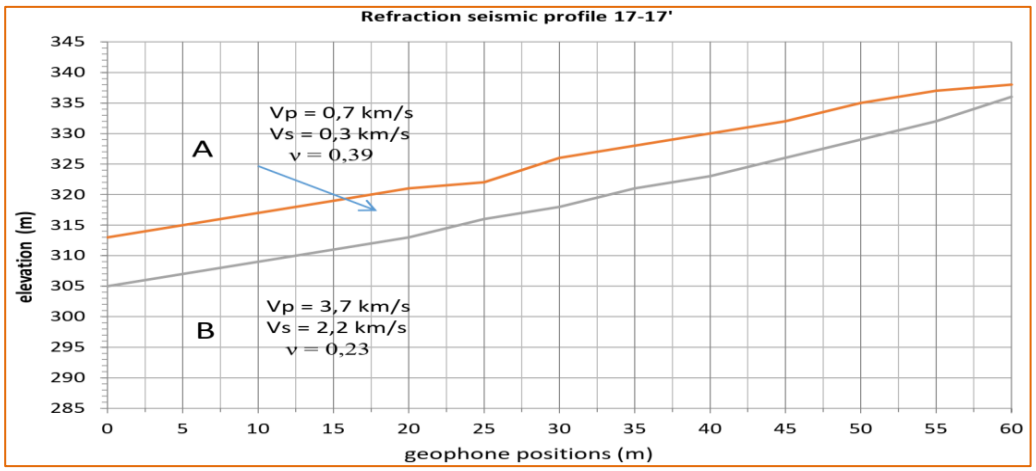


Figure 5. Distinct geomechanical environments on profile 17-17'

Two geomechanical environments with different seismic characteristics were identified, labeled as A and B.

A: This geomechanical unit is located at the surface and reaches a depth of approximately 8 meters, with a longitudinal seismic wave velocity of Vp = 0.7 km/s and v = 0.39. It consists of a humus cover and clayey and granular material. According to the classification by Novosel et al., it has an axial strength of 3-10 MPa, φ < 30°, and cohesion of 100-150 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 0.7 km/s is calculated as E ~ 392.00 MN/m², the shear modulus G ~ 144.00 MN/m², and density ρ ~ 1,595.00 kg/m³.

B: The geomechanical unit at depths greater than 8 meters has a measured longitudinal seismic wave velocity of Vp = 3.7 km/s and a calculated Poisson's ratio of v = 0.23. This is a weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD of 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 3.7 km/s is calculated as E ~ 28,552.00 MN/m², the shear modulus G ~ 1,171.00 MN/m², and density ρ ~ 2,418.00 kg/m³.

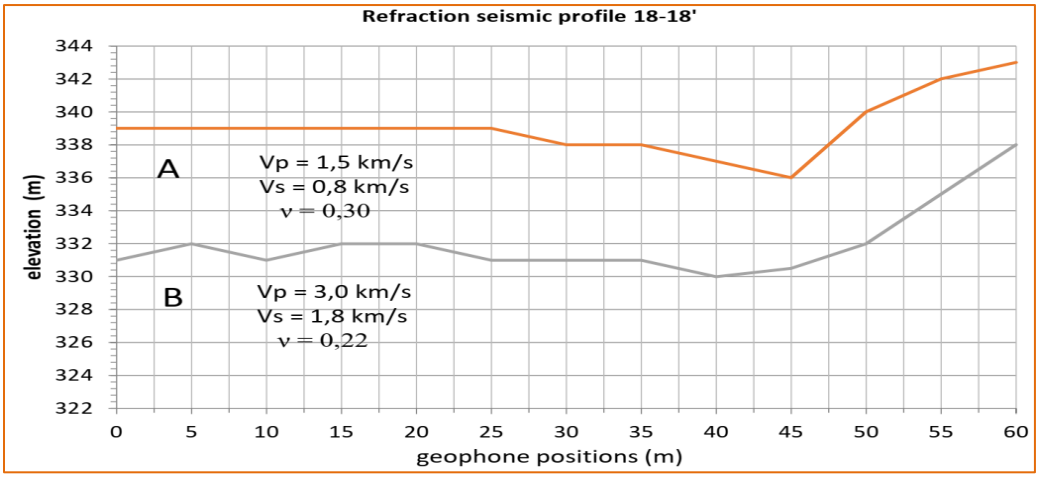


Figure 6. Distinct geomechanical environments on profile 18-18'

Two geomechanical environments with different seismic characteristics were identified, labeled as A and B.

A: This geomechanical unit is located at the surface and reaches depths from 5 to 8 meters, with a longitudinal seismic wave velocity of Vp = 1.5 km/s and v = 0.30. It consists of a thinner humus cover and the remaining weathered surface part of solid rock mass. According to the classification by Novosel et al., it has an RQD of 25-50%, an axial strength of 25-50 MPa, φ = 35-40°, and cohesion of 200-300 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 1.5 km/s is calculated as E ~ 3,225.00 MN/m², the shear modulus G ~ 1,235.00 MN/m², and density ρ ~ 1,930.00 kg/m³.

B: The geomechanical unit at depths greater than 5-8 meters has a measured longitudinal seismic wave velocity of Vp = 3.0 km/s and a calculated Poisson's ratio of v = 0.22. This is a weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD between 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from Section 2.1, the dynamic modulus of elasticity for Vp = 3.0 km/s is calculated as E ~ 18,086.00 MN/m², the shear modulus G ~ 7,434.00 MN/m², and density ρ ~ 2,295.00 kg/m³.

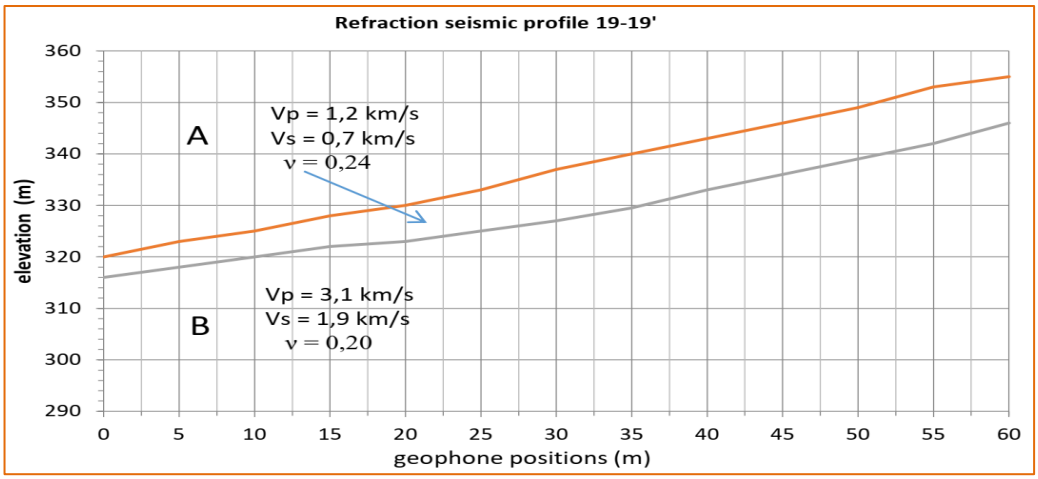


Figure 7. Distinct geomechanical environments on profile 19-19'

Distinct geomechanical environments A and B

A: This geomechanical unit is located at the surface of the terrain, extending to depths of 4 to 9 m, with a longitudinal seismic wave velocity of Vp = 1.2 km/s and v = 0.24. It consists of a thin humus cover and a weathered surface layer of solid rock mass. According to Novosel et al.'s classification, it has an RQD of 10-25%, axial strength of 10-25 MPa, φ = 30-35°, and cohesion of 150-200 kPa. Using the formulas from section 2.1, the dynamic elastic modulus for Vp = 1.2 km/s is E ~ 2,230.00 MN/m², shear modulus G ~ 895.00 MN/m², and density ρ ~ 1,825.00 kg/m³.

B: The geomechanical unit below the 4 to 9 m depth range has a measured longitudinal seismic wave velocity of Vp = 3.1 km/s and a calculated Poisson's ratio of v = 0.20. It consists of weakly weathered rock mass, which according to Novosel et al.'s classification has an RQD of 75-90%, axial strength of 75-100 MPa, φ > 45°, and cohesion C > 500 kPa. Using the formulas from section 2.1, the dynamic elastic modulus for Vp = 3.1 km/s is E ~ 20,007.00 MN/m², shear modulus G ~ 8,351.00 MN/m², and density ρ ~ 2,314.00 kg/m³.

3. RESULTS AND DISCUSSION

The interpretation of seismic data enabled the differentiation of the rock mass based on the level of weathering. The data showed that zones with lower wave velocities (Vp < 1500 m/s) correspond to highly weathered rocks, characterized by the frequent occurrence of very small blocks, wide fractures filled with clay and rock fragments. On the other hand, zones with P-wave velocities above 3000 m/s represent rock masses with minimal damage, stable formations, as shown in Figure 8.

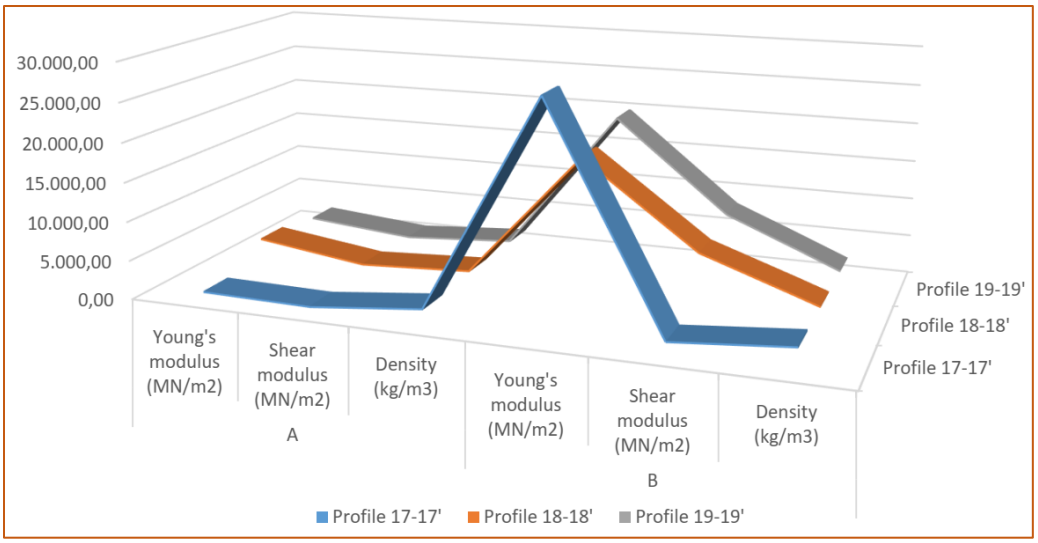


Figure 8. Elastic properties of the rock mass in the tunnel excavation area of Vranduk

Comparison with laboratory tests of rock samples revealed a good correlation between seismic velocities and mechanical parameters of the rock mass. These data were used to optimize excavation methods and the selection of the tunnel subgrade.

4. CONCLUSION

The application of seismic refraction in the tunnel excavation area of Vranduk on the Corridor Vc route proved to be an effective method for determining the geomechanical parameters of the rock mass. This technique enabled the differentiation of the rock mass based on its degree of weathering and provided key information about the underground conditions. The identification of zones with lower seismic velocities (Vp < 1500 m/s) indicated highly weathered rocks with fractures filled with clay and rock fragments, while areas with P-wave velocities above 3000 m/s represented more stable formations with less damage.

The obtained results showed a good correlation between seismic velocities and mechanical parameters of the rock mass, confirmed by laboratory testing. These data allowed the optimization of exploration works by defining the optimal number and location of exploration boreholes, thereby reducing costs and research time. Furthermore, the interpretation of seismic data was crucial for optimizing excavation methods and selecting the appropriate tunnel subgrade, contributing to the safety and efficiency of the works.

The results of this study confirm the importance of applying seismic refraction to determine the geomechanical parameters of the rock mass in the tunnel excavation zone. This method enables informed decision-making in the early stages of design, leading to improvements in the technical and economic aspects of tunnel construction and other underground facilities.

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Research paper

ARCHITECTURAL DESIGN TOOL BASED ON KOENIGS MESHES

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Abstract

Koenigs meshes should be more explored in the field of architectural design due to their various fabrication efficiency factors for doubly curved grid-shells. Beside being planar quad meshes (PQ-meshes) they have additional property of duality and are closely linked to graphical statics: their diagonals and those of their dual mesh represent form and force diagrams in equilibrium under a normal unit load. These meshes also fulfill essential geometric criteria such as planar panels suitable for glass cladding. Special subclasses—like discrete isothermic surfaces and discrete minimal surfaces—offer additional advantages, including quad blocks with planar lateral sides (zero geometric torsion) and constant edge offsets. The latter allows for simplified fabrication using straight, discrete strips. Koenigs meshes remain underutilized in architectural practice. This research develops design morphology techniques and parametric tools that preserve their geometric properties, and introduces computational methods for constructing and exploring designs with these networks. The study offers new design strategies of dual meshes and presents practical workflows for implementing Koenigs nets in architectural applications.

Key words: *discrete Koenigs surfaces, discrete isothermic surfaces, discrete minimal surfaces, architectural geometry, PQ meshes*

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1. INTRODUCTION

Koenigs meshes are discrete analog of Koenings patches with specific fabrication and structural advantages, making them highly relevant in grid-shell architecture. They represent planar quad meshes (PQ-meshes) that also support duality, making them highly relevant for construction applications. Their structural significance arises from their direct relationship with their dual meshes, particularly in graphical statics, where the diagonals (of the quads) of a Koenigs mesh and its dual represent the *form* and *force* diagram of one another. This property enables them to reach static equilibrium under an external normal unit load [1, 2]. Additionally, they satisfy essential geometric criteria for design, including planar quad faces, which facilitate prefabrication of their panels on the flat platform or glass cladding. Furthermore, the intersecting diagonals points of adjacent faces produce planar panels, presenting a promising solution as a second option for glass covering, when the primary construction is derived from the diagonals.

Within the scope of Koenigs meshes class is their subclass of *discrete Isothermic Surfaces (or IS-meshes)* which further contain *discrete Minimal Surfaces (or MS-meshes)*. They bring additional fabrication advantages to the construction elements such as: „square-like“ proportionality of the panels, zero geometric torsion (face sides without twisting) [1], and in the case of discrete minimal surfaces also: *constant edges offset* blocks whose planar lateral sides unfold to a straight band. These properties are very rare in the doubly curved grid-shells, but enable simpler fabrication techniques with the possibility of material savings during production since the elements can be produced by cutting and folding parallel stripes of material [3].

While their methods of construction and properties are known among mathematicians and researchers within discrete differential geometry [2], [4–6], they have not been widely explored for applications in the design of doubly curved grid-shells. For the first time, this research applies transformation principles that preserve the geometric properties of Koenigs meshes to broaden the range of design variations within pre-rationalization design approch. The main contribution of this paper is developing the tools and algorithms for constructing these meshes is based on defined steps, driven from geometry theory, within parametric modeling.

2. GEOMETRY DEFINITIONS

In this section we will talk about geometry definitions and main properties of the Koenigs meshes as well as their subclasses of IS-meshes and MS-meshes. The theory from this section will be used for development of the design tool for K-meshes grid-shells.

2.1. Koenigs meshes (K-meshes)

In this paper, by mesh we mean a quad mesh that is, a 2-dimensional array of points in the standard 3-dimensional Euclidean space. When the faces of the mesh are planar we call this a *Planar Quad mesh* (or PQ-mesh), note that all the meshes studied here are PQ. Next, a Koenigs mesh (K-mesh) is a PQ-mesh that admits a dual K-mesh. To understand this, we begin by defining the dual of a quad. So let (A,B,C,D) be a starting quad, then, its dual transform, denoted *(A*,B*,C*,D*),* is a quad such that all the edges are parallel to the initial quad while opposite diagonals are parallel (Figure 1).

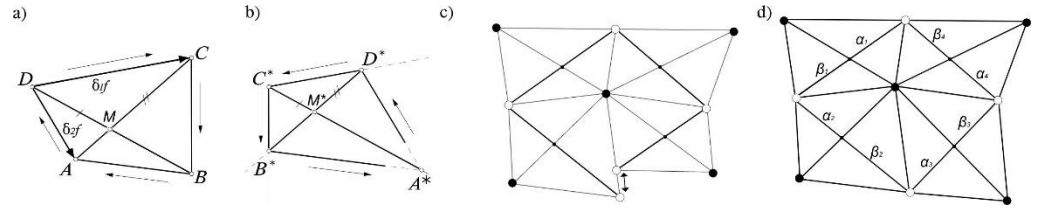


Figure 1. a) Elementary quad b) Its dual transformation; c) Dual of four arbitrary quads d) Closure condition on K-mesh

The dual transform of a quad defined above is the central operation that we will use here. We can then say, that a K-mesh is PQ-mesh that admits a dual mesh, which is another mesh where the corresponding elementary quads are related by the dual transform described. This is intuitive enough; however, it does not tell us how to construct a K-mesh. A natural way to explore, is to start by a PQ-mesh and apply the dual transform to each of its quads. The result set of quads will not necessarily close together properly into a neat mesh (Figure 1c). For this to happen we have to impose another condition on the initial PQ-mesh, that we call the closure condition. To this end, given a point with its four adjacent planar faces, we define the distances (on the diagonals) denoted by $\alpha_1, \alpha_2, \ldots$ as seen in Figure 1d. Now the closure condition is that at every point the relation (1) is satisfied. Intuitively, it can be said that the diamond net around every point has to be closed. For further details and proof, see [2].

It then follows, that a K-mesh can be defined as a mesh that satisfies:

- Planarity of faces (being PQ-mesh)
- Closure condition (admitting a dual mesh).

$$\frac{\beta_1}{\alpha_1} \cdot \frac{\beta_2}{\alpha_2} \cdot \frac{\beta_3}{\alpha_3} \cdot \frac{\beta_4}{\alpha_4} = 1 \qquad (1)$$

Interesting and unique geometric property of K-meshes beyond planar elementary quadrilaterals is that the intersection points of the diagonals that belong to four adjacent quadrilaterals are coplanar [5]. Additionally, Koenigs meshes are projectively invariant, meaning their two fundamental properties (planarity and closure condition), remain unchanged under projective transformations (PT). In intuitive design exploration, the PT can be seen as a transformation that stretches the mesh in different directions while preserving face planarity and keeping the diamond nets around each point closed. This characteristic will be the basis of their construction in this paper. Now, PT (in dimension 3) can be interpreted as an operation on the standard Euclidean space given by the mapping:

$$(x', y', z') = \left(\frac{a_1x + a_2y + a_3z + a_4}{d_1x + d_2y + d_3z + d_4}, \frac{b_1x + b_2y + b_3z + b_4}{d_1x + d_2y + d_3z + d_4}, \frac{c_1x + c_2y + c_3z + c_4}{d_1x + d_2y + d_3z + d_4}\right) \qquad (2)$$

where the 4x4 matrix whose rows are given by the input parameters a_1,a_2,a_3,a_4; b_1,b_2,b_3,b_4; c_1,c_2,c_3,c_4, and d_1,d_2,d_3,d_4 has a non-zero determinant. These are used to generate shape variations. Particulary this equasion is used to transform the coordinates of starting points (x, y, z) of the mesh into a new set of points of the gained mesh with coordinates (x', y', z').

2.2. Discrete Isothermic surfaces (IS-meshes)

IS-meshes are in fact a specialization of K-meshes where we require more constrains on the meshes. More precisely, we first require that quads of our PQ-mesh to be Cyclic, that means that all the vertices are co-circular (lie on the same circle), we call such a mesh a circular mesh. Further, we require the circlular mesh to satisfy what is called the Cross- Ratios

condition. This means that the lengths of the four edges of adjacent quads must satisfy a specific relationship. To understand that, we recall that the cross-ratio of a cyclic quad (A, B, C, D) is defined by the relations $\left(\frac{|AB|}{|BC|}\right).\left(\frac{|CD|}{|DA|}\right)$, where | | means the length of the edge. Given a point of a circular mesh and its four adjacent faces, let q_1, q_2, q_3, q_4 be the cross- ratios of these faces, the Cross-Ratios condition is given by the relation:

$$q_1 \cdot q_3 = q_2 \cdot q_4 \tag{3}$$

An IS-mesh is thus defined as a mesh satisfying:

- Circularity (being circular mesh)
- Cross-Ratio condition [5].

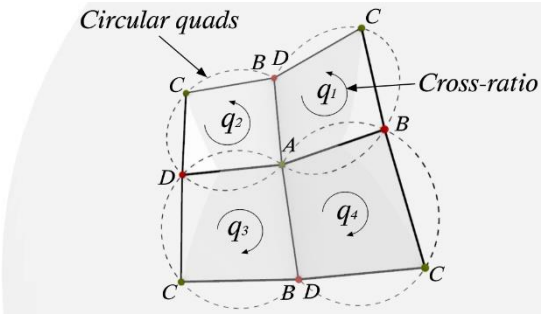


Figure 2. Cross-Ratios of four adjacent faces at a point

Being in particular a K-mesh, an IS-mesh naturally admits *a dual mesh, using the dual* transform of its elementary quads as seen above. However, in the case of IS-mesh this dual transform will be called a Christoffel dual transform, reflecting its origin in smooth classical setting. Furthermore, the two fundamental *properties of IS*-meshes are not invariant (they change) under PT however, they are invariant under Mobius transformations (MT), which will be explained later on. Finally, it is known that being a circular mesh is equivalent to being a Vertex-Offset mesh (VO-mesh) [1], [7], [8]. This means that their neibouring discrete normals are coplanar which is a significant fabrication advantage for modular faces and nodal construction elements.

2.3. Discrete minimal surfaces

MS-meshes belong to a subclass of IS-meshes that is called s-IS-meshes. These are defined as collection of vertices one black (b-vert) and two types of whites (c-vert) and (s-vert). Moreover, they satisfy the following conditions:

- the four b-vertices surrounding a c-vertex are co-circular (lie in same circle)
- the four b-vertices surrounding a s-vertex are co-spherical (lie in same sphere)
- these circles and spheres intersect orthogonally (at the b-vertices).

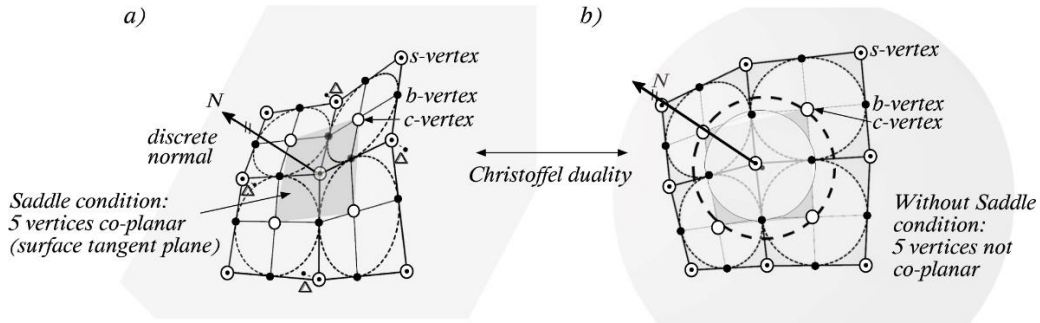


Figure 3. Properties of discrete minimal surface and Koebe

We will call the above conditions the s-IS-mesh condition, and thus a mesh satisfying this will be called an s-IS-mesh, and we index only the s-vertices as our mesh points. Furthermore, it can be observed that the four s-vertices surrounding a c-vertex are co-planar, and their face has inscribed circle (centered at the c-vertex and passing through the b-vertices), as seen in Figure 3a) [6]. Now, if we require that the s-vertices, are co-planar with their surrounding c-vertices (before they were co-spherical), then we observe that the four adjacent faces at every s-vertex take the saddle-like configuration. We call this the Saddle condition.

We can thus define an MS-mesh as a mesh that satisfies the two conditions:

- s-IS-mesh condition (being s-IS-mesh)
- Saddle condition (every white vertex is co-planar with its white neighbors).

The s-IS-mesh condition is invariant (does not change) under MT while the Saddle condition is not. Now, as the others, MS-mesh admits a Christoffel dual mesh, which is known to be an s-IS-mesh on the sphere—that is, a Koebe mesh. We will use exactly this property to construct MS-mesh. Then lets see what is a Koebe mesh.

2.1.1. Koebe polyhedral and edge offset – EO mesh

Note that the plane obtained at the s-vertex with its surrounding c-vertices is the tangent plane to the MS-mesh and the normal to this plane is the discrete normal at the s-vertex (Figure 3a). When transformed into its dual, it can be seen that its edges are tangent to the unit sphere at the transforms of the b-vertices, while the transforms of the s-vertices lie outside the sphere. Such a mesh is called a Koebe mesh [9]. It follows that each face (defined by the transformed of the s-vertices) has an inscribed circle which is precisely the intersection of the face in question and the sphere (Figure 4). So far, we explained that the Christoffel dual of an MS-mesh is a Koebe mesh, however we want to do the opposite construction. Namely, constructing a Koebe mesh then getting an MS-mesh by taking the Christoffel dual. To this end, we recall that a Koebe mesh can be directly constructed from the two orthogonal Circle Packings (CP) on the unit sphere, which in turn give us MS-mesh by applying Christoffel dual transform [4]. In this paper, we construct the two orthogonal CP by constructing them in the plane (the (u, v) domain) then send them to the unit sphere using the inverse of the stereographic projection (which is known to preserve circles), denoted by N_o and given by:

$$N_o(u,v) = \left(\frac{2u}{u^2 + v^2 + 1}, \frac{2u}{u^2 + v^2 + 1}, \frac{u^2 + v^2 - 1}{u^2 + v^2 + 1}\right) \quad (4)$$

Secondly, we can pre-compose N_o with I, the inversion in a circle of radius R, or in general

with ψ, an MT (in the Complex plane), given respectively by:

$$I(u,v) = \left(\frac{R^2}{u^2+v^2}\right)(u,v) \quad with\ R\ non-zero \tag{5}$$

$$\psi(\mathrm{T}) = \frac{aT+b}{cT+d} \text{ with } T = u + iv \text{ and } a,b,c,d \text{ such that } ad-bc \text{ non-zero} \tag{6}$$

The resulting conformal map from these pre-compositions $(N_o \circ I,\ N_o \circ \psi)$ will be denoted N (parametrization sending the circle packing pattern on the sphere). Furthermore, we can also post-compose these with an MT (in 3-dim.). The MT can be formulated as a combination of scaling, translation and inversion. The third one can be intuitively described as a motion of turning the mesh "inside out" through a sphere or a plane. It keeps the geometry of circles and spheres as well as angles. That is why it can be implemented on IS-meshes without changing their properties. Also, it can be implemented on MS-meshes, where only the first condition is kept, so we get s-IS-mesh from MS.

Despite being somewhat less intuitive a MT can be more conveniently defined as a 5x5 matrix μ. whose generators are the matrices denoted by A, B, C, D. These are themselves parameterized respectively by a, b, c, d varying between -1 and 1 (cf. digital tool). The reason for the 5 dimensions, comes from the rather abstract realization of the Mobius transformations as Lorentz transformations preserving a light-cone in Minkowski space of dimension 5. The data of the transform is sent to and from this using stereographic projection in dimension 3. For more details about its construction see [10].

In order to construct a proper circle packing by using these parametrizations it is important to divide the parametric domain into squares which can have inscribed circles. This can be made by having the same u, v domain and dividing them by same number $ndu = ndv$, or all values can be varied but by keeping the same step value $(u_n - u_{n+1} = v_n - v_{n+1})$. After using the chosen combination of mapping we have the circles on the sphere. Since here we are looking at the quad subdivision, the four planes P_1, P_2, P_3, P_4 of adjacent circles should intersect into one point A (Figure 4b). The intersection of the each of neighboring two planes gives us the tangent edges of the sphere. If repeated for the all four adjacent circles, we get all the vertices and edges of the Koebe mesh.

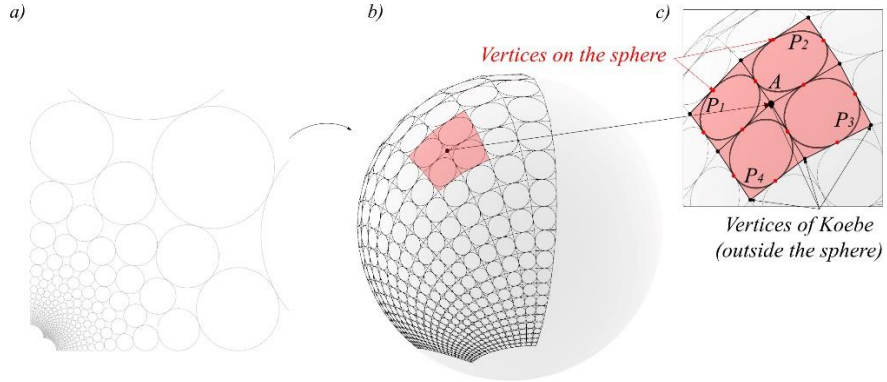


Figure 4. Construction of Koebe polyhedra by using inversion in plane and inverse stereographic [11]

Now that we showed how we can easily construct a Koebe mesh, we go back to its relation with MS-meshes. As mentioned above, a Koebe mesh is the discrete Gauss map of

an MS-mesh (which is also its Christoffel dual), this means that this MS-mesh is Edge Offset (EO) mesh, i.e. admitting an offset mesh with constant edge to edge distance [1].

Similarly, as the Koebe mesh is as well an EO-mesh (since it is its own discrete Gauss map). In practical terms, if denote the Koebe mesh by M1 and its EO-mesh by M2, the corresponding edges are parallel (since at constant distance) and that if connect the corresponding b-vertices they all meet at the center (origin) of the unit sphere, as seen in Figure 5. Note that the b-vertices on M_1 all lie on the unit sphere and are the points of tangency between it and the Koebe mesh.

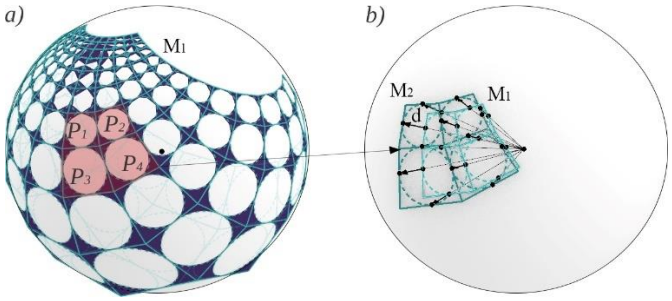


Figure 5. a) Koebe polyhedra M_1; b) Four adjacent faces with tangent edges on the sphere M_1 with its offset mesh M_2 [11]

2.1.2. Edge offset straight unfolding property

It turns out that the MS-meshes (and negatively curved meshes in general) posses an extra property among the EO-meshes (i.e. meshes having their discrete Gauss maps as Koebe meshes). That is, the EO-block B obtained by connecting the EO-mesh with it offset, will have not only planar lateral sides (zero geometric torsion) but also the *unfold into a straight strip*, as seen in Figure 6. This is a direct consequence of the Saddle condition. To understand this intuitively, take a point on the MS-mesh and its four adjacent faces, and the Face Offset (FO) blocks (in red) from the Face normals constructed at these faces. It is then not so difficult to see that the saddle condition of the MS-mesh will force the common faces of four adjacent EO-blocks B to always lie between the faces of the FO-blocks. In particular, they (B) overlap in one direction and drift apart in the other, as seen in Figure 6 (middle). This in turn will induce a specific angle θ for each EO-block by which the planes of its lateral faces will rotate in and out in an alternating manner, as seen in Figure 6 (right). This alternation of rotation is the cause of the lateral sides unfolding into a straight strip, as seen in Figure 6 (right). This clearly provides us with a significant fabrication advantages, as the EO-blocks can be cut from straight pieces reducing cutting time and material loss.

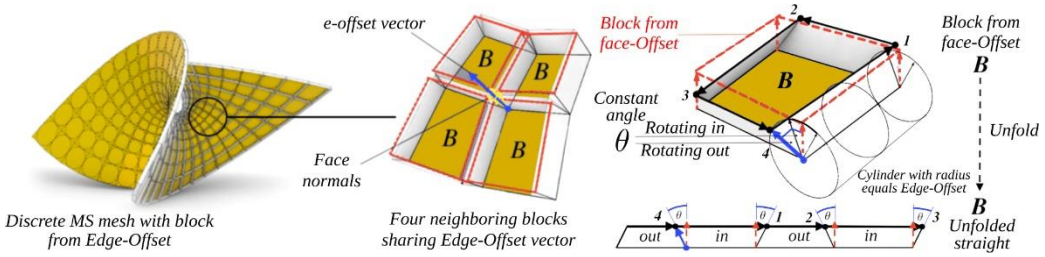


Figure 6. Example of the discrete MS mesh with the construction of its edge offset and proof of its straight unfolded sides [11]

3. DESIGN WORKFLOW AND MORPHOLOGY

This section focuses on constructing a different Koenigs nets and its subclass by using appropriate transformations based on the geometry theory shown in Section 2 for expanding the design space of grid-shells using Koenigs meshes. The goal is to showcase the developed tool for parametric design of these meshes as well as give instructions on how to use the separate tools to generate one of the three mentioned mesh types. The setup of the construction is done by starting from the most rigid level and loosening the geometric properties with transformations, getting the other two.

Three construction starting points are presented for designing grid-shells with dual meshes (Figure 7). The design process always begins with a square grid in the u, v plane, ensuring that the divisions remain square. After this, Mobius transformations are used to deform the grid in plane and inverse stereographic projection is applied to create two orthogonal circle packings on the sphere (giving rise to a Koebe mesh). In third case the conformal mapping of tangent circles is done directly on the sphere. All of the steps are divided into different Grasshopper (GH) components with their input parameters which makes possible to combine them easily and intuitively without the necessity of geometry theory from the Section 2 (Figure 7).

Dual meshes are divided into three levels: Level I represent MS-mesh, obtained by applying Christoffel duality to the Koebe meshes. Level II is achieved by applying a Möbius transformation to *Level I*, which relaxes the minimal surface condition but retains the isothermic mesh properties. Level III can be achieved by applying a projective transformation to Level II, losing the circular mesh property but maintaining the Koenigs property. Alternatively, a projective transformation can be applied directly to Level I, resulting in Level III. Despite differences in geometric properties, all mesh levels are Koenigs, sharing the advantages of dual meshes.

It is also important to emphasize that, except in the case of Level I, in the other two levels (II and III), it is possible to alternate the application of Möbius or projective transformations with Christoffel duality in order to obtain different forms of Level II or III (indicated in yellow and green in Figure 7). This property enables the generation of an unlimited number of different forms of dual meshes. In the continuation, the application of the strategies for constructing dual networks across the three levels is presented in following subsections.

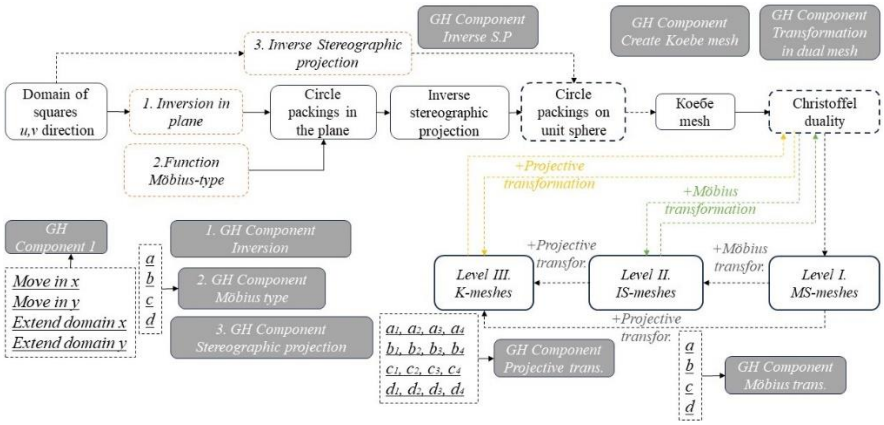


Figure 7. Strategies for constructing Koenigs meshes within three defined levels with their GH components and input parameters

3.1 Procedure for Constructing Discrete Minimal Surfaces – Level I

The first subsection outlines the procedure for constructing Level I dual meshes – discrete minimal surfaces. Since this represents the level with most geometrical constrains, the fabrication advantages include not only planar panels, but also nearly orthogonal edges, square-like quad proportions, and straight unfoldable strips of all box elements. These properties remain unchanged regardless of the design steps taken using GH components. To construct them parametrically, the three conformal mapping cases are considered (Figure 7), with corresponding design procedures. The first case involves applying an inversion to a 20x20 square grid with the origin at $(0,0,0)$ (Figure 8a), resulting in a deformed circle packing (Figure 8b).

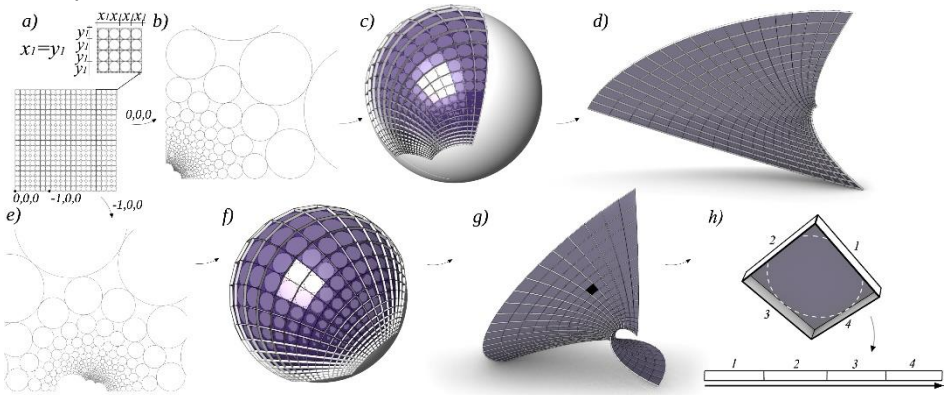


Figure 8. Level I mesh: Start with a square grid (u, v), apply circle inversion, then use inverse stereographic projection to create a Koebe mesh. Apply Christoffel duality to obtain the MS-mesh.

Next, the inverse stereographic projection is applied sending the circle packing in the (u, v) domain to a circle packing in the sphere. The Koebe mesh is then constructed using these circles and the offset, defined by the normals at the tangent points of the mesh edges (Figure 8c). All Level I networks thus have an edge offset. The Christoffel duality procedure is then applied to create an MS-mesh of Enneper type [4] – Level I (Figure 8d). The discrete normals are used to construct its edge offset mesh (EO-mesh) of the Enneper mesh, which give rise to quad blocks, that unfold straight. This holds true for all the presented Level I cases (Figure 8h, Figure 9h, Figure 10h).

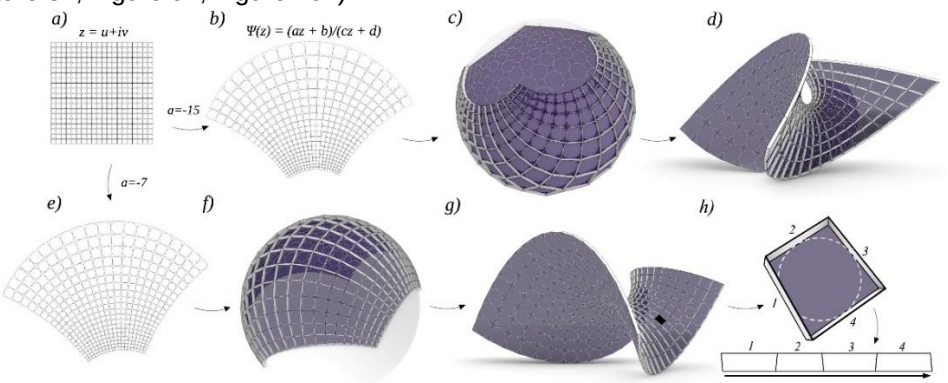


Figure 9. Level I: Möbius map and inverse stereographic projection yielding discrete minimal surfaces via Christoffel duality.

This MS-mesh of Enneper type construction itself is not new, but this work focuses on developing tools and input parameters for experimenting with shell forms. By adjusting the position of the initial u, v plane relative to the inversion circle's center, the grid resolution, and the inversion circle's radius, different mesh forms can be generated. For example, shifting the starting plane from (0,0,0) to (-1,0,0) alters the circle packing (Figure 8d), Koebe mesh (Figure 8f), and final Enneper mesh form (Figure 8g). Increasing the grid rows stretches the mesh, revealing a larger mesh domain. These steps are implemented as components in the GH program, allowing users to modify the grid-shell form at each stage by changing the components input parameters.

The second example of a discrete minimal surface is derived from a Möbius-type conformal mapping Ψ in the plane. Starting with the division of the u,v plane into the standard initial circle packing (Figure 9a), the mapping is applied, creating a deformed circle packing in u, v plane (Figure 9b). Using inverse stereographic projection, the circles are mapped onto the circles in the sphere, which give rise to in the Koebe mesh (Figure 9c). Applying Christoffel duality then generates the discrete minimal surface (Figure 9d). The Möbius transformation generator parameters $a, b, c,$ and d control the mesh's form, with changes shown in Figure 9d, e, and f.

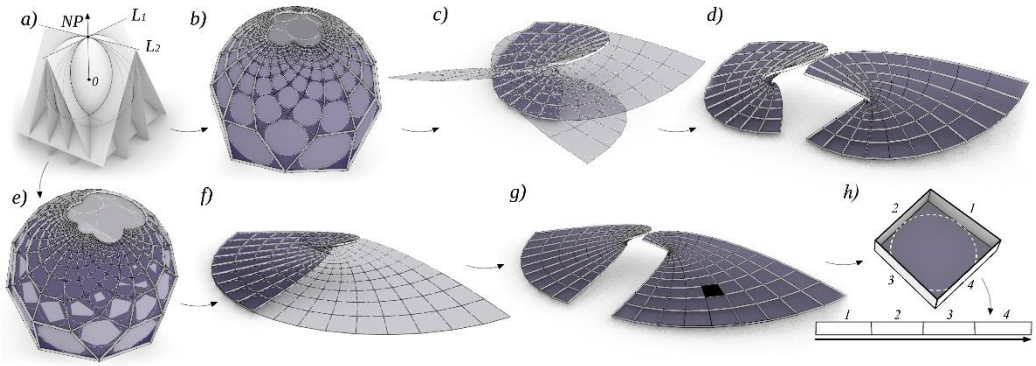


Figure 10. Level I: Construction via orthogonal plane strands and Christoffel duality for discrete minimal surfaces.

The last example involves constructing the conformal parametrization of the sphere using inverse stereographic projection. A geometric intuition of the mapping No (inverse stereographic projection) is as follows. It is network (on the sphere) can be obtained as the intersections of two sets of planes passing through orthogonal lines L_1 and L_2 at the north pole (Figure 10a). Once again, to obtain circle packing, we divide the u, v domain into squares upon which we have the initial standard circle packing, which is then sent by No to a circle packing on the sphere. Following the process, the Koebe mesh is constructed, and Christoffel duality is applied to form a discrete minimal surface (level I). If self-intersection occurs, an asymmetric section is extracted and adjusted symmetrically. A second variant is created by changing the domain parameters from the first GH component. To confirm that all surfaces derived from Christoffel duality are discrete minimal surfaces, the properties are checked according to geometry theory (cf. Section 2.3).

3.2 Procedure for Constructing Isothermic Meshes – Level II

This subsection focuses on constructing IS-meshes (Level II). In this case, the IS-mesh retains all fabrication advantages from the previous level, except for straight unfolding of box

edges, as it is no longer an EO-mesh. Planarity, near orthogonality, and square-like quad proportions still remain. These are obtained by applying Möbius transformation (MT) to Level I meshes. Doing that, they also retain the properties of s-IS mesh of the quads as the MT keeps the inscribed circles and spheres inhereted from discrete minimal surface. However, the saddle condition is no longer garantied. The first example is the MS-mesh of Enneper type (Level I), transformed using MT based on formulas from Section 2.1.1, with parameters $a = 0.5, b = 0, c = -0.4, d = 0$. The result is an s-Isothermic mesh with kept circular mesh which is not an MS-mesh (Figure 11b). Duality is verified by constructing panels via diagonals and checking their planarity, which is satisfied, as well as their cross-ratios condition (Figure 11b, right detail).

As mentioned, the isothermic (circular) mesh has constant vertex offset, when defining the shell thickness. This discrete normal at a vertex is defined as the avergage of the four face nomales of the adjacent quads meeting at this vertex. Planarity checks confirmed no geometric torsion, as expected for circular meshes. As mentioned above, this is an important fabrication advantage as these planar lateral faces are the basis for the beams in the grid-shell.

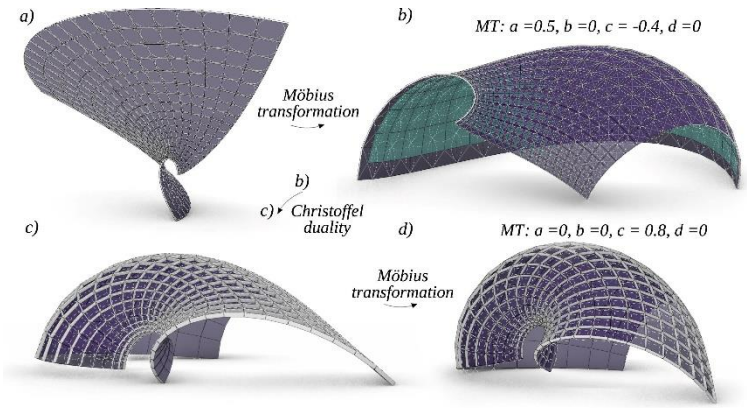


Figure 11. Level II Isothermic mesh variants from Enneper type MS-mesh via Möbius transformations and Christoffel duality.

To demonstrate the design tool, alternating Christoffel duality and Möbius transformation were applied, generating two more mesh variants (Figure 11c, d), with new MT parameters: $a = 0, b = 0, c = 0.8, d = 0$. A second iteration of the same principle was applied to a discrete minimal surface generated using a Möbius transform (in the plane), then applying the process described above (Figure 12a). To reach level II, a Möbius transformation was applied with parameters $a = 0.5, b = 0, c = -0.4, d = 0$ (Figure 12b). The resulting mesh retained circular properties, and Koenigs mesh properties were applied to generate (green) panels constructed along white diagonals that are also planar and therefore can be also fabricated as flat secondary covering (Figure 12b). The main (purple) panels are also planar, satisfy closure condition and therefore duality. Offset points were generated as before, confirming absence of geometric torsion.

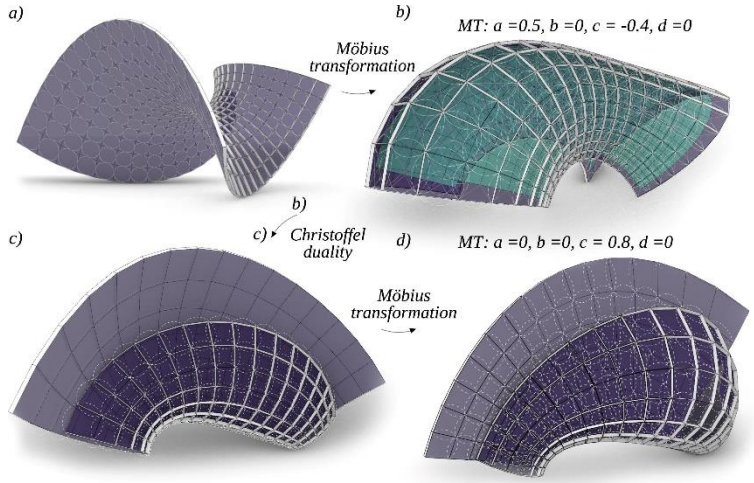


Figure 12. Level II Isothermic mesh variants from Christoffel duality and Möbius transformations.

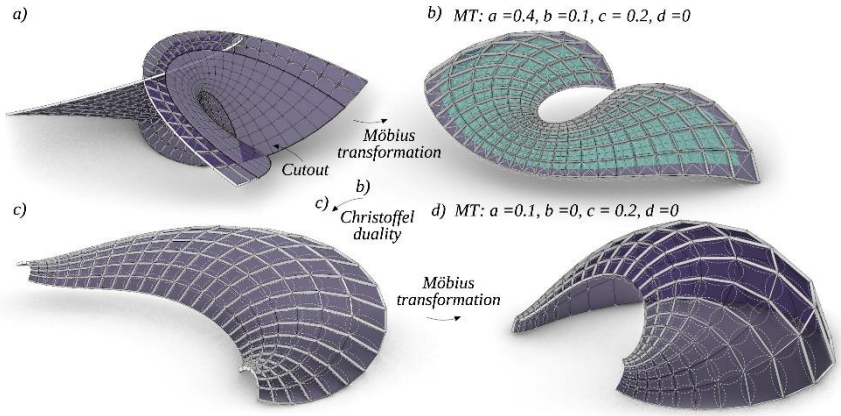


Figure 13. Level II Isothermic mesh variants from pencil of planes MS-mesh via Möbius transforms and Christoffel duality.

Two additional examples demonstrate alternating Christoffel duality (Figure 12c) and Möbius transformations ($a = 0, b = 0, c = 0.8, d = 0$, Figure 12d), showing how different isothermic mesh variants can be generated through iterative application. This process can be repeated for further exploration using the input parameters of the GH components and apply them successively.

The last case shows level I discrete minimal surfaces (from inverse stereographic projection) transformed into level II isothermic meshes (Figure 13a). The results are shown in Figure 13b–d. Parameter experiments revealed that: a and b increase asymmetry, c alters curvature, and d scales the grid-shell. The initial mesh position and size also influences the transformation effect—placing the mesh at $(0,0,0)$ and scaling it properly is recommended. Like mentioned, separate Grasshopper components were created for Möbius transformations and Christoffel duality, allowing easy alternation and further shape exploration. Thanks to the developed approach and tools, no matter which mesh shape is obtained the fabrication properties of the quads are kept. However, to demonstrate the

strategy's full potential, the next step is level III, defined purely by Koenigs meshes without additional properties.

3.3. Construction Method of Koenigs Meshes – Level III

Level III meshes, defined as Koenigs meshes, involve only the application of duality4 and lack properties of minimal or isothermic meshes. At level III, the mesh retains only quad planarity as a fabrication advanatge. Being the least constrained, they can be generated in various ways. Recall that level III contains all the other levels in it. More precisely, level I is contained in level II which is contained in level III. In other words, an MS-mesh is an IS-mesh and a K-mesh and any IS-mesh is also a K-mesh. But not the other way around.

Koenigs meshes are preserved by projective transformation (PT), which maintains planarity but not IS-meshes nor MS-meshes. PT is applied by putting their formula presented above in Grasshopper as a component that recalculates point positions. Like with Möbius transformations, PT can alternate with duality to generate diverse mesh forms. Note that, since PT preserve planarity, the application of PT to IS-mesh including their planar later face (obtained by their normals) will result in K-meshes with later faces that are planar. However, the lines of intersections of these tranformed later faces are no longer functioning as vertex normals (recall K-meshes are not circular). This presents one additional fabrication advantage of also fabricating boxes from PQ strips (but not straight like in MS-mesh).

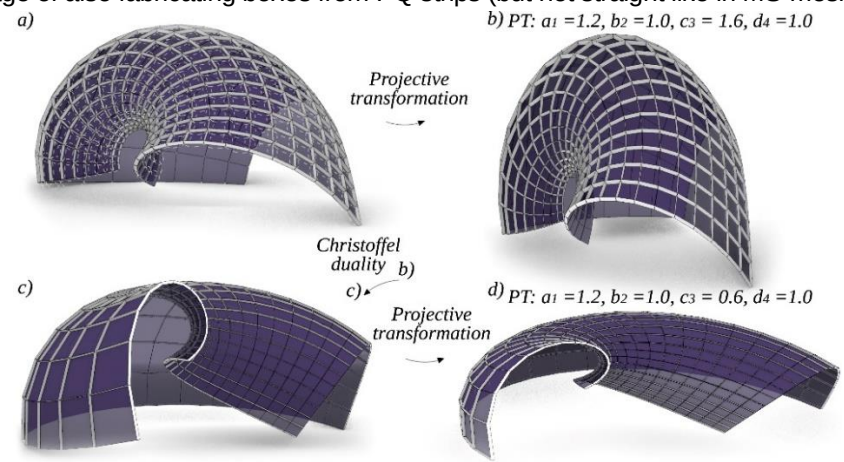


Figure 14. Koenigs mesh Level III variants via projective transformations and Christoffel duality from isothermic mesh from Figure 11d

The first example begins with a Level II mesh created by alternating Möbius transformation and Christoffel duality. A projective transformation is applied ($a_1 = 1.2, b_2 = 1.0, c_3 = 1.6, d_4 = 1.0$) resulting in a Level III mesh. When parameters a_1, b_2, c_3, and d_4 equal 1.0 (others are 0), the mesh remains unchanged—serving as a starting point for gradual adjustments to observe shape changes. Applying duality afterwards yields a different mesh shape, while a second PT further deforms it, producing another Level III variant. Three more Koenigs mesh examples are constructed similarly. Initial meshes were chosen from prior

[4] Note that we refer to it as Christoffel duality for IS and MS meshes, but simply as duality for Koenigs meshes—following smooth geometry conventions, even though the discrete construction is identical – same GH component.

example types. Starting from either Level I or II, PT and duality is applied iteratively using GH components and its input parameters to produce various Level III mesh forms.

In each example, the planar condition of panels and absence of geometric torsion were checked as well as planarity of the secondary mesh constructed by intersection of diagonals, which are both crucial fabrication benefits of Koenigs meshes. While planarity is naturally ensured by the projective transformation (PT). It is crucial to treat the initial mesh and its offset carefully when applying PT to an isothermic mesh, as was explained in the previous paragraph, namely the PT sends two (vertex) offsets of IS-meshes to two K-meshes that are not themselves offsets in the strict term (as the circularity is lost). Now, applying further a Chrsitoffel dual transform will further exacerbate the situation as the planarity of these later faces will be lost as well. To summarize, in dealing with purely K-meshes the notion of an offset mesh is not as clear as it is in IS-meshes (with their notion of Vertex Offset) or the MS-meshes (with their notion of Edge Offset). Thus, for K-meshes, we use the discrete normal at a vertex as the avergage of the four face nomales of the adjacent quads meeting at this vertex, checking if the resulting faces have no geometric torsion for the given offset, which turned out to be the case in all showcased examples.

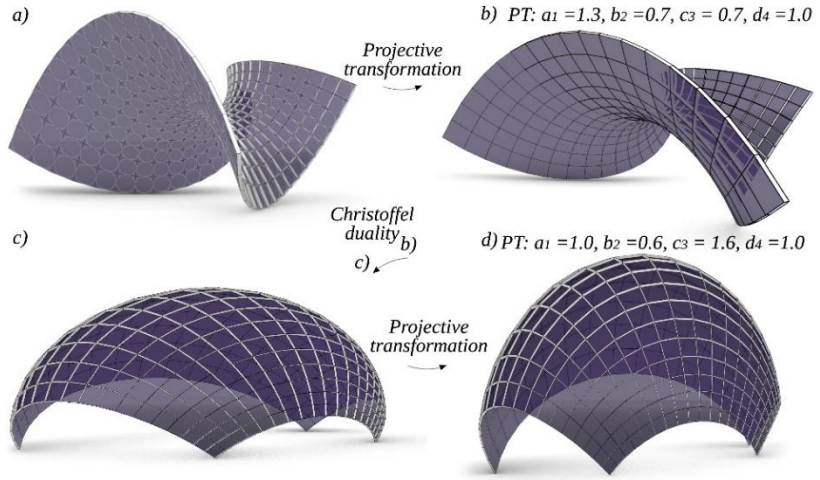


Figure 15. Koenigs mesh Level III variants from discrete minimal surface via projective transformations and Christoffel duality from mesh at Figure 12a

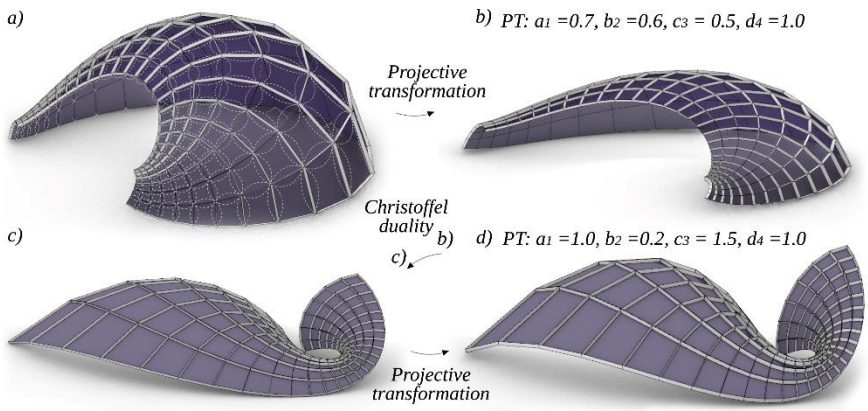


Figure 16. Koenigs mesh Level III variants from isothermic mesh via from Figure 13d projective transformations and Christoffel duality.

Experimenting with various PT input parameters revealed its effects differ significantly from those of the Möbius transformation. PT is more intuitive, as it involves affine transformations such as translation, scaling, rotation, reflection, and their combinations. Analyzing the examples, we found that parameters a and b stretch the mesh along the x and y axes, c stretches along the z-axis, and d scales the mesh. Like Möbius transformation, translating the global mesh in space will have a strong effect on the deformation of the outcome transformed mesh. In general, to better understand the morphological effect of the parameters it is advised to first keep the mesh in its standard position with respect to the origin before applying the transformation.

4. CONCLUSION

In this paper construction methods for Koenigs meshes in modular grid-shell design, were studied. Design strategies for discrete isothermic surfaces were formulated, a topic not extensively explored in architectural context. The same is done for the discrete minimal surfaces which possess special edge offset with straight unfolding quad blocks and square-like element proportions, favorable for lots of fabrication techniques.

Tools for designing these meshes were developed, categorized, and presented across three levels based on their fabrication constraints. Möbius and Projective transformations were then applied to preserve key geometric properties within each level while enabling limitless spatial variations. By following simple geometric rules, the developed methods and tools from different levels (I, II and III) can be used together by combining the developed GH components and trying out different input parameters. This flexibility increases design freedom and solutions within controlled local geometry of module which is one of main advantages of the developed strategy. The distinction between levels is crucial for the architectural implementation of the tools, as it should directly inform design decisions based on the available fabrication methods, as explained at the beginning of each subsection in Section 3. Also, developed tools help visualize the benefits and enable the intuitive implementation of fabrication-oriented design within pre-rationalization approach. They educate designers about these special mesh types that would otherwise be inaccessible and hard to implement. Algorithms were written in Grasshopper (GH) using a combination of available components and Python scripts with GH Python Remote. As separate components, these tools can be easily combined with each other and integrated with other Grasshopper components. This flexibility is crucial for adopting the framework across diverse architectural projects. Project-specific parameters—such as mesh orientation, scale, position, and element size or shape—can be defined by the designer and manipulated using the presented input parameters to suit the specific needs of each project.

ACKNOWLEDGMENTS

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Review paper

SHAPING THE SPACE OF CONCERT HALLS AS CULTURAL VENUES THROUGHOUT HISTORY AND ITS INFLUENCE ON CONTEMPORARY DESIGN

Marko Jeremić[1]

Abstract

The development of concert halls throughout history reflects the innovation of architectural and acoustic principles, adaptation to social, cultural and technological changes, as well as changes in the needs of performers and audiences. The design process, from the first spaces intended for musical performances to today's multifunctional concert halls, has been accompanied by adaptation to various aesthetic and functional requirements. The paper analyzes key historical periods in concert halls, starting from ancient and medieval spaces, through baroque and classicist halls, to contemporary concert buildings. The focus is on architectural features and acoustic principles that have developed over the centuries and created contemporary concert space design. The aim of the research is to identify, through an analysis of historical development, the key principles that have shaped the development of concert halls throughout history, as well as to examine their impact on the application of the principles in contemporary architectural design. Special emphasis is placed on sustainability, innovative technological approaches and adaptation to contemporary requirements of performers and audiences.

Key words: *Concert halls, Historical development, Contemporary design, Architectural design*

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1. INTRODUCTION

The architecture of concert halls has always played a complex role in the cultural and urban life of the community. Their development throughout history reflects aesthetic, technological and social changes, with the relationship between performer and audience remaining a central shaping element. Starting with ancient amphitheatres, through richly decorated Renaissance and Baroque halls, all the way to modernist and contemporary buildings, the space of the concert hall was constantly subject to evolution. Historical forms and acoustic principles of design provided the basis for the creation of flexible, functional and technologically advanced spaces, which respond to contemporary demands for multifunctionality, sustainability and urban integration [1].

In the contemporary context, concert halls are seen as cultural centers that connect art, technology and society. Their designs increasingly include adaptable stage configurations, energy efficiency and digital systems, but still draw inspiration from historical spatial-acoustic solutions. Therefore, analyzing the historical development of these buildings is not only an academic reflection, but also a necessary prerequisite for the creation of modern architectural solutions that serve the cultural, educational and urban needs of society.

The subject of the research paper includes the specificity of the design of the space of concert halls through historical periods, focusing on the development of spatial, architectural and acoustic characteristics, as well as the identification of the principles that influenced the concepts of modern concert halls. The goal of the research is to analyze the historical development of concert halls to systematize the key spatial, form and acoustic principles that have influenced the architecture of contemporary halls and to identify concepts for implementation in contemporary design with a focus on sustainability, technological innovation and adaptation to modern demands of the audience and performers. During the preparation of the paper, the applied research methods are data collection and analytical method, for the sake of systematic presentation of historical periods, data analysis and comparative method, which identified and compared spatial and acoustic characteristics through different periods, as well as the case study method, which enabled the analysis of modern realized objects in order to recognize the application of historical principles.

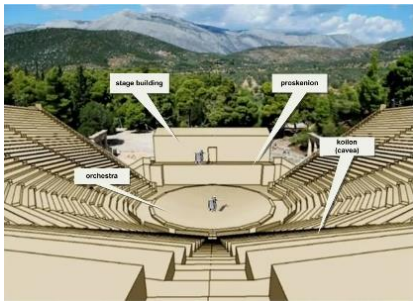
2. HISTORICAL DEVELOPMENT OF CONCERT HALLS

The historical development of concert halls reflects the centuries-old evolution of architectural, technological and musical concepts. From the first public spaces for music to precisely designed concert halls, each historical stage brings new spatial, acoustic and social values that influence the shaping of cultural objects.

2.1. Ancient and medieval music spaces

The earliest form of public buildings designed for the efficient communication of theatrical and musical performances before large audiences were the ancient open amphitheatres, which date back to BC. The open ancient theater marks the starting point of the meeting between architecture, acoustics and theatrical performance. This simple structure consists of a large stepped audience space in the shape of a truncated cone, a flat stage area for the choir ("orchestra") and a stage building with a raised stage for the actors (Fig.1a). One such type of amphitheater is Epidaurus in Greece (Fig.1b). The "good acoustics" of these

amphitheatres, and Epidaurus in particular, was the result of a number of parameters: sufficient sound amplification on the stage, uniform spatial acoustic coverage, low reverberation, improvement of voice tone, which contributes to perfect intelligibility even on seats 60 meters away, provided that the noise in the environment is low [2].

a 

b 

Figure 1a - Structure of the open-air theater of the Hellenistic period, https://acoustics.org/ and 1b - Amphitheater in Epidaurus, Greece, https://www.lonelyplanet.com/

During the Middle Ages, musical performances were moved to sacred buildings - churches, cathedrals and monasteries, where new acoustic possibilities based on reverberation and vertical spatiality arose. In this period, there are no separate concert halls; the music is a function of the liturgy and the spaces are not designed for the purpose of acoustic optimality, but they still provide inspiration for later forms.

2.2. Renaissance and Baroque halls

At the beginning of the Renaissance, there was an increase in interest in secular music and public performances outside the church framework. The first halls in palaces and courts, like those in Florence and Venice, were rectangular in shape, often decorated with frescoes and with high ceilings, but still without standardized acoustics.

The Baroque period brings significant development: the first specially designed music halls appear. Prominent examples are the Musikverein in Vienna and the Gewandhaus in Leipzig. In this period, the typology of the rectangular hall ("shoebox" form) begins to develop, which will later become a classic model for concert halls. Ornamentation, richness of decoration and connection of music and architectural expression dominate these objects, while acoustic characteristics begin to gain importance in design.

The first recorded public concerts took place in London in 1672. Although the idea worked well there, Germany and France did not follow their example until 1722 and 1725, respectively. Dedicated rooms for public concerts appeared in the following years, but it was only by the mid-18th century that they became firmly established as the dominant venues for musical art [3]. The architecture of concert halls, due to the increase in audience size and the corresponding growth in the number of musicians in the orchestra, had to respond to these new demands. The construction of Hicksford's Rooms (1738) and Holywell Music Room (1748) in England (Fig.2a) provided seating for 300 people. This trend of increasing seating capacity and longer reverberation time continued with the Hanover Square Rooms from 1775 in London (Fig.2b), which accommodated 800 people and had a reverberation time of approximately 1 second, as well as the 1781 Leipzig Altes Gewandhaus (Fig.2c) for 400 people with a reverberation time of 1.3 seconds [3].

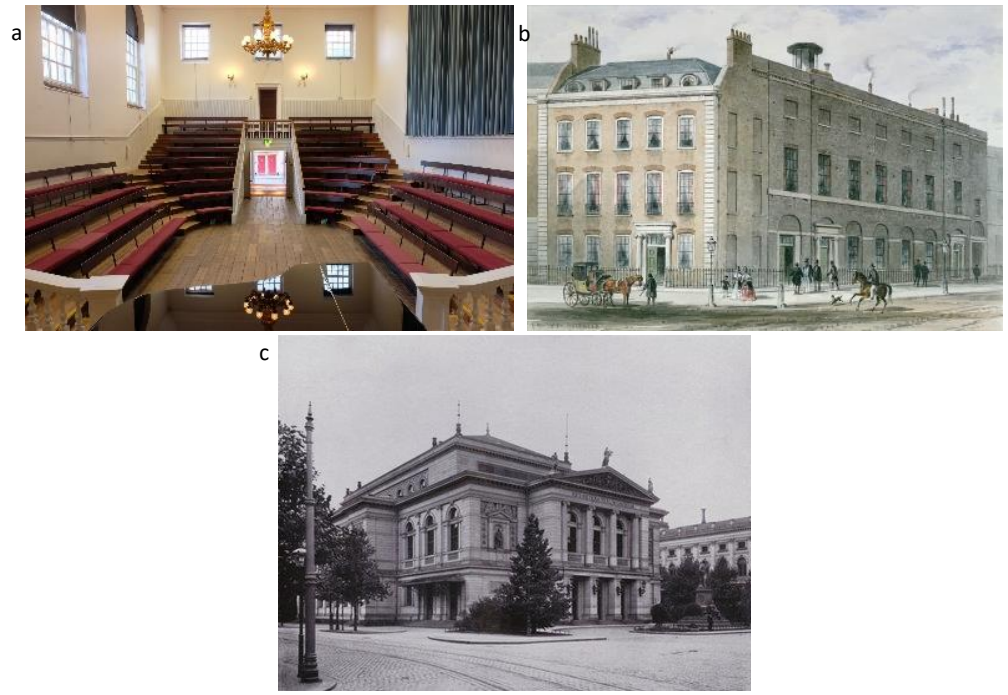


Figure 2a - Holywell Music Room, Oxford, England – interior view, https://www.musicatoxford.com/, 2b - Hanover Square Rooms, London, England, https://www.alamy.com/ and 2c - Leipzig Altes Gewandhaus, Germany, https://www.gewandhausorchester.de/haus/historie/

2.3. Classical concert halls of the 19th century

This period is considered the golden age of the development of concert halls. The first public facilities dedicated exclusively to the performance of music were built, such as the Musikverein in Vienna (1870) (Fig.3a) and the Concertgebouw in Amsterdam (1888), which are still considered one of the most acoustically high-quality halls in the world. Typical features of these spaces include a rectangular shape ("shoebox" shape), high ceilings, vaulted galleries and decorative elements that contribute to the diffusion of sound [4].

The development of instruments and the expansion of the orchestra, together with the increasingly numerous audience, led to an increase in the dimensions and capacity of concert halls. At the same time, the awareness of the importance of the choice of materials and the finishing of surfaces for sound quality is developing, which makes the architecture of concert halls a combination of acoustic science and artistic expression.

Along with the growth of the orchestra came the need for a conductor - a role that did not exist in the modern sense until then. Numerous performers are more difficult to coordinate without clear leadership, so the conductor becomes a key figure. Also, in the compositions of this period, the accent increasingly shifts from the melody to the tone color, which additionally affects the acoustic requirements of the space.

In parallel with this development, the role of concert halls goes beyond a purely musical function. Facilities such as the Royal Albert Hall in London (1871) (Fig.3b) and Carnegie Hall in New York (1891) (Fig.3c) became large cultural centers, intended not only for concerts but also for various events, which further confirms the importance of such spaces in the urban and social context [5].

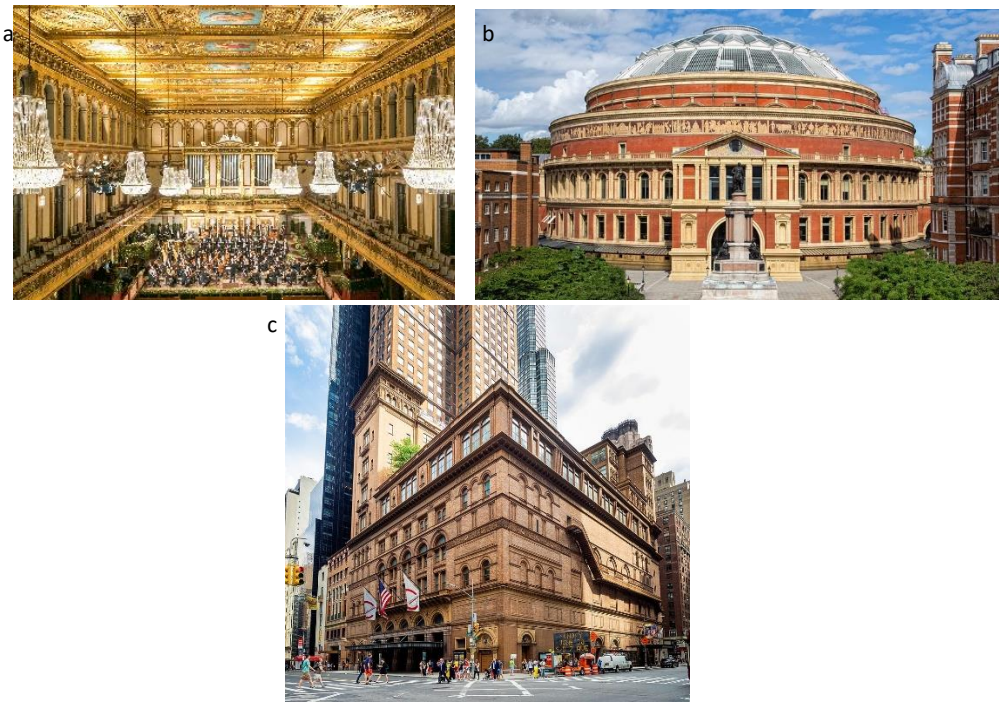


Figure 3a - Musikverein, Vienna, Austria – interior view, https://concert-vienna.com, 3b - Royal Albert Hall, London, England, https://www.londontheatre.co.uk and 3c - Carnegie Hall, New York, United States, https://www.waltersgroupinc.com

2.4. Beginnings of the Modern Approach in the 20th Century

In the 20th century, technological progress, especially in the field of acoustics and modern building materials, brought significant changes in the design and construction of concert halls. New approaches enabled the emergence of increasingly sophisticated facilities, adapted not only to classical music, but also to a wider range of musical genres and other types of events. The diversity of musical expressions and the growing needs of performers and audiences have led to the emergence of multi-purpose halls, capable of transforming according to the demands of the program — from symphonic concerts, through rock performances, to conferences and multimedia events.

One of the first significant examples in this new era is the St. Petersburg Philharmonic Hall (Fig.4a), built in 1900. Located in the then cultural center of the Russian Empire, this hall played a key role in the promotion of classical music in the 20th century, hosting numerous world-famous orchestras, conductors and soloists. Its opening symbolically marks the transition between traditional design principles and a new, modern approach that will become dominant in the following decades [3].

As the century progresses, concert halls deviate more and more from the classic "shoebox" typologies. Architects began to experiment with different spatial solutions - wind-shaped forms, arena and amphitheater layouts appeared, as well as so-called "vineyard" configurations, among which the most famous example is the Berliner Philharmonie (Fig.4b and 4c), opened in 1963 according to the project of Hans Scharun. These new models emphasize not only the acoustics, but also the visual communication between the performer and the audience, as well as the flexibility of the space [4].

a 

b 

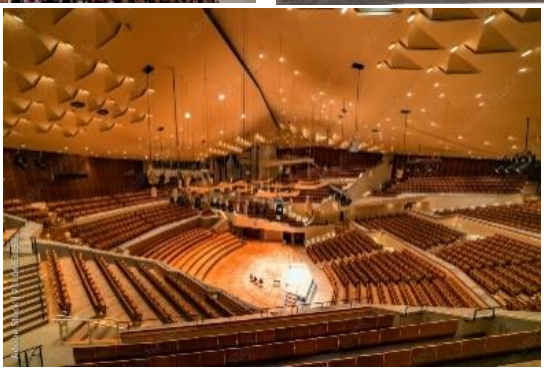
c 

Figure 4a - Saint Petersburg Philharmonia, Russia – interior view https://guideforyourussia.com, 4b - Berliner Philharmonie, Berlin, Germany and 4c - Berliner Philharmonie, Berlin, Germany – interior view, https://www.archdaily.com

At the same time, variable acoustic elements - movable panels, ceilings and curtains - are introduced into the concert halls, which enable the optimization of the sound environment in accordance with the type of performance. Concert halls become multifunctional spaces, intended not only for music, but also for education, conferences and digital artistic performances, thus gaining a new social and cultural role in the contemporary urban context.

3. ARCHITECTURAL AND ACOUSTIC PRINCIPLES THROUGH HISTORY

The design of concert halls is the result of a long-term historical evolution in the domain of architecture and acoustics, conditioned not only by aesthetic aspirations, but also by the development of the science of sound, technological progress and social changes. From the original spaces adapted to music - such as court halls and churches - purpose-designed halls, with clear spatial and acoustic goals, have been developed over the centuries.

Classical "shoebox" forms, such as the one in the Musikverein in Vienna, dominated in the 18th and 19th centuries due to their favorable acoustic characteristics, while the 20th century brought experimentation with new spatial concepts, such as windward and arena forms, as well as the "vineyard" configuration - the most famous example being the Berliner Philharmonie from 1963. Over time, the concert hall grows into a complex cultural facility that, in addition to the main hall, includes spaces for education, social activities, rehearsals and multimedia events [6].

Historically speaking, acoustic solutions were primarily the result of experience and tradition, with the use of natural materials such as wood and fabrics. With the development

of acoustics as a science at the end of the 19th century, more precise design began based on physical parameters such as reverberation and absorption. Today, advanced computer simulations and flexible elements (movable panels, curtains, diffusers) are used in the design of halls, which allows adaptation to different musical genres.

Technological innovations significantly influence the architecture of these spaces. The use of modern materials such as concrete, steel and glass leads to larger spans and freer forms. The use of electroacoustics opens up new possibilities in sound transmission, but also poses challenges in the relationship between natural and amplified acoustics. Information technology, including BIM, enables precise modeling and optimization of the project before construction itself. In the last decade, the emphasis is increasingly on sustainability, energy efficiency and the integration of buildings into the urban and ecological whole [7].

4. CONTEMPORARY APPROACHES IN CONCERT HALL DESIGN

Contemporary concert hall architecture faces a series of new challenges that go beyond traditional acoustic and aesthetic requirements. Today's facilities are designed as multifunctional and technologically flexible spaces, designed to respond to the diverse cultural needs of the community. In addition to classical music performances, they are increasingly used for theater performances, electronic performances, film screenings, conferences and educational programs. This diversity requires the implementation of movable stage elements, flexible seating, variable acoustic panels and modern digital systems, which allow for rapid adaptation to different types of events [8].

In parallel, sustainability is becoming a central theme in contemporary design. Concert halls are built using energy-efficient materials, passive ventilation and lighting systems, solar panels, green roofs and smart energy management systems. The aim is to reduce the negative impact on the environment, while at the same time increasing the comfort of the users and the long-term economic viability of the facility [9].

Numerous contemporary examples confirm the successful application of these approaches. The Elbphilharmonie in Hamburg, the Walt Disney Concert Hall in Los Angeles, the Harpa in Reykjavík and the Musiikkitalo in Helsinki stand out as buildings that combine architectural innovation, a high level of acoustic precision, sustainability and social openness. Through integration with the urban space, technical sophistication and diverse functionality, these buildings represent new standards in the design of concert venues around the world.

5. THE INFLUENCE OF HISTORICAL PRINCIPLES ON CONTEMPORARY DESIGN

The historical development of concert halls has strongly influenced contemporary design, which, despite technological innovations and more complex programs, still retains the fundamental spatial and acoustic values of the past. Classic forms, such as the rectangular "shoebox", remain relevant due to their proven acoustic efficiency and ability to provide an optimal experience for listeners. On the other hand, new approaches such as the "vineyard" seating arrangement are being developed to achieve a better visual and acoustic connection between audience and performers, creating a more intimate and inclusive atmosphere.

These forms are not just architectural forms, but are the result of centuries of research into acoustics and the organization of space [7].

Architectural references to Baroque and Classicism are still present, but today appear in abstract and modernized forms. They are manifested through the careful selection of materials, the way of using light and the internal forms of the space that are reminiscent of historical models, but are adapted to modern aesthetic and functional requirements. In contemporary projects, traditional elements are often combined with the most modern technologies and design solutions. Natural materials, such as wood and stone, are used not only for their visual appeal, but also for their ability to improve acoustics and create a warm, pleasant atmosphere that contributes to the overall experience of visitors [10].

Also, the rhythm and repetition of motifs characteristic of classical architecture are transferred into contemporary expressions through the use of panels, lamellar structures and acoustic elements, which simultaneously serve aesthetic and functional purposes. Light, which in history often had a symbolic meaning associated with spirituality and ceremoniality, is today a key design tool for shaping the atmosphere of a space and the emotional experience of the audience. In this way, contemporary concert hall design achieves continuity with a rich heritage, but at the same time does not remain trapped in the past – historical principles are not mechanically copied, but are creatively reinterpreted and adapted to the needs of contemporary society and art forms, allowing spaces to be functional, aesthetically relevant and culturally significant.

6. CONCLUDING CONSIDERATIONS

The design of concert halls as objects of culture is the result of a long-term and continuous evolutionary process in which artistic expression, technological innovations, acoustic knowledge and socio-cultural context were intertwined. From ancient theaters and medieval churches, through baroque and classical halls, to today's multi-functional and technologically advanced buildings, the architecture of concert spaces has developed in accordance with the needs of the audience, performers and the wider cultural community.

Historical models, such as the "shoebox" and "vineyard" form, remained relevant as typological and acoustic inspiration, and traditional elements such as proportion, centrality and materiality gained new meaning in the contemporary context. Today's projects do not represent a radical break with the past, but a deliberate synthesis of tradition and innovation. This is best reflected in the effort to make buildings energy efficient, adaptable to different programs and aligned with modern technological and social requirements.

Observing current trends, it can be concluded that the future of concert spaces will be directed towards greater openness, digitization of the experience, integration of new media and social inclusiveness. At the same time, there will remain a strong influence of historical principles that serve as proven foundations in the search for harmony between form, function and experience.

By understanding the past and its creative transformation, architects and urban planners can design concert halls that not only meet high technical and aesthetic standards, but also actively contribute to the cultural identity and dynamics of contemporary society.

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Research paper

MODELING, MAPPING AND ANALYSIS OF URBAN FLOODS - CASE STUDY: SKOPJE 2016

Violeta Gjeshovska[1], Denis Jankulovski[2], Bojan Ilioski[3]

Abstract

An increasing trend of urban floods in Macedonia from past several years causes major damages on the infrastructure, agriculture and human life. Uncontrolled urbanization, inadequate exploitation and management of forest and agricultural land in combination with climate change increase the possibility of more frequent and more intense floods, especially flash floods in urban areas. The subject of this research is the devastating flood that affected the region of Skopje in August 2016, the analysis and determination of the formation process of the flood wave, the modeling and mapping of the flooded zones. A detailed hydrological analysis of the region was developed to determine the reasons for the large peak of the flood wave and a 2D hydraulic model was prepared for the simulation of the propagation of the flood wave and mapping of the flood zones. A digital terrain model (DTM) by applying the GIS tools ARC Map and QGIS was prepared and the physical-geographic characteristics of the watershed were determined. For the needs of the hydrological analysis, information about the land use, pedological, geological and climate characteristics were obtained and substrates were developed. For the generation of surface runoff hydrographs, hydrological models with the application of the WINTR 55 software program were created. By applying the HEC-RAS software package, a two-dimensional (2D) hydraulic model was created and flooding zones in the Skopje region have been defined. Calibration and verification of the model was done with aerial photogrammetry of the flood after 72 hours from the beginning of the flood. The results are presented on maps of maximum depths, maximum velocities and maximum shear stresses in the flood zone.

Key words: *Urban floods, intensive rainfall, GIS, hydrological and hydraulical modeling, flood mapping.*

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1. INTRODUCTION

In the past decades, thousands of lives have been lost, directly or indirectly, by flooding. Every year floods cause enormous damage all over the world. Floods are among the most recurring and devastating natural hazards, impacting human lives and causing severe economic damage throughout the world. It is understood that flood risks will not subside in the future, and with the onset of climate change, flood intensity and frequency will threaten many regions of the world [1]. The study with high developing urbanization is potential about flood. In addition, the urban area that has bigger potential effect is not always has the bigger flood vulnerable in extreme climate condition. The system can effectively show urban flooding vulnerability [2]. Heavy convective rainfall often results in flooding in urban areas. Urbanization results into conversion of agricultural land, natural vegetation and wetlands to built-up environments and construction on natural drainages as well increase in the population of those living in flood vulnerable areas such as flood plains and river beds [3]. There is a direct relationship between urbanization and hydrological characteristics; decreased infiltration, increase in runoff, increase in frequency and flood height [4]. Small streams in urban areas can also rise quickly after heavy rain due to higher generated runoff and less concentration time [5]. Changes in the urban area and in storm intensity produce higher flows that exceed the capacity of small culverts under roads designed for non-urbanized areas. Although such structures can be adequate when designed, their capacity may turn out to be inadequate and thereby cause overflows onto the roads creating new water paths and flood the built-up areas. In developing countries, inadequate maintenance of the drainage channels, and debris and solid waste disposed into such drainage systems may accentuate the situation [6]. Those reviewed studies show that the study of flood vulnerability has to pay attention in urban area.

The objective of this study is to analyze and determine the formation process of the flood wave that affected the region of Skopje in August 2016.

The analysis will show that the dominant factors for the formation of the flood wave can be located in the extreme intense rainfall, but the influence of urbanization as well as the inadequate drainage system: culverts and channels and their maintenance/non-maintenance is huge.

1.1. Case Study: Skopje 2016

In August 2016, a flood occurred in the region of Skopje, which caused huge material damages. The estimated value of the total damage is 35.7 million euros, and unfortunately 21 victims [7]. The causes of this catastrophic flood according to different experts are different [8].

The aim of this research is to locate the possible reasons for this situation through the simulation of the flood wave caused by the intense rainfall, measured on the day of the flood [9].

The analysis was done with an appropriate hydrological analysis of the wider region where the flood was observed and a hydraulic model for the propagation of the flood wave downstream.

1.1.1. Study Area

The study area is located in the southwest part of the City of Skopje. It is located in the lower part of the mountain Skopska Crna Gora, in the area of the villages Stajkovci and Smilkovci. The mountain is characterized with rivers descending from high points and carrying eroded materials. Additionally, the geological composition of the region is complicated as there are new sediments in the west, Mesozoic layers in the middle and old Paleozoic layers in the east. The villages Stajkovci and Smilkovci are lowland villages, with 99% agricultural land and close to the City of Skopje which contributes for the villages to be highly populated.

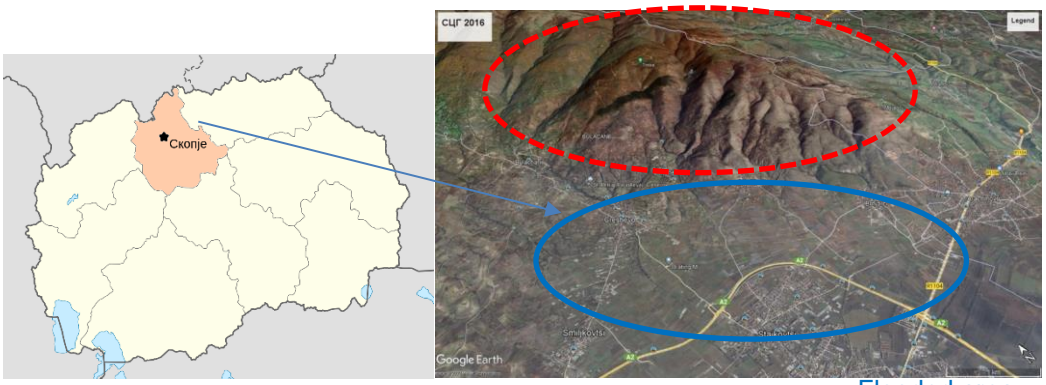


Figure 1. Study Area

1.1.2. Data sources

In this research the data used is measured rainfall for a period of 24 hours in the Skopje region on the day of the flood [8] [10]. The rainfall that is registered is for the period from 17:00 to 22:30 on 06.08.2016, in several automatic measuring stations: Zajcev Rid, Gazi Baba and Karposh and information about the total rainfall according to the pluviograph located at Zajcev Rid, Figure 2. The information shows that the rainfall has an extreme spatial distribution. In further analyses, data from the station in Gazi Baba is used, as the closest one to the flooded area, Figure 3.

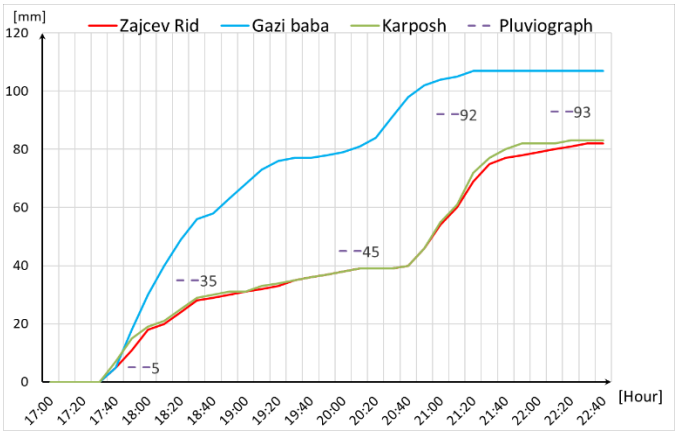


Figure 2. Rainfall hyetograph

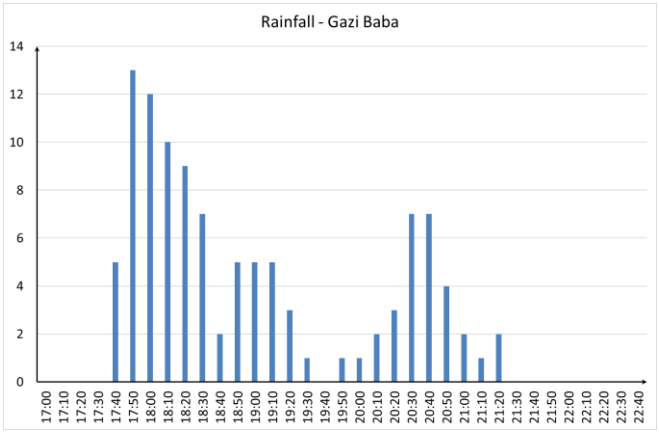


Figure 3. Rainfall hyetograph in measuring station Gazi Baba – histogram display

Digital terrain model of Macedonia in raster format with a resolution of 5x5m was used as a terrain model [11], and information about the land use in this research was obtained by applying the data from the CORINE Land Cover database from 2018 [12]. The information for the soil textures of the land was obtained from the Pedological Map of Macedonia [13] and the geological structure of the subject area from the Geological Map of Macedonia.

2. METHODOLOGY

2.1. Hydrological modelling

The hydrological modelling was done with the use of the software WinTR55. The delineation of the river basins and the defining of their physical-geographical characteristics is done with the help of GIS tools. The raster data is processed through the GIS software ArcMap [14], and with the help of the module ArcSwat the delineation of the 6 river basins was performed, Figure 4. With the analyzes carried by the module ArcSwat, in addition to the creation of individual DTM, the physical-geographical characteristics of each sub-basin were calculated, Table 1. Detailed maps have been created in order to showcase the basic pedological and geological characteristics (Figure 5a, 5b), climatological and meteorological characteristics, as well as land use according to the CORINE Land Cover databases (Figure 5c). Input data for the model for the transformation of rainfall into surface runoff are rainfall hyetograph and spatial distribution of CN. The runoff curve number (CN) is an empirical parameter for predicting direct runoff or infiltration from rainfall excess, known as a “SCS runoff curve number” [15]. A hydrological simulation of the runoff of six watercourses within the subject area was made, namely: Rashtanska river, Bulacanska (Creshnevska) river, Vinicka river, Stracinski watercress, Stracinski torrent and Brnjarska river. The results of the simulations refer to the output profile of the analyzed basins for 7 scenarios with return periods of 2, 5, 10, 25, 50, 100 and 1000 years, Table 2. A typical runoff hydrograph from the model is shown on Figure 6.

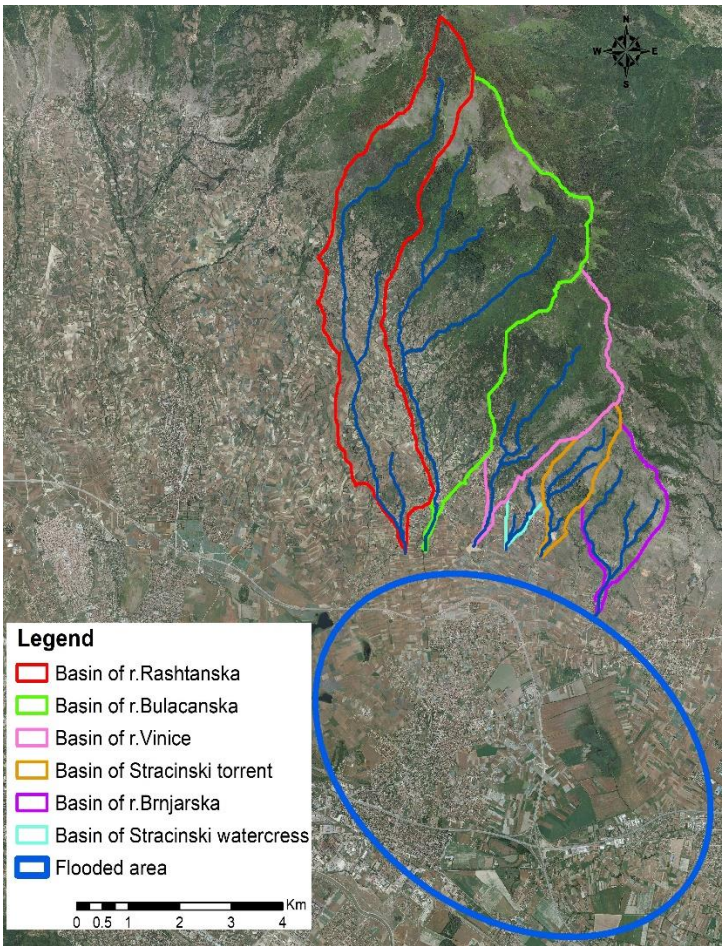


Figure 4. River basins gravitating towards the flooded area

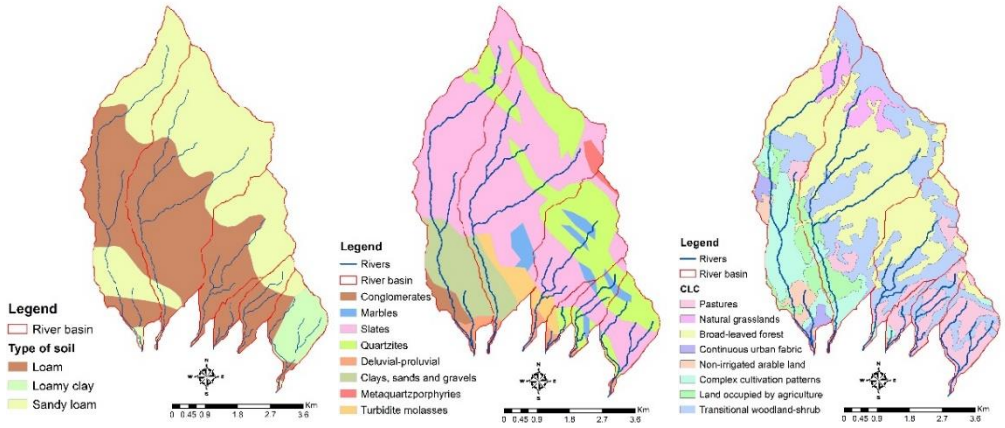


Figure 5. a – Pedological map, b – Geological map, c – CORINE Land Cover map

Table 1. Basic geometric characteristics of the river basins

	F [KM^2]	O [M]	S_S [%]	Z_{MAX} [MASL]	Z_{MIN} [MASL]
Rashtanska river	10.97	19514.66	27.53	1627	288
Bulacanska (Creshevska) river	15.45	22056.14	37.47	1575	287
Vinichka river	6.17	13628.14	38.96	1316	306
Stracinski watercress	0.82	4536.47	29.58	851	310
Stracinski torrent	1.63	8964.44	36.85	1070	331
Brnjarska river	2.77	10047.46	37.03	1016	274

F – area of watershed, O – perimeter of watershed, S_s – average slope of watershed, Z_{max}-maximum elevation in the watershed, Z_{min} – minimum elevation in the watershed.

Table 2. Results from the hydrological analysis

Watercourse	T – period [years] / Q – maximum high waters [m^3/s]						
	2	5	10	25	50	100	1000
Rashtanska river	10.47	21.01	29.11	37.42	49.81	62.89	113.39
Bulacanska river	11.61	25.31	36.06	47.32	63.15	77.73	144.90
Vinichka river	7.38	13.69	19.09	25.64	35.06	42.92	72.65
Stracinski watercress	1.21	2.25	3.15	4.08	5.39	6.46	10.47
Stracinski torrent	2.24	4.11	5.83	7.64	10.19	12.30	20.21
Brnjarska river	4.45	8.36	11.51	14.74	19.25	22.94	36.57

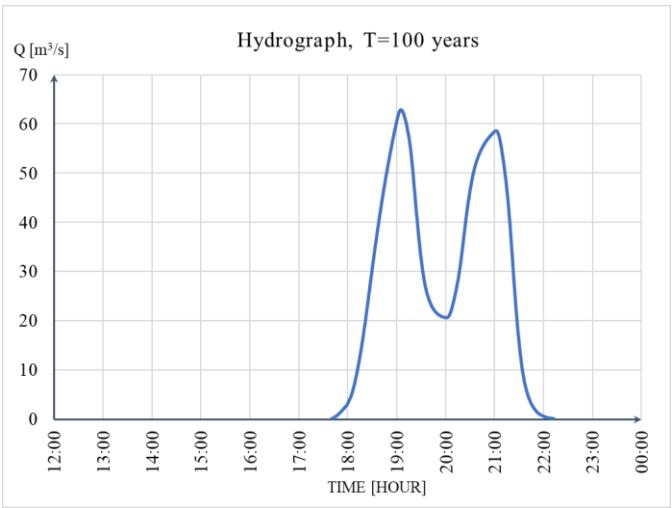


Figure 6. Runoff hydrograph

2.2. Flood Modelling

In the hydraulic analysis for the watercourses within the subject area of Skopska Crna Gora, the software package HEC-RAS was used, made and developed by The Center for Hydraulic Engineering (HEC) of the US Army Corps of Engineers (USACE) [16]. HEC-RAS enables hydraulic analyzes to be performed using one-dimensional, two-dimensional and

combined 1D/2D models for the simulation and analysis of runoff in river systems, as well as unconcentrated surface runoff. Additionally, the software package features sediment transport modules. For the purposes of this research, hydraulic analyzes of the subject area were performed using a 2D model.

The boundaries of the computational grid are defined by an iterative procedure, with successive simulations determining the maximum range of flooded areas in the subject area and based on those simulations the limits of the computational grid are determined.

The flooded areas are modeled with cells with lower density in order to achieve rational durations of the simulations, while in more sensitive zones of the subject area, the grid is more detailed in order to improve the precision of the simulations.

The grid is structured by over 50 000 square cells with maximum dimensions of 30x30m in zone of wide flat flooded areas, while in the zone of the river bed with dimensions of 2x2m (i.e. 1x1 in zones of culverts, bridges, and the ring road itself). The grid cells along the length of the river bed, around the ring road and local roads are correctly oriented with the local landforms by applying break lines, Figure 7a. Based on the land use map the CN is defined in the ranges from 73 to 86, Figure 7b and the roughness coefficient, Figure 7c. The Manning's roughness coefficient varies in the range of 0.013 to 0.1 depending on the land cover, where the lowest is for urban zones and the highest for forest.

Boundary conditions are defined as input and output boundary condition (upstream and downstream) for selected scenario for the occurrence of a flood wave with a return period of 100 years. The upstram (input) boundary condition is defined by importing the runoff hydrographs of all the analyzed watercourses, where the main condition for flow distribution through the inlet profiles is the slope of the energy grade line in the zone of the boundary condition. For the downstream (output) boundary condition of the two-dimensional grid, a normal depth in the output profile zone is defined.

For the simulation, the calculations are done using the diffusion wave equations [17]. The adopted duration of the simulation for the analyzed scenario is 72h, while the calculation interval Δt has a variable value and it is controlled by the condition that the Courants number C ranged from 1 to 3.

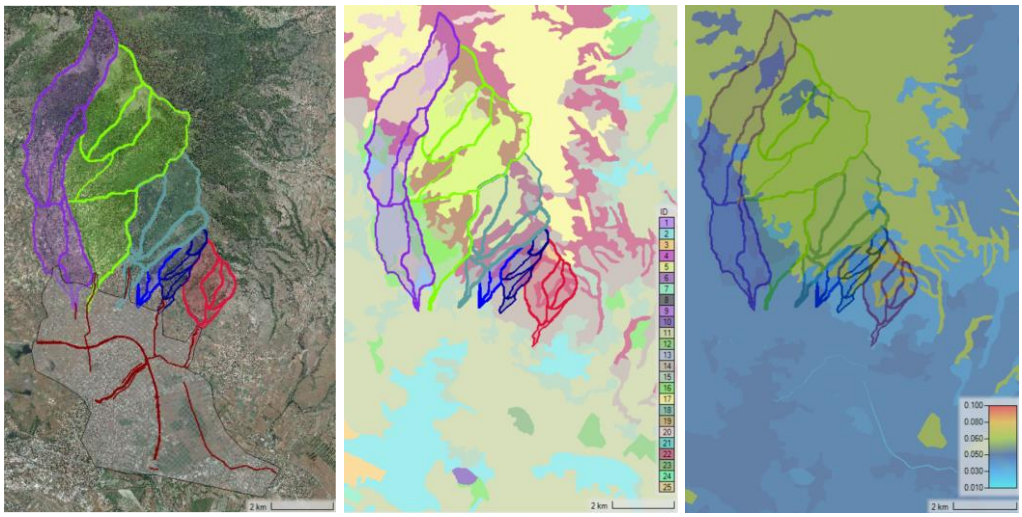


Figure 7. a – 2D computational grid, b – CN, c – roughness coefficient

2.3. Validation Method

For the validation of the model, a comparative technique was used to define the parameters in the model that affect the final results, i.e. the comparison of the calculated and measured parameters. The process of verification of the obtained results is a comparative analysis of flooded areas obtained after 72h according the hydraulic model and flooded areas obtained with aerial photogrammetric images taken two days after the flood.

3. RESULTS

As relevant results of the hydraulic simulation of the water flow at the subject area are separated envelope maps of the maximum values of depths, velocities and shear stresses of the water flow for an analyzed return period of 100 years, Figure 8, 9 and 10.

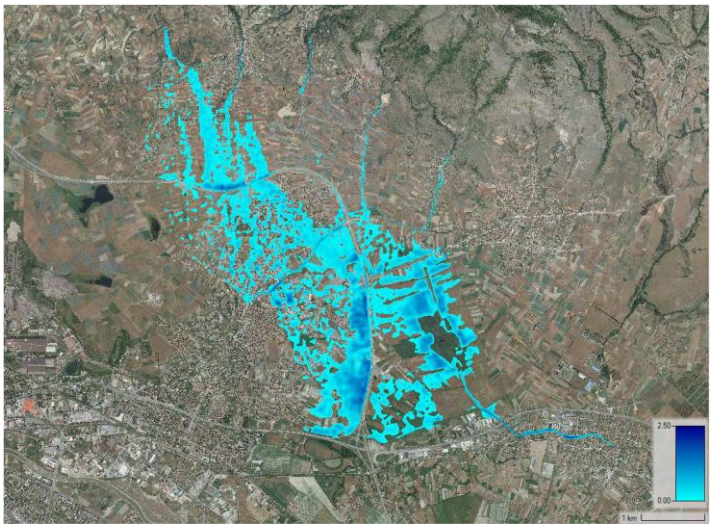


Figure 8. Map of maximum water depths

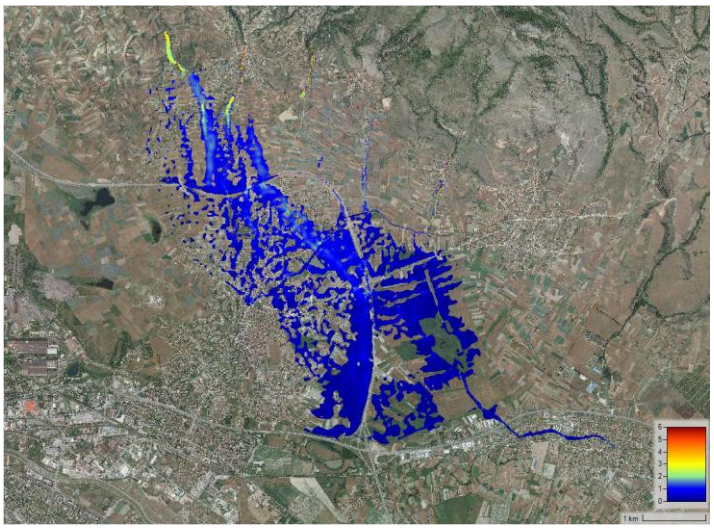


Figure 9. Map of maximum flow velocities

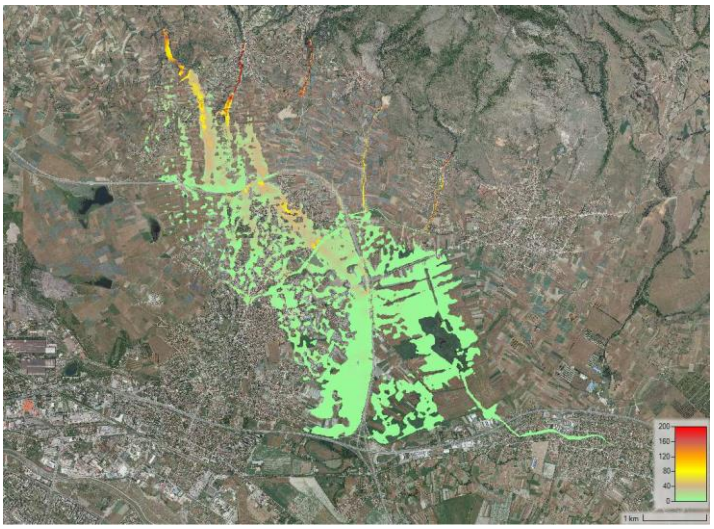


Figure 10. Map of maximum shear stress

Table 3. Monitoring of flood wave and flooded areas

Time period	Flooded area	
	[m^2]	[km^2]
06.08.2016 19:20	1,434,375.00	1.43
06.08.2016 19:50	2,273,425.00	2.27
06.08.2016 20:50	3,370,850.00	3.37
06.08.2016 21:10	3,872,175.00	3.87
06.08.2016 21:40	**4,054,675.00**	**4.05**
06.08.2016 22:40	3,778,995.00	3.78
07.08.2016 17:40	3,030,975.00	3.03
08.08.2016 17:40	2,400,275.00	2.40
09.08.2016 17:40	2,164,875.00	2.16

4. DISCUSSION

By analyzing the results, it can be concluded that there is a significant flooding of part of the urban surface and the arable land in all the settlements, with the biggest flooding being in the area of Stajkovci and Smilkovci. The overflow from the riverbed threatens densely populated residential buildings in populated areas as well as a significant area of arable agricultural land above the ring road of the City of Skopje. The most critical zones occur in close vicinity of the stretch Smilkovci-Stajkovci as well as in the southeastern region of the village Stajkovci. The depth of the dissipated flows from the overflow ranges from a few centimeters to 30 cm, while in the zones around the ring road, channels and rivers, depths of up to 2.5m were reported. The velocities in the zones where the overflow is concentrated reach values of up to 2.5 m/s, causing significant damage to exposed surfaces, objects and unfortunately also human casualties. Along the riverbeds, where most of the flow is concentrated, velocities reach values of over 6 m/s. On most of the flooded areas, the shear stress is greater than 30 N/m^2, which result in the erosion of the agricultural areas. The

maximum shear stress occurs in the zones of the concentrated flows, where they reach up to 200 N/m^2 in individual watercourses due to large longitudinal slopes

The propagation of the flood wave is monitored by analysis of the flooded area, Table 3. The first major impact of flood wave appears at 19:40 immediately after the first peak of the hydrograph. It floods agricultural areas in the attar of Smilkovci and breaks through the ring road of the City of Skopje. Thirty minutes after the arrival of the peak of the flood wave (19:50), the flooded surface increase intensively, covering a residential area in settlement of Stajkovci. In the central area of Stajkovci transits a drainage channel that receives the surface runoff water and transport it to the recipient. At this moment, it reaches its maximum capacity and accepts part of the surface runoff waters, while part of it overflows through it and floods a part of Stajkovci towards the eastern part of the Skopje ring road.

Ninety minutes after the arrival of the first wave of the flood wave (20:50), the flooded area in the urban area in Stajkovci is increasing. The box culvert on the eastern part of the ring road reaches its maximum capacity and creates a slowdown. At this moment the embankment from the eastern part of the ring road acts as a dam and limits the flood wave from spreading in the urban part of Stajkovci.

At 21:10 the flood wave reaches its second peak, resulting in increase of the flooded areas around the northern and eastern part of the ring road. Thirty minutes after the second peak of the flood wave (21:40) the flooded areas along the eastern part of the ring road increase.

Immediately after the end of the rainfall around 22:40, the propagation of the flood wave due to the short time of concentration of the surface runoff ends, and in that moment the draining process begins.

Comparative analysis of the flooded areas obtained after 72h according to the hydraulic model and aerial photogrammetric images taken two days after the flood, Figure 11, shows that the flooded areas from the hydraulic model coincide with the polygons made from the aerial photogrammetric images. The shapes of the areas differ due to the geometric characteristics from the digital terrain model, as well as the time period of the photogrammetric recordings.

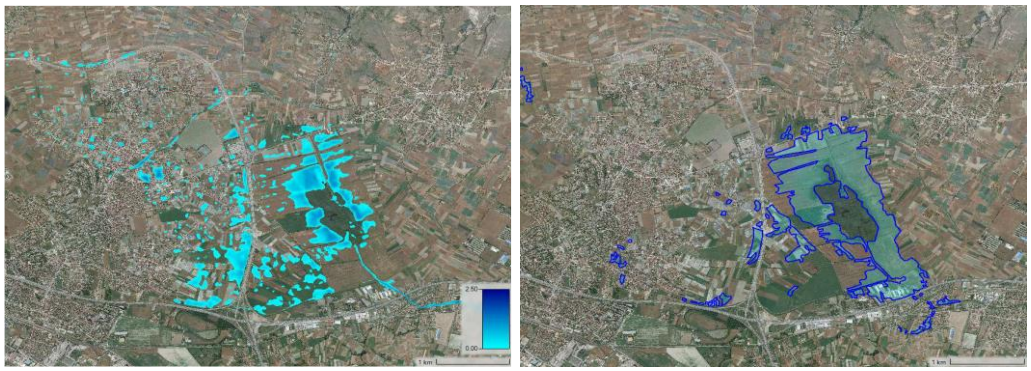


Figure 11. Map of flooded areas from the hydraulic model – t = 72 h (09.08.2016 17:40), left and Map of flooded areas from aerial photogrammetric imaging, right (Source: Agency for real estate cadastre)

5. CONCLUSION

The reasons for the flood in Skopje from 06.08.2016 are primarily the high intensity rainfall for a period of nearly 4 hours [18]. According to the official data of the Hydrometeorological service, about 93 mm of rainfall fell per square meter, that is 107 mm for a time period of 24 hours [8]. According to the analysis of the rainfall, the rain that fell during 24 hours corresponds to the rainfall with return period of T=100 years [19], [20]. Additional reasons for the flood include the bareness of the southern slopes of Skopska Crna Gora which are characterized by small, torrential catchment areas, which conditions the sudden accumulation and rapid surface runoff of water from the higher areas to the lower areas in the river basins. If the afforestation was greater or the vegetation cover was greater, a significant part of the rain would have been absorbed in the vegetation and into the soil, which unfortunately has been completely washed away due to the bareness. An extremely important role as the cause of floods is the catastrophic condition of the drainage systems and facilities for the safely implementation of flood waters. Abandoned channels, full of debris, blocked riverbeds from wildly constructed structures, roads without sufficient number of culverts, low bridges with low capacity [21]. All of this cause accumulation of water and create large flood areas.

This research encourages as massive as possible use of hydrological and hydraulic modeling, and emphasizes their importance in early detection of the critical zones of the flooding and contribute in preventing the effects of flooding.

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Review paper

PROCESS OF URBAN REGENERATION OF MULTI-FAMILY HOUSING AREAS – COMPARATIVE ANALYSIS OF THE BEST PRACTICES FROM EUROPE

Maša Ranđelović[1], Natalija Stanković[2]

Abstract

Every city has pockets of underutilized land, underdeveloped urban areas, or areas that are currently in a state of disrepair. Such spaces weaken the image of the city as well as the living conditions. Also, in addition to the shortcomings of the physical structure, one of the main problems of the multi-family housing areas (MFHA) is caused by individual residents, or rather its social structure, which is primarily affected by the occurrence of vandalism. Any aspiration and any attempt to change the urban landscape is a complex process. However, today there are a large number of positive examples of the regeneration of certain areas. With that, the term regeneration and transformation of small and large cities, complexes and other open areas became even more striking and resonant, and the term regeneration itself became more convincing and significant for the people and the executive authorities. The goal of the work is based on the presentation of the urban regeneration of MFHA with a focus on promoting ecological, social and spatial well-being. In the first part of the paper, the concept of MFHA regeneration is defined and three selected examples of the best practice from Europe are analyzed that show the entire course of its realization. Rosenhøj in Aarhus and Buchheimer Weg in Köln, were selected as examples of the best practice. In the second part of the paper, a comparative analysis of two examples is performed and the best definition of the process of urban regeneration.

Key words: *urban regeneration, multi-family housing areas, comparative analysis, Rosenhøj, Buchheimer Weg*

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1. INTRODUCTION

Urban areas are complex and dynamic systems in which a wide range of activities are carried out every day and which are increasingly populated due to the constant urbanization that is present in the XXI century. They are daily subjected to various influences and challenges that are reflected in environmental, social and economic aspects. Urban regeneration can be seen as a result of the interactions between the mentioned influences and as a response to the mentioned challenges. Although the aspiration and attempt to bring about changes in the urban landscape is a complex process, today the term of regeneration and transformation of smaller and larger urban areas is increasingly sound and significant for the people and the executive authorities. There are a growing number of examples of positive regeneration in the world, both in areas with multi-family housing and areas with mixed functions, as well as brownfield areas, central city cores and coasts.

The paper focuses exclusively on areas with multi-family housing (MFHA), on the analysis of selected examples of good practice in Europe - Rosenhøj in Aarhus and Buchheimer Weg in Cologne. The aim of the paper is a comparative analysis of the regeneration of both examples. This includes the analysis of their appearance and the problems that existed before the initiation of the regeneration, the analysis of the objectives, the types of applied measures and activities defined by the regeneration project, the overview of the initiators and actors and the analysis of the effects after the regeneration itself.

2. PRESENTATION OF THE BEST PRACTICE EXAMPLES OF URBAN REGENERATION OF MFHA

Examples from Europe - from Denmark and Germany - were selected to show adequate urban regeneration of MFHA.

2.1. Rosenhøj, Aarhus, Denmark

2.1.1. Analysis of the state before regeneration

The MFHA Rosenhøj was built between 1968 and 1970 and consists of twenty-seven four-story buildings. It is located in the city of Aarhus in Denmark (Figure 1). It represents a typical post-war MFHA, built as part of the southern Jutland plan, developed by the Ministry of Housing. The designer of the MFHA was Børge Kjær, and it was intended for mass, prefabricated construction across the country [1]. The main emphasis was on the spatial organization of the interior of the space, which was treated as flexible with the possibility of different spatial organization depending on the needs of the tenants. Very little attention was paid to the organization and design of the exterior space.



Figure 1. The position of MFHA Rosenhøj in Aarhus, Mette Mechlenborg, 2019

The plan envisaged buildings of regular geometric shapes arranged in parallel tracts (Figure 2a). One of the characteristics of the complex was the planning of the infrastructure designed to create an independent neighborhood with shops and related functions along with housing. Over time, these qualities contributed to the separation of the area from the rest of the city. Recognized shortcomings of the settlement are reflected in the design and layout of residential buildings, which were characterized by concrete facades and the same typology of all units, which resulted in a monotonous environment composed of identical units. Poor organization of the infrastructure, where certain streets were designed as dead ends (Figure 2b), resulted in inefficient movement of cars within the settlement. The open spaces in the complex were poorly organized (Figure 2c), and the contents included large undefined and unsightly green areas and large parking spaces. This way of restricting open areas could not offer tenants a variety of content that would satisfy their basic needs for gathering, relaxation and recreation.

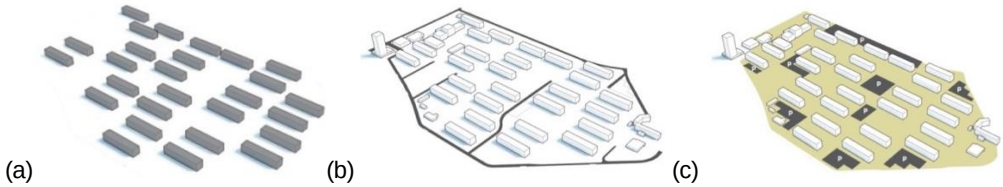


Figure 2. Schematic representation of the disposition of housing units, cul-de-sacs and the contents of open spaces, https://www.effekt.dk/

Despite the good intentions of the original plan, more socio-economically developed families gradually moved out of the complex, and in later years this area experienced problematic development. Years ago, the settlement was characterized by social challenges, insecurity and a bad reputation. The settlement was accompanied by a bad social image, a high crime rate, low incomes, an unfavorable educational structure of the inhabitants and a high concentration of emigrants. The complex became marginalized and neglected. Due to the aforementioned shortcomings as well as development in the wrong direction, it was decided to start the process of regeneration of the residential area.

2.1.2. Urban regeneration process

- **Project initiators**

The reason why the settlement is considered a symbol of the Danish ghetto is the frequent riots that took place during 2005. As a direct response to the national ghetto policy of 2004, the municipality of Aarhus presented its local strategy in 2007 with the aim of creating lasting positive changes in the Rosenhøj neighborhood. The process of forming the strategy involved large public investments as well as political engagement [2]. This program represents the cooperation between the municipality and the housing association, with the municipality as the main initiator of the program. Until May 2011, the housing association carried out targeted engagement of tenants by holding general meetings, city walks, as well as individual meetings with families whose homes are planned for demolition, if the renovation is approved. Tenants had a part in making the decision to start the regeneration phase of the complex. After preparations that lasted a couple of years, an architectural competition for the regeneration of this residential complex was announced in the summer of 2010 [1].

- **Project goals**

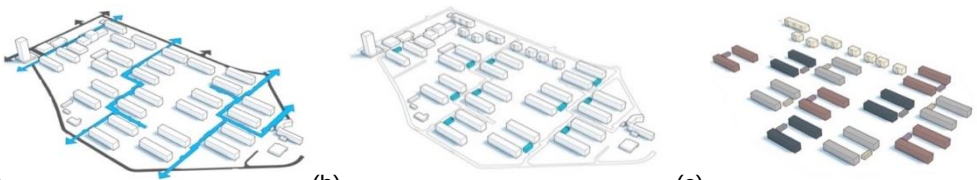
The main reasons for starting the process of urban regeneration of the Rosenhøj residential complex were to restore the lost reputation of the settlement, to prevent the emigration of tenants and to provide a higher level of quality of life in this area [3]. The urban regeneration plan of the MFHA meant solving defined problems by achieving the intended goals. The main goals can be grouped into goals for improving the physical and socio-economic structure, and among them we recognize the following: infrastructural improvement with the reorganization of traffic connections; improving the visual-aesthetic image of the MFHA while solving the problem of monotony and uniformity of the MFHA; remodeling of open areas; creating better visibility of the block with interventions on individual buildings; creating a better connection between the interior of the block and the peripheral areas; improving the energy efficiency of residential units; adaptation of the block to the elderly and persons with disabilities and solving basic social problems while implementing measures that will prevent the emigration of residents and the settlement of new categories of population.

The regeneration project involved working at different levels to achieve predetermined goals. The fact that today this area has a significantly higher level of population speaks about whether the goals were achieved and the problems solved.

- **Types of measures applied**

The urban regeneration project of the Rosenhøj MFHA in Aarhus, Denmark included the implementation of measures to improve the physical and socio-economic structure.

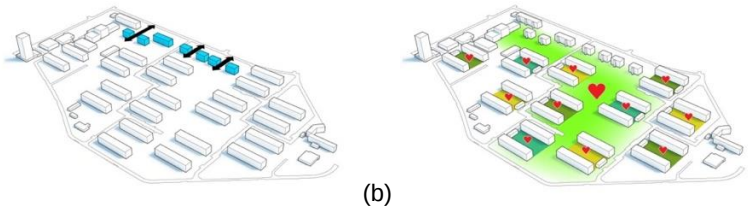
As part of the measures to improve the physical structure, the infrastructural separation of the entire complex into three units is recognized, along with the introduction of newly formed vehicular communications (Figure 3a), to provide users with a clear connection to the surrounding roads. Along these communications, evenly distributed parking spaces were formed, so that each residential unit has faster and easier access to the parking space [3]. Newly built semi-detached houses were added to the existing structure (Figure 3b) so that with two existing residential units each they form 11 smaller sub-units (Figure 3c). In this way, the goal of obtaining a more dynamic structure of individual and multi-family housing was achieved.



(a) (b) (c)

Figure 3. Schematic representation of newly built road connections, semi-detached houses and formed sub-units, https://www.effekt.dk/

In order to provide the location with better visibility and connection with the surrounding area, four residential units on the perimeter of the location were crushed along with the formed penetrations, so that seven smaller of a different structure (Figure 4a). The interior of the block is connected by a communication network to the primary and secondary schools located on the perimeter. The open spaces are organized in such a way that, in addition to common public spaces, there are also 11 smaller semi-public "gardens" on the site, which provide residents with greater privacy compared to other public spaces (Figure 4b).



(a) (b)

Figure 4. Schematic representation of the fragmentation of residential units and representation of the organization of open areas, https://www.effekt.dk/

Entire open spaces are equipped with a variety of content for outdoor recreation, gathering and relaxation. A student dormitory, a home for the elderly, an office building with premises on the ground floor can also be considered social measures with the aim of attracting new categories of the population to the MFHA. The characteristic concrete facade of all 27 residential units was transformed with the aim of visually grouping the buildings into "horseshoe" formations. Also, thermal insulation with a thickness of 20 cm, a mechanical system for ventilation and heating was applied, the carpentry was replaced, and solar cells were applied on the roofs of the buildings. Aluminum panels, concrete slabs and slate slabs were used as facade cladding [1]. Balconies were added on the southern facades. In order to adapt the housing complex to persons with disabilities, every fourth housing unit is adapted to this category of users. The real transformation of the residential area is yet to come.

- **Types of actors and interest groups represented**

The new Rosenhøj was created in close cooperation between the Aarhus area and the residents. The architects of MFHA project were Børge Kjær [1] and Arkitema, an architecture company that enhances the appearance and characteristics of Scandinavian cities while also taking into account sustainability, beauty and economy. The main and responsible engineers of the project were the employees of Vigo Madsen. Architects and engineers worked closely together on renovation solutions. One of the project collaborators was the Center for Sport and Architecture, UiWE (Urgent Agency) [4]. The design team consisted of 17 people who worked on the project. The entrepreneurs of the project were the construction companies Enemaerke og Petersen A/S and Wicotec Kirkebejg.

- **Funding sources represented**

The construction costs, including the regeneration of the housing project, amounted to 950.000.000 Danish kroner [5]. Residents gave a huge mandate for the renovation. The Rural Development Fund supported the project.

2.1.3. Sublimation of regeneration effects

The social change as well as the regeneration of the neighborhood itself, which lasted between 2014 and 2017, made the Rosenhøj more attractive to live in and created the conditions for a better life in the city. "In 2017, the share of insecure residents was halved, and the share of residents with trust in their neighbors increased by 37% compared to 2008. There are fourteen times more citizens on the waiting list for housing today than in 2010. Evictions from settlements decreased by 2.7% from 2015 to 2017." [6] Also, the facades of residential buildings were renovated to create greater diversity and better energy efficiency (Figure 5a). Green areas and recreational areas are further enhanced by the installation of plinths and wooden decks. (Figure 5b). Now they are characterized by lawns, meadow flowers and other plants [7]. The space now has new furniture chosen by the tenants and outdoor activities, such as an outdoor gym, football, children's play area, etc. (Figure 5c).

Rosenhøj has become accessible to users with special needs. The MFHA is now open to the immediate surroundings, integrating the area into the city. Also, the new infrastructure and pairing of blocks two by two created new types of open spaces and communal courtyards.



Figure 5. Appearance of the site after regeneration, (a) https://renover.dk/, (b) http://www.vibysyd.dk/, (c) https://www.arkitema.com/dk

The regeneration of the MFHA Rosenhøj on an area of 7,1 hectares received the following awards: the 2017 Aarhus Municipality Architecture Award, the RENOVER Award that rewards the best transformation in Denmark in 2017 and the highest review score from the Danish newspaper Politiken. The project was also nominated for the VAN award for a social housing solution. The new Rosenhøj is a real example of how it is possible, through adequate renovation and transformation, to "raise" a dilapidated residential area into an attractive residential area.

2.2. Buchheimer Weg, Köln, Germany

2.2.1. Analysis of the state before regeneration

The MFHA Buchheimer Weg was created in the period from 1954 to 1958, as part of a program to remove bunkers at the beginning of the war-torn metropolis of the Rhine. A total of 1037 social housing apartments were built, many of which were modernized from 2002 to 2011 (Figure 6) [8].



Figure 6. The position of Buchheimer Weg in Köln and a view of its immediate surroundings, https://www.gag-koeln.de/

MFHA had important advantages: good lighting, surrounding greenery and a certain urban spaciousness. The buildings in this residential area were in very poor condition. Between the residential units in the three-story building in a row, mostly with regular foundations, there were poorly organized green spaces, without adequate furniture for the tenants' activities. The apartments were small in square footage, mostly without balconies. In urban terms, this was a monotonous space without clearly defined boundaries.

2.2.2. Urban regeneration process

- **Project initiators**

The future of the MFHA Buchheimer Weg was considered by the owners of the complex, in fact there was a debate whether to keep and renovate this complex or to demolish it. Buchheimer Weg is owned by the non-profit construction organization GAG Imobilien (Gemeinnützige Aktiengesellschaft) [9]. This association has announced a competition for the proposal of a conceptual solution project for the regeneration of this MFHA. In the competition in 2005, ASTOC Architects&Planners. After the competition, two years later, the first phase of construction began. The owners of Buchheimer Weg initiated the renovation of this residential complex, while ASTOC architects and planners designed the entire project.

- **Project goals**

The main reasons for initiating urban regeneration were to enable a better quality of life in the settlement, to prevent the emigration of residents and to provide apartments for residents with low incomes through a cheap construction method. The goals that initiated the entire regeneration process can be divided into goals related to the improvement of the physical-economic structure and the socio-economic structure. The regeneration process is defined by achieving certain goals such as: increasing the population density and forming housing units for low-income residents, reorganization of the contents and renovation of open areas, ensuring a better quality of life for the residents of the residential complex, enabling greater safety for residents and visitors. The project itself involved a lot of work in order to achieve the established goals. The motive of the entire project is to enable a better quality of life for the residents of this settlement.

- **Types of measures applied**

The concept of urban regeneration project of this MFHA was designed to adequately achieve the defined goals and give the entire complex a new look. MFHA has an extremely favorable location, there are railway and bus stations nearby, and it can be said that the traffic connection is very favorable. With the new project, it was necessary to preserve all the advantages of the settlement, and one of them is the favorable orientation, good ventilation and lighting.

Considering the settlement itself, the plan was to renovate the existing buildings, however, looking at the overall costs, it was decided that the first measure would be the demolition and construction of new ones in the same place. One of the measures focused on the new, more innovative design of Buchheimer Weg, which focused on creating a unique green color but in different shades of facades that will be the main feature of this neighborhood. These colors are pleasant and not at all boring and at the same time contribute to the feeling of novelty and a new beginning. Four-story buildings with two to three apartments at the base are designed that basically bend at irregular angles. The very entrance to the building is emphasized with a concrete canopy and brightly colored panels. By designing a diverse structure of apartments, this complex was adapted to different structures of residents. On the higher floors, the apartments have their own balconies, which did not exist before. The next measure is the creation of public and dynamic spaces that are formed based on the shape of the buildings. Each building individually shapes the exterior space and makes it unique in a meaningful way (Figure 7). At the very corner of the site, four buildings form one large central public space. It is defined for different purposes and contains playgrounds for children, gardens and basketball courts. Private courtyards are formed next to the buildings and are intended exclusively for

tenants. One of the measures was the creation of a wide network of pedestrian paths that connect the entire area, but also connect it to a large park nearby.



Figure 7. The orientation of buildings and public spaces, https://www.gag-koeln.de/, https://astoc.de/de/

In order to differentiate pedestrian and motor traffic and to achieve safety, the measure of relocating the parking lot was implemented. Public areas are entirely intended for pedestrians

- **Types of actors and interest groups represented**

The entire regeneration process was led by the housing company GAG Immobilien (Gemeinnützige Aktiengesellschaft), [9] which contracted with ASTOC architects and planners to renovate and upgrade the housing complex in the Ostheim district of Cologne. The concept of the ASTOC company represents a model solution for the reconstruction of this settlement and allows its character to survive, with the application of numerous design elements that adapt to the environment. The facades of the residential units were designed by Hans Karl Burgeff, a German sculptor and art professor. Landscape architects also participated in the project [10].

- **Funding sources represented**

The construction was financed by the non-profit housing company GAG Immobilien (Gemeinnützige Aktiengesellschaft), (https://www.deutsche-digitale-bibliothek.de/). Compared to similar social housing projects, this project is one of the more successful. Gross construction costs amounted to about 28.000.000 euros.

2.2.3. Sublimation of regeneration effects

The regeneration project on an area of 5.16 hectares was successfully implemented. Today, there are 18 buildings in which there are a total of 434 apartments, which are intended to accommodate a heterogeneous population. The Buchheimer Weg MFHA now offers its residents a significantly higher quality of life. Careful urban planning of buildings, differentiated but socially safe open spaces, enable this neighborhood to meet the needs of users in the long term, and thus improve the urban quality of the settlement. Organizing the settlement around a central area that is slightly more than one hectare in area, and also providing smaller courtyards for each building, gives the residents enough opportunities to relax outside the apartment (Figure 8). There is no motorized traffic in the central part. Parking is provided along the street itself, as well as in smaller lots next to the road. Parking is also available in two underground garages.



Figure 8. Spaces for gathering, recreation and relaxation, https://www.gag-koeln.de/

The residential area now also includes a cafe for residents, office space nearby and a hall of residence for people with disabilities and dementia. The concept of care and support for these residents relies on the activation and participation of citizens who come together to form a civil-legal partnership so that they can care for each other as a community. GAG Immobilien is dedicated to the activities of tenants in the settlement. A successful example is the days of culture, which are held every spring. GAG Immobilien together with the tenants' council and the youth center offered many original practical activities. A music workshop was formed, stone reliefs were carved, and together with the tenants' council, large planters were planted and gardens were arranged. The flowers were later nurtured and grew over the years, while ceramic mosaics still adorn the neighborhood. This was very well received by the residents, so culture days are still held. From this it can be concluded that the social structure in the settlement has risen to a higher level. As for heating, certain measures have been implemented with the aim of achieving energy efficiency.

Facade materials, such as mineral-based plaster, clad the buildings and are painted in green tones that vary throughout the complex (Figure 9a). Residents appreciate the unique choice of color, which makes the neighborhood easily recognizable, and besides, green is the color of optimism, so pleasant tones contribute to the feeling of novelty. The accentuated entrances of residential units (Figure 9b) are very characteristic, and the access to the buildings is designed with two entrances located on both sides of the building.



Figure 9. Buildings after regeneration, (a) https://www.gag-koeln.de/, (b) Brown, 2019

In 2012, GAG Immobilien was awarded the German Construction Award in the categories "New Buildings" and the "Open Space Design in Housing" award.

3. DISCUSSION - COMPARATIVE ANALYSIS OF URBAN REGENERATION OF SELECTED EXAMPLES OF THE BEST PRACTICE

The urban regeneration projects Rosenhøj in Aarhus and Buchheimer Weg in Köln have a sufficient number of specific points in the previous appearance and the very process of project realization according to which it is possible to compare them, i.e. to carry out the necessary analysis of their urban regeneration. At the very beginning of the analysis, it is necessary to

point out the fact that the urban regeneration of MFHAs is in question. Both are identical in size, but the Rosenhøj housing estate in Aarhus, Denmark occupies a larger area.

When comparing the previous conditions of residential areas, Rosenhøj in Aarhus was characterized by a poor social structure, the existence of criminal groups and a sense of insecurity among residents. In the example of Buchheimer Weg in Cologne, there were no such problems. Both examples were characterized by poor organization of open spaces, insufficient use and appearance of greenery, inadequate and insufficient furniture for children's recreation, gathering and play, as well as the appearance of "gray" ie. identical facades of residential buildings.

As far as the initiators are concerned, here, also in Aarhus, the main initiators were the inhabitants of the settlement, that is, the residential community, together with the municipality of the city as well as the city itself. In Buchheimer Weg, the future of a multi-family housing complex was considered by the company that owned it.

The urban regeneration projects of the presented examples are characterized by very similar goals that led to the final results. Both examples of urban regeneration projects are characterized by the implementation of goals aimed at improving the physical and socio-economic structure of residential complexes. The objectives of improving the physical structure with the aim of achieving better energy efficiency of residential units, as well as the reorganization of the interior of residential units with the aim of adapting to different user structures, which are characteristic of the Rosenohøj and Buchheimer Weg neighborhoods, were recognized. In the case of both settlements, the goals of the regeneration project were aimed at the reorganization of open areas, but also at adapting housing units to different population structures, creating better connectivity and improving the aesthetic image of the complex. The selected examples of urban regeneration are characterized by goals that would lead to the improvement of the social structure by encouraging the population to live together in open areas with the newly formed content of open areas. The common feature of these projects is reflected in the basic motive for launching the initiatives for the urban regeneration project, which is to solve the basic social and physical long-term problems in the settlements.

Within the measures applied in both cases of urban regeneration projects of residential complexes, we recognize the application of measures to improve the physical and socio-economic structure. The residential complexes were subjected to regeneration measures that included the reorganization of open areas, the relocation of parking spaces, and the creation of better connectivity of the location. A clearly visible common characteristic of the settlement regeneration project, within the applied measures, is reflected in the application of the measure that contributed to the improvement of the aesthetic appearance of the location. Both examples are characterized by a new look of residential units with clearly emphasized entrances, however, the Buchheimer Weg neighborhood underwent the demolition of existing residential units and the construction of new units of a specific form with a characteristic facade in a green shade. Each of these two examples of the urban regeneration project includes the implementation of a series of measures related to the improvement of the social structure, which is manifested through the encouragement of mutual gathering, socializing and recreation of tenants in the open areas of the residential complex with newly formed content. In the Rosenohøj settlement, the improvement of the social structure was also achieved through the improvement of the functional structure by diversifying the accompanying

contents in addition to housing with the planned projects of a student dormitory, a home for the elderly and a business building, which will attract various structures of the population. Recognized measures to improve the economic structure of projects of urban regeneration of residential complexes are reflected in the improvement of facades with the aim of reducing excessive energy consumption in order to save funds intended for heating and cooling residential units.

4. CONCLUSION

MFHAs built during the second half of the last century exist today as witnesses of time and lifestyle. Old and neglected complexes are not attractive enough and attract only those groups of residents who do not have the opportunity to provide themselves with a better place to live. Complexes like this are neglected, unmaintained and very often the target of problem residents. In recent years, we have witnessed the realization of numerous urban regeneration projects motivated by the idea of solving perceived problems and restoring these complexes to their lost reputation.

The observed problems are recognized on several levels, and concern both the physical and functional, as well as the socio-economic structure. Such complexes, built according to the standards that corresponded to the period in which they were built, today cannot satisfy the needs of the users of the complex, which have changed over time and adapted to new circumstances. The analyzed examples of MFHAs today exude a new look, have a higher utility value and attract a larger number of users. The process of urban regeneration has contributed to making these complexes no longer monotonous and gloomy, and to the fact that an increasing number of residents are choosing to live in precisely such settlements. It can be concluded that the processes of urban regeneration, based on the analyzed available literature, have exclusively positive aspects both on the regenerated complex itself, and on the entire environment and the city in which they are located.

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Review paper

THE INFLUENCE OF LE CORBUSIER ON THE INTERIORS OF GREEK MODERNISM

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Abstract

Le Corbusier, a leading figure of modern architecture, introduced revolutionary principles that redefined spatial composition and living environments. His work significantly influenced Greek architects during both the interwar and postwar periods, shaping the evolution of Modern Greek architecture. This study explores how Le Corbusier's design principles—such as the Domino system, open floor plans, pilotis, elongated horizontal windows, and the emphasis on natural light and ventilation—were integrated into the interiors of Greek modern buildings from the 1930s to the 1970s. The research employs a qualitative methodology, combining bibliographic analysis and case studies of key Greek architects, including Polivios Michailidis, Thoukididis Valentis, Aristomenis Provelengios, and Nikos Valsamakis. Their designs not only embraced modern construction techniques but also proposed a new way of living, departing from the traditional and neoclassical house. The Esprit Nouveau ideology became a fundamental reference, influencing the spatial organization of interiors. Comparative analysis highlights how Le Corbusier's concepts were adapted to the Greek architectural context. The study examines how materiality, structural expression, and the interplay between interior and exterior spaces evolved under his influence. Findings indicate that Le Corbusier's influence on Greek modernist interiors was not limited to aesthetic choices but extended to fundamental spatial principles. His renowned five points of architecture and material preferences shaped the identity of interior spaces, emphasizing spatial fluidity, structured compositions with integrated furnishings, expressive materiality, selectively applied bold colors, and industrial-style movable furnishings. Greek architects of the modern period who drew inspiration from his work adopted these principles in their own projects, reshaping domestic spaces and redefining the visual language of modern living in Greece. This research highlights how global architectural movements are locally reinterpreted, reinforcing modernism's lasting impact on Greece's built environment.

Key words: *Le Corbusier, Greek Modernism, Interior Architecture, Spatial Composition, Materiality*

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1. INTRODUCTION

The architectural discourse of the 20th century was profoundly reshaped by figures whose visions transcended national boundaries. Among them, Le Corbusier stands out as a catalytic force, challenging established notions of form, space, and habitation. His approach proposed not merely a new architectural style, but a fundamentally new way of living — prioritizing functionality, natural light, and spatial openness — which initiated a paradigmatic shift in modern design thinking.

In Greece, the interwar period provided fertile ground for the reception of modernist ideas. A group of pioneering architects engaged with international architectural movements, including Le Corbusier's innovations, while negotiating the persistence of eclectic and neoclassical forms that continued to characterize urban environments, particularly in Athens. Postwar reconstruction and the rapid process of urbanization created new imperatives. The urgent demand for mass housing and the emergence of a new urban middle class aligned with the principles of modernism, offering a broader platform for its application. Within this context, Le Corbusier's theories and built works provided a model for addressing emerging social and spatial challenges.

Moreover, his exposure to Mediterranean landscapes — especially through his travels in Greece — deeply informed his architectural vocabulary [1]. The whitewashed cubic volumes, semi-outdoor transitional spaces, and spatial fluidity he observed would later become hallmarks of his work. Thus, the influence of Le Corbusier returned to Greece in a cycle of mutual exchange: having drawn inspiration from its landscapes and vernacular architecture, Greek architects in turn reinterpreted his modernist principles through a local lens.

This study investigates the impact of Le Corbusier's compositional principles on the interiors of Greek modernist architecture from the 1930s to the 1970s. It focuses particularly on how the open plan, the integration of natural light and materials, and the articulation of fixed and movable furnishings were reflected in the design logic and spatial qualities of modern Greek interiors. Through case studies of key Greek modernist architects, the research examines how Le Corbusier's principles were interpreted and adapted to fit the local cultural, climatic, and urban conditions.

The study is guided by the following research questions:

- What are the defining characteristics of Le Corbusier's design phases, and how did they influence Greek architectural production between 1930 and 1970?
- How was the modern lifestyle proposed by Le Corbusier (L'Esprit Nouveau) expressed in selected works by Greek architects?
- In what ways did the application of Le Corbusier's compositional principles redefine the spatial qualities of Greek modernist interiors?

2. METHODOLOGY

The material required for the composition and completion of this study was collected through bibliographic research, fieldwork, press research, online sources, as well as through the analysis of recorded interviews and presentations.

The methodology adopted combines comparative and interpretive approaches, aiming to investigate how Le Corbusier's ideas were assimilated and reinterpreted within the Greek

architectural context. The paper examines the influence of Le Corbusier on selected works of Greek modernist architects, with a particular focus on interior design.

The research is structured around two main chronological periods: the interwar period and the postwar period. These two phases correspond to distinct stages in Le Corbusier's work, shaped by the profound social, political, and economic transformations brought about by the two World Wars of the 20th century.

The structure of the research is organized into four main units, as follows:

- Interwar Period
    - Le Corbusier during the Interwar Period
    - The influence of Le Corbusier on Greek Architects during the Interwar Period
- Postwar Period
    - Le Corbusier during the Postwar Period
    - The influence of Le Corbusier on Greek Architects during the Postwar Period

3. FINDINGS (RESULTS)

3.1. Interwar Period

3.1.1. Le Corbusier during the Interwar Period

During the interwar period, the architect Le Corbusier, a leading figure of the modernist movement, through his explorations and architectural applications, contributed decisively to the development of the spatial experiments that defined the modern architectural vocabulary. Le Corbusier (1887–1965), inspired by the world of machines, sought the "Esprit Nouveau", reinterpreted the classical ideal of the Parthenon [2], and placed his trust in avant-garde industrial materials such as reinforced concrete and metal. His five architectural principles—pilotis, free floor plan, horizontal ribbon windows, roof garden, free façade—along with the Domino system, and the industrial-style furniture he designed, formed the architectural envelope and defined the spatial qualities of his interior compositions [3].

More specifically, Le Corbusier's interiors are characterized by simplicity and economy of means, with a strong emphasis on hygiene (light and ventilation). The absence of ornamentation, the careful selection of color on specific walls and elements, the predominance of white, metal railings, elongated horizontal openings with metallic frames, and built-in furniture of industrial aesthetic, often designed by Le Corbusier himself, convey a strong sense of rational order. Additional elements include the exposed structural frame, the meticulous integration of mechanical systems (such as radiators), double-height spaces, ramps, and sculptural staircases—all of which emphasize the plasticity of the new structural material, such as reinforced concrete. Collectively, these components defined a new kind of interior spatial experience.

These principles were first publicly introduced at the International Exhibition of Modern Decorative and Industrial Arts in Paris, with the Pavilion of L'Esprit Nouveau, and were later refined in the iconic Villa Savoye [4]. Figures 1 present these two groundbreaking works, where Le Corbusier illustrates and proposes a new model for modern living through an almost scenographic spatial expression.




Figure 1 Left: Interior view of the Pavilion of L'Esprit Nouveau, source: www.archiweb.cz. Right: Interior space of Villa Savoye, source: www.archdaily.com

3.1.2 The influence of Le Corbusier on Greek architects during the Interwar Period

The interwar years marked a period of significant transformation in the architectural production of modern Athens. A crucial factor in this shift was the rapid dissemination of Modernism across Europe, which reflected the optimistic and assertive spirit of an emerging middle class and, gradually, influenced the lower-middle class of society as well.

Greek architects such as Stamos Papadakis, Kyriakos Panagiotakos, Patroklos Karantinos, Thoukididis Valentis, Polivios Michailidis, Aristotelis Zachos, Vasilios Douras, and Konstantinos Kitsikis, among many others, drew inspiration from the Modernist movement and found fertile ground in Athens for applying its principles. Their works expressed modernity not only through external form but also through internal spatial transformations that redefined the functional layout of space.

A particularly representative example of an Athenian apartment building that fully embodies the formal characteristics and compositional principles of Le Corbusier is the one designed in 1933 by Polivios Michailidis and Thoukididis Valentis at Stournari Street [5]. In this project, the architects employed Le Corbusier's renowned domino system to create freely articulated interiors through the use of open floor plans. Additionally, by setting back the structural columns from the external walls, they were able to compose freely designed façades with continuous horizontal window bands of varying lengths. This structural technique directly recalls numerous works by Le Corbusier from the same period, such as the Villa Cook and Villa Stein, where the same compositional principles are evident.

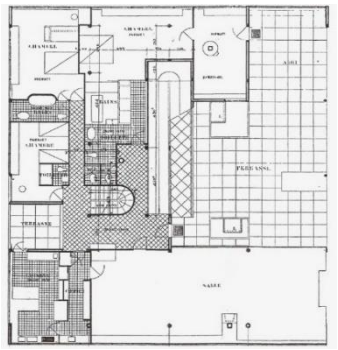
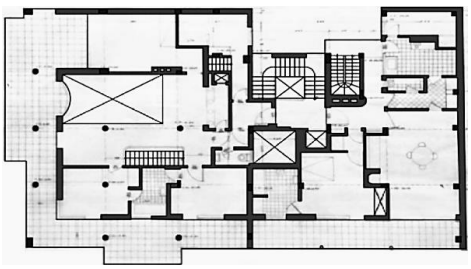



Figure 2: Left: Floor plan of Villa Savoye, source: Ruegg A., 1999, p.24. Right: Fifth floor plan of the Michailidis-Valentis apartment building, source: Xirokostas M. et al., 2016, p.37.



Figure 3 Left: Interior views of Villa Savoye, source: www.archdaily.com. Right: Interior views of the Michailidis-Valentis apartment building, source: Xirokostas M. et al., 2016, p.34.

The large, elongated openings that allowed for ample and unobstructed interior ventilation and lighting—both essential for hygienic living—were sealed with sliding metal frames, which at the time represented a significant innovation compared to traditional construction techniques. These metal-framed openings, widely employed by Le Corbusier, highlight the structural possibilities of metal and glass in modern architecture.



Figure 4: Left: Villa Stein, source: www.divisare.com. Right: Apartment building by Michailidis and Valentis, source: Fillipidis, 2001, p. 99.

Another of Le Corbusier's five points of architecture that can be identified in the work of Michailidis and Valentis is the accessible roof terrace. A previously non-utilitarian space is transformed into an urban escape and a vital extension of the privileged penthouse apartment, establishing a unique relationship between the resident and the vast scale of the urban skyline and landscape.

Regarding the interior of the residence, there is once again a direct reference to Le Corbusier's work, notably through the creation of an interior atrium and the incorporation of a characteristic curved window, which is almost identical to that of the Villa Cook. The key difference lies in the placement of the openings along the curved surface [6], adapting Le Corbusier's original concept to the specific spatial conditions of the project.



Figure 5: Left: Roof terrace of the Michailidis and Valentis apartment building, source: Xirokostas M et.al, 2016, p.16, p.396. Right: Roof terrace of Villa Savoye, source: www.archdaily.com.

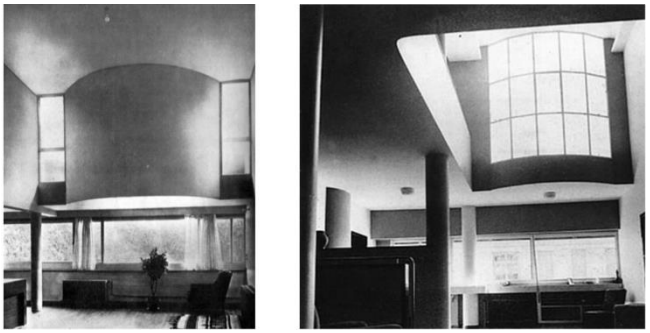


Figure 6: Left: The curved window of Villa Cook, source: www.fondationlecorbusier.fr. Right: The curved window of the Michailidis and Valentis apartment building, source: Fessa E., 2009, p.396).

Finally, the furniture designed by the two architects, featuring simple and clean lines in metal and leather, corresponds directly to that of Le Corbusier [7]. It reveals their intention to shape a functional space, stripped of all superfluous elements. Beyond the formal similarities with the modernist movement, these interiors embody its essence: a new way of living, grounded in the principles of modernity.

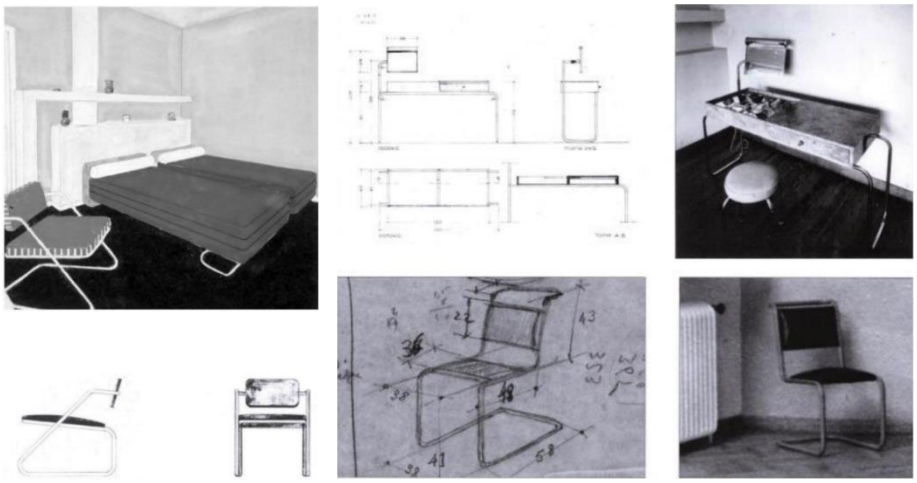


Figure 7: Photographs and drawings of the fixed and movable furnishings of the apartment building by Michailidis and Valentis. Source: Xirokostas M et.al, 2016, p.21.

As Professor Panagiotis Tournikiotis characteristically notes:

"Michailidis and Valentis design an architecture that simultaneously proposes a way of life — a different way of life, far removed from the traditional neoclassical house. A lifestyle linked to new technologies, to the logic of communal living, to vertical habitation, and to the conquest of the rooftop as a space for summer outdoor activities and, at the same time, as a platform for viewing the broader environment." [8]

In the same year, architect Stamos Papadakis, in the design of a summer house in Glyfada, also reveals strong influences from Le Corbusier in both its external form and its interior spaces. A free structural grid allows the floor plan to unfold with flexibility, while curved elements appear both in the shell and in the terrace, echoing the volumetric gestures of Le Corbusier [9]. Prominent features include large elongated rectangular windows, which, although interrupted by structural columns, maintain their horizontal emphasis and significantly shape the interior quality by allowing unobstructed penetration of natural light. Metal is prominently used, particularly in the ground-floor railings, and the overall composition is dominated by the use of white, in direct reference to modernist aesthetic principles.

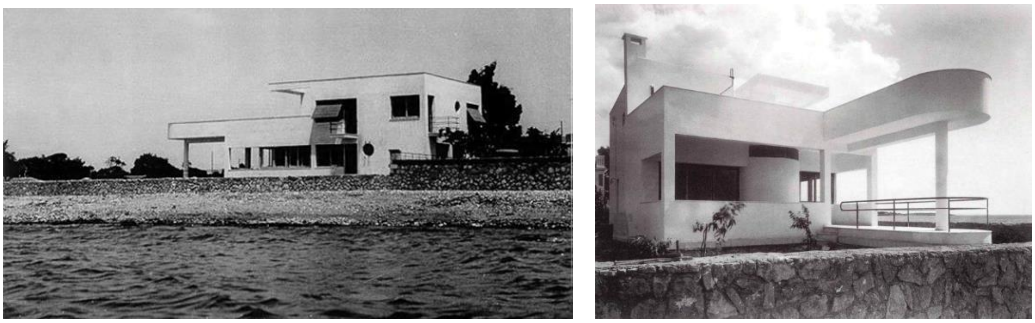


Figure 8: Various views of the Fakidis Residence in Glyfada, Source: www.gradreview.gr

Aristotelis Zachos, despite his commitment to the "values of Greek vernacular architecture", appears to have been well acquainted with the modern vocabulary of Le Corbusier, as demonstrated in 1934 with the design of the residence of Petichakis in Psychiko. Although at first glance the association between this residence and Le Corbusier's works may not be immediately evident, the building's volumetric composition of pure geometric forms, as well as the circular design of the greenhouse volume featuring large metal-framed glazing, clearly reflect modernist principles. Furthermore, the use of white throughout the composition once again refers Le Corbusier's architectural language.

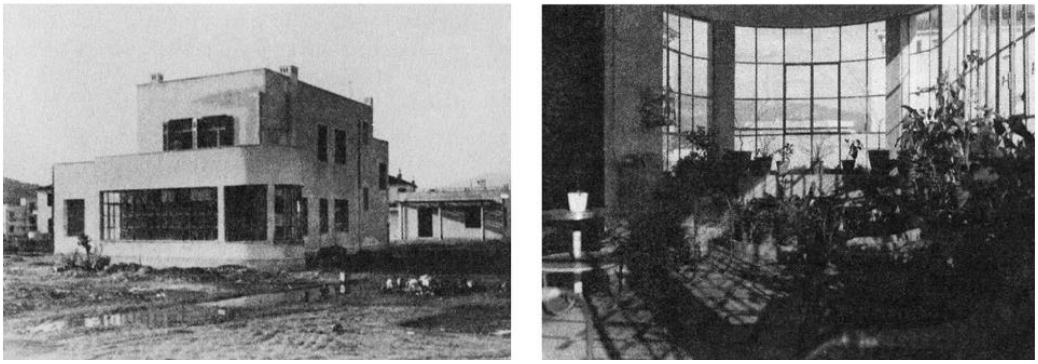


Figure 9: Left: Exterior view of the Petichakis Residence. Right: Interior view, source: www.archetype.gr

In 1933, Michailidis and Valentis designed a three-story residence for Stathakis at Drosopoulou Street, which, like the apartment building in Stournari Street, exhibits multiple similarities with Le Corbusier's works from the same period. Notable features include elongated horizontal openings on the ground and first floors, ensuring adequate sunlight penetration, as well as the setback of structural columns along the façade to allow for its free design. Metal elements are widely used: the railings on the recessed third floor, the pergola covering the semi-outdoor space, and all the window frames throughout the residence are made of metal. The fixed and movable furnishings inside the house also follow simple, clean lines, consistent with modernist principles. Particularly notable is the treatment of the storage unit and the fireplace, which directly reference similar elements found in Le Corbusier's Villa Savoye and Villa La Roche. Simple geometries, wooden detailing, and the use of circular columns further emphasize the building's conceptual and formal affinities with Le Corbusier's design vocabulary.



Figure 10: Left and center: Façade and interior view of the Stathakis residence, source: www.gradreview.gr. Right: Fireplace of Villa Savoye, source: www.cargocollective.com

3.2 Postwar Period

3.2.1. Le Corbusier during the Postwar Period

In the postwar years, Le Corbusier, influenced by the rapid changes and upheavals in society, economy, and politics, shifted his trajectory and adopted a new architectural vocabulary. Although this new vocabulary did not dramatically deviate from that of his earlier period, it introduced distinct typological and morphological differences. The plastered surfaces that previously covered the interiors and exteriors of his interwar projects gave way to the raw, grey concrete left exposed exactly as it emerged from the casting and curing process [10]. This material, known as béton brut, signaled a reduction in construction costs and eliminated the need for high-precision or specialized technologies.

Despite the material shift towards exposed concrete, bright colors did not disappear from Le Corbusier's work during the postwar period. Instead, he applied them extensively, directly onto the raw concrete surfaces. A characteristic example from this era is the Unité d'Habitation in Marseille, one of his most significant experiments addressing the housing crisis that followed the devastation of the Second World War. Through this project, Le

Corbusier sought to provide low-cost yet high-quality housing for a large number of low-income residents. Drawing upon the experience of his earlier work, he designed a residential building capable of accommodating a significant population, while aiming to secure dignified and quality living conditions for all inhabitants.

3.2.2. The influence of Le Corbusier on Greek architects during the Postwar Period

During this period, Athens underwent a complete transformation. The aftermath of the Second World War, combined with the massive wave of urban migration following the Greek Civil War, created an urgent need for mass housing for a large population with limited financial means. This demand triggered a building surge, which found theoretical and practical support in Le Corbusier's experiments with fast, economical construction methods that ensured healthy living conditions. The application of his principles became a pressing necessity, with Greek architects called upon to adapt these ideas to the specificities of Greek identity and Mediterranean climatic conditions.

A representative example of postwar architecture following this direction is the apartment building at Asyrmatos, near the Philopappou Hill ring road in Athens, designed by Elli Vasilikioti in 1967, as part of the studies conducted by the Housing Service of the Ministry of Public Works. This building strongly recalls Le Corbusier's Unité d'Habitation, both in terms of the needs it addresses — housing a large number of residents in compact apartments — and in its formal expression. The façade is articulated through a grid system created by the horizontal slabs of the balconies and the vertical structural elements. These continuous balconies functionally connect to the interior spaces of the apartments, acting as extensions of the living areas and effectively blurring the boundaries between interior and exterior. Moreover, the building incorporates Le Corbusier's concept of the accessible rooftop terrace, which, as in the Unité d'Habitation, becomes a communal space for social interaction and outdoor activities, providing sunlight and a venue for building interpersonal relationships among the residents. Finally, the pilotis system is also employed, raising the mass of the building and freeing the ground level for circulation and collective use.



Figure 11: Apartment building at Asyrmatos, source: www.doma.archi.

In a similar manner, in the apartment building designed by architect Nikos Valsamakis on Semitelou Street in 1951, the façade is organized through a grid system of horizontal and vertical elements, integrated with the balconies that provide extension spaces for the residents — areas directly connected to the interiors of the apartments [11]. At the building's entrance, the use of natural materials such as stone and marble, along with the sculptural

treatment of space and the carefully chosen color palette, reflect Le Corbusier's efforts during this period to integrate elements of nature into architectural interiors.



Figure 12: Left: Façade of the apartment building on Semitelou Street. Center: View from the balcony. Right: The staircase, source: Valsamaki M., 2007, p.28-31.

In 1956, Aristomenis Provelengios designed the house and studio of the Spiteri couple on Kykladon Street in Kypseli, faithfully embracing modernist architectural principles. Clearly influenced by what Panagiotis Tournikiotis describes as the "Le Corbusian poetics" in his presentation for the architectural television program Urban Landscape (Astiko Topio), Provelengios shaped a space based on Le Corbusier's Modulor system, creating what he described as:

"An architectural exercise where everything has its own scale, its own precision, its own complexity — while remaining simple."

Tournikiotis continues:

"Exposed concrete, squared glass surfaces, and opaque reinforced planes. A three-dimensional space, free and fluid, with staircases weaving up and down like an Escher painting. It is not simply a modern building; it is a modernism endowed with a human scale — embracing size, imperfection, and unpredictability — traits of a human character rather than just technical features of a structure. Provelengios was deeply influenced by Le Corbusier, even before he worked at his office." [12]



Figure 13: Left: Façade of the Spiteri House and Studio, source: www.karouzo.com. Center: The staircase, source: www.ek-mag.com. Right: View of the upper level, source: www.archaiologia.gr

In 1967, architect Seva Karakosta designed her own residence in Old Psychiko, Athens. Although through the volumetric composition and the choice of materials — such as white plastered surfaces, Pentelic marble flooring (used both indoors and outdoors), and low stone retaining walls — she sought to infuse the project with a sense of Greek identity, the interior spaces display strong affinities with Le Corbusier's work. Exposed concrete surfaces, sometimes painted in grey or bold colors, the absence of visible beams, the attachment of

fixed furniture directly onto the walls in correlation with the grid system of the wooden window frames, and the integration of heating systems as compositional elements are all features that clearly reveal the influence of the Swiss architect. Particular attention was also given to establishing a strong relationship with nature and ensuring ample natural lighting, both fundamental principles in Le Corbusier's own projects. It is also worth noting that during the postwar period, Le Corbusier's renewed focus on the natural dimension in architecture extended to the use of natural materials within interiors — such as wood, stone, and marble — as well as the aesthetic value he attributed to exposed concrete, perceived as a "man-made stone", thus reinforcing a sense of material authenticity.



Figure 14: Interior views of the Karakosta residence, source: www.archetype.gr



Figure 15: Left: Interior views from Villa Shodhan. Right: Interior views from Maisons Jaoul, source: www.en.wikiarquitectura.com

4. DISCUSSION

Reviewing the examples presented, it becomes clear that the architecture introduced by Le Corbusier — along with the new way of life he proposed — could not leave Greece unaffected, a country from which he drew essential elements to formulate his own architectural vocabulary. Greek architects of the Modernist movement, whether through direct collaboration with Le Corbusier in his atelier or indirectly through the study of his works, identified principles that they believed could be successfully adapted to Greek conditions.

During the interwar era, examples such as the apartment building at Stournari Street by Michailidis and Valentis demonstrate an almost complete adoption of Le Corbusier's interwar design principles. Their work also reflects a deep engagement with the new lifestyle proposed through *L'Esprit Nouveau*. In the postwar period, Le Corbusier's new spatial explorations and expressive means — such as the use of exposed concrete, often colored, and the redefinition of the relationship between architecture and nature through light and materials — deeply influenced Greek architects. These impacts are clearly observable in the examples analyzed in the Findings section.

Concerning interior spaces, Le Corbusier was not an architect who meticulously designed every furnishing detail. Instead, it was his broader compositional principles that determined

the spatial quality of his works — including his famous five points of architecture and his material choices. Plasticity, structured interior layouts with integrated furniture, material expressiveness, selectively applied bold colors, and movable furnishings of industrial aesthetic are the key characteristics that define the interiors of his projects — features that Greek modernist architects consciously incorporated into their own designs.

5. CONCLUSION

In conclusion, the influence of Le Corbusier on Greek modernist interiors was both profound and multifaceted. His principles, initially adapted selectively during the interwar period, evolved into fundamental guidelines for postwar architectural practice in Greece. By integrating spatial plasticity, the free floor plan, natural light, and material honesty, Greek architects not only reinterpreted Le Corbusier's ideas but also rooted them within the specificities of the Greek context — climate, culture, and urban needs.

This influence was particularly evident in interior spaces, where a new approach to domestic spatial organization and material expression emerged — informed by the ideals of modernism. Ultimately, Le Corbusier's vision contributed to redefining the living environment in Greece, forging a bridge between international modernism and local architectural expression.

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Research paper

HYDROLOGICAL AND HYDRAULIC MODELING OF RIVER CRNA FOR EVALUATING RIVER BASIN RESTORATION MEASURES

Violeta Gjeshovska[1], Simona Jankulovska[2], Bojan Ilioski[3]

Abstract

The degradation of the rivers and river basins caused by natural and/or anthropogenic factors can be prevented or significantly reduced by taking restoration measures. To define the restoration measures, it is necessary to perform a hydrological analysis of the river basin as well as a hydraulic analysis of the watercourse in the river basin. In this research, the hydrological-hydraulic analysis is carried out for the river Crna, for a characteristic section from the estuary of the river Crna in the river Vardar to the bridge on the E75 highway, at the Stobi archaeological site. This section is of great importance for the Republic of Macedonia because apart from the archaeological site of Stobi, which is a national institution in the field of culture, there are also the railway bridge on the "Skopje-Thessaloniki" railway and the bridges on the regional road R1102 and the highway E75, which are buildings of the first category. During the hydrological analysis, different methods are used, due to insufficient and discontinuous data. To determine the basic hydrological parameters, measured annual maximum flows (from 1961 to 1996) are used, and by using the databases of modern GIS, the physical-geographical characteristics of the river basin, height representation, geological, hydrogeological and pedological characteristics as well as land use are determined. By applying the HEC-RAS software package, a one-dimensional hydraulic model was created for the simulation of unsteady flow in the riverbed. With the hydraulic modeling, the hydraulic consequences are defined (flood surfaces, active erosion zones and sediment filling zones), and the most critical points are determined. The obtained results of the hydraulic analysis are analyzed, and measures are proposed in order to reduce the consequences of a flood wave.

Key words: *river basin restoration, hydrology, hydraulics, modeling.*

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1. INTRODUCTION

River basin restoration is an increasingly common approach utilized to reverse past degradation of river basins and to mitigate the anticipated damage from future development and resource-extraction activities. With new efforts to evaluate river basin restoration projects that use channel reconfiguration as a methodology growing exponentially over the last several decades, there has been little evidence for measurable ecological improvement or achieving the legally mandated goals of improving the structure and function of streams and rivers [1]. The complexity of restoration as a task, by which a degraded ecosystem is returned to its original state, requires a good hydrological-hydraulic analysis to be performed in order to determine the most appropriate restoration measures. In order to prevent errors in determining restoration measures, it is necessary to perform an assessment and monitoring of a specific ecosystem. However, the effects of river restoration on hydraulic and hydrological processes are complex and are often difficult to determine because of the long-term monitoring required before and after restoration works. For an effective river base restoration, detailed pre-restoration and post-restoration hydrological data is required to provide important insights into the hydrological effects of river basin restoration [2]. Due to different models obtaining different results on the same problem, incomplete or absent data, and climatic/social/cultural changes, the designers and managers of such projects frequently face high levels of uncertainty [3]. With the increase of flood risks all over the world, the approach to river flood management is beginning to make way for a paradigm shift towards 'living with water'. The ecological co-benefits of this shift, where rivers are given the space they need to migrate on the landscape, have so far been undervalued [4]. Methods like embankment removal or returning the channel to its natural, pre-engineered dimension for floodplain rehabilitation, can be a valuable part of the flood management strategy of a river. Both measures lead to increased inundation of the floodplain, which can be positive for ecological restoration [5]. River restoration as part of a river basin restoration is an appropriate solution for rivers which are degraded, yet have the potential to return to natural condition. Proposition of a new strategic plan for river restoration based on quantitative analysis rather than only qualitative assessment gives better results [6]. Hydrologic and hydraulic modeling allow to satisfy all regulatory requirements and ensure that natural, agricultural, and social resources are not damaged by flooding induced by modifications to the river system [7].

The objective of this study is to analyze and determine the problems and to define the most appropriate restoration measures for the river basin and also river restoration of the river Crna in the area around the archeological site Stobi.

The analysis will show the importance of a good hydrological and hydraulic modelling is the base for choosing and implementing the best solutions for river basin restoration and river restoration.

1.1. Case Study: River Crna

The degradation of the watershed of the river Crna is causing the river to overflow from its river bed even in the case of small quantities of rainfall and historically, the biggest problems of river Crna occur at the archaeological site of Stobi, the railway bridge on the "Skopje-Thessaloniki" railway and the bridge on the regional road R1102.

The aim of this research is to identify the problems and define the most appropriate restoration measures for the river basin.

The analysis was done with an appropriate hydrological analysis of the river basin and a hydraulic model for the propagation of the flood wave to determine the flooded areas and identify the critical zones for which restoration measures are recommended.

1.1.1. Study Area

River Crna is the biggest right tributary to the river Vardar and its river basin extends across two countries: in the southwestern part of the Republic of Macedonia and in the northern part of the Republic of Greece.

The study area is located from the mouth of the river Crna to the bridge on the E75 highway, at the archaeological site of Stobi. On this section there is also the railway bridge on the "Skopje-Thessaloniki" railway line, which connects Europe with the port of Thessaloniki.

The area of the river basin of river Crna is 5861.19 km^2 and has a developed and rich hydrographic network, consisting of 20 tributaries longer than 10 km with a total length of 461 km. Due to the favorable hydropower conditions in the river's Crna river basin, around 35 reservoirs have been built. The geological composition of the region is composed of three tectonic zones, with Paleozoic and Triassic formations in the upper and western parts, Precambrian rocks in the middle part and mix of shists, granites, flysch, tuffs, limestones, dolomites and marbles in the lower part of the river basin.

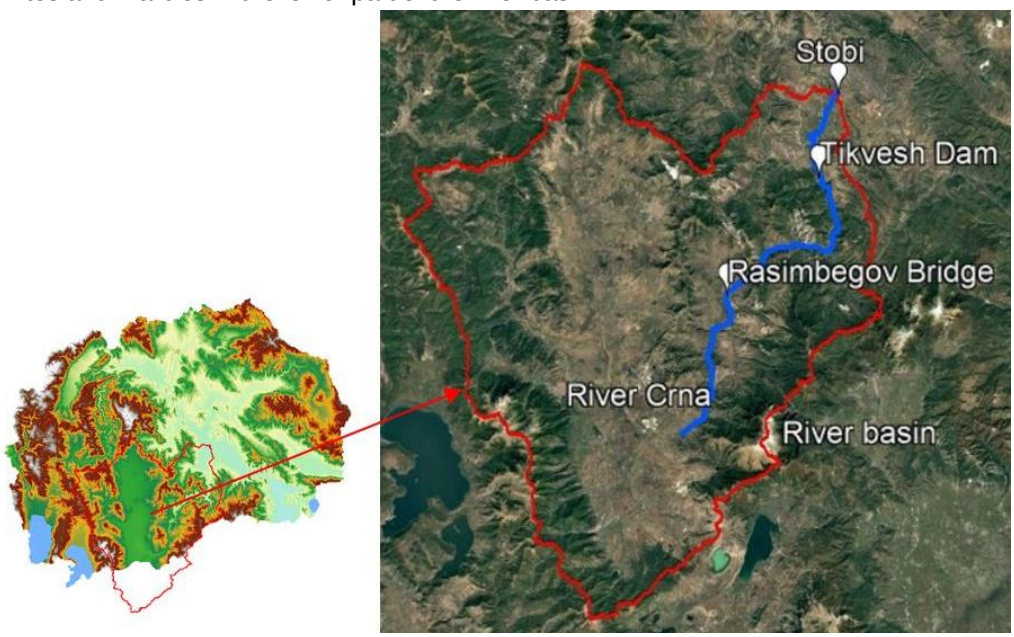


Figure 1. Study Area (source: Google Earth)

1.1.2. Data sources

In the river basin of river Crna there are two measuring stations for measuring flow. One is the measuring station Vozarci near the the archaeological site of Stobi, downstream of the Tikvesh Dam and the other is Rasimbegov bridge, upward of the Tikvesh Dam. The measuring station Vozarci is seriously damaged and it is not in use, and because of that the flows that are used in this research are from the measuring station at Rasimbegov Bridge. The data about the flows are annual maximum flows that were monitored and measured

continuously for the period from 1961 to 1996, Figure 2, (source: Hydrometeorological Service-HMS).

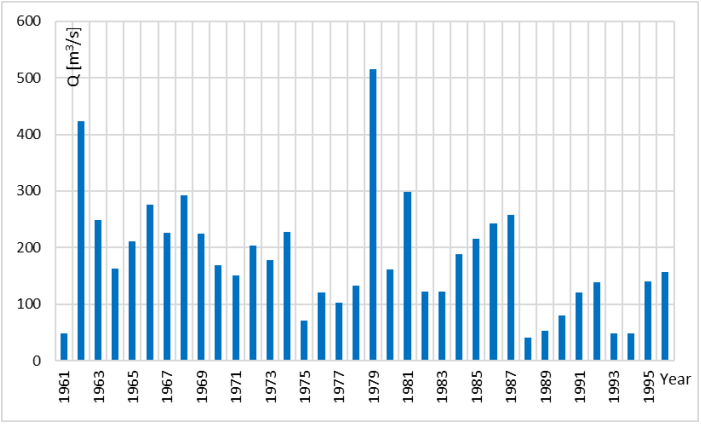


Figure 2. Maximum annual flow (Rasimbegov Bridge 1961 – 1996)

Digital terrain model of Macedonia in raster format with a resolution of 5x5 m was used as a terrain model, and information about the land use in this research was obtained by applying the data from the CORINE Land Cover database from 2018 [8]. The information for the soil textures of the land was obtained from the Pedological Map of Macedonia 2015 and the geological structure of the subject area from the Geological Map of Macedonia (according Arsovski 1997).

2. METHODOLOGY

2.1. Hydrological modeling

Hydrological modeling of the river basin of river Crna up to the mouth in river Vardar was done to determine the maximum flood waters in the analyzed section around the Stobi archaeological site. The delineation of the river basins is done with the help of GIS software ArcMap, module ArcSwat [9] and the physical-geographical characteristics of each sub-basin were calculated, Table 1. Detailed maps have been created in order to showcase the basic geological characteristics (Figure 3a), pedological [10], climatological and meteorological characteristics, as well as land use according to the CORINE Land Cover databases (Figure 3b).

Due to insufficient and discontinuous information for measured flow, combination of methods is used to determine the maximum flood waters in the subject area [11,12,13]. The calculations of the maximum flood waters for the river basin of river Crna were done in three steps, Figure 4.

The first step is up to Rasimbegov Bridge where the measured data from the measuring station is used and with the help of statistical analysis the maximum flood waters in that point were determined.

From the Rasimbegov Bridge to the Tikvesh Dam, for determination of the maximum flood waters a method of regional analyses is used. This method is based on the principle of hydrological analogy, i.e. comparing the ungauged basin with an analogous studied basin. Due to the existence of the dam and its influence on the water runoff, an analysis of the

transformation of the flood wave through dam with a return period of 100 years was done. The input and output hydrograph of the Tikvesh Dam for the scenario where the flood wave reaches the spillway height and all the evacuation spillways are in use is shown on Figure 5 (Qd – input flow, Qi – output flow and Qpr – overflow over spillway). Input data for the transformation of the flood wave through the Tikvesh Dam are the available accumulation space, the type of spillway, as well as the law of discharge of the accumulation, depending on downstream conditions.

The last step is from the Tikvesh Dam up to the mouth in the river Vardar. To determine the maximum flood waters at the mouth, surface water runoff was calculated for this section and added to the maximum water output from the Tikvesh Dam.

Table 1. Basic geometric characteristics of the river sub-basins

	F [KM^2]	O [M]	S_S [%]	Z_{MAX} [MASL]	Z_{MIN} [MASL]
Rasimbegov Bridge	4515.04	505.69	23.38	2598.00	357.00
Tikvesh Dam	5346.08	586.22	25.66	2598.00	210.00
Mouth in Vardar	5861.19	595.29	25.98	2598.00	117.00

F – area of river basin, O – perimeter of river basin, S_s – average slope of river basin, Z_{max} – maximum elevation in the river basin, Z_{min} – minimum elevation in the river basin.

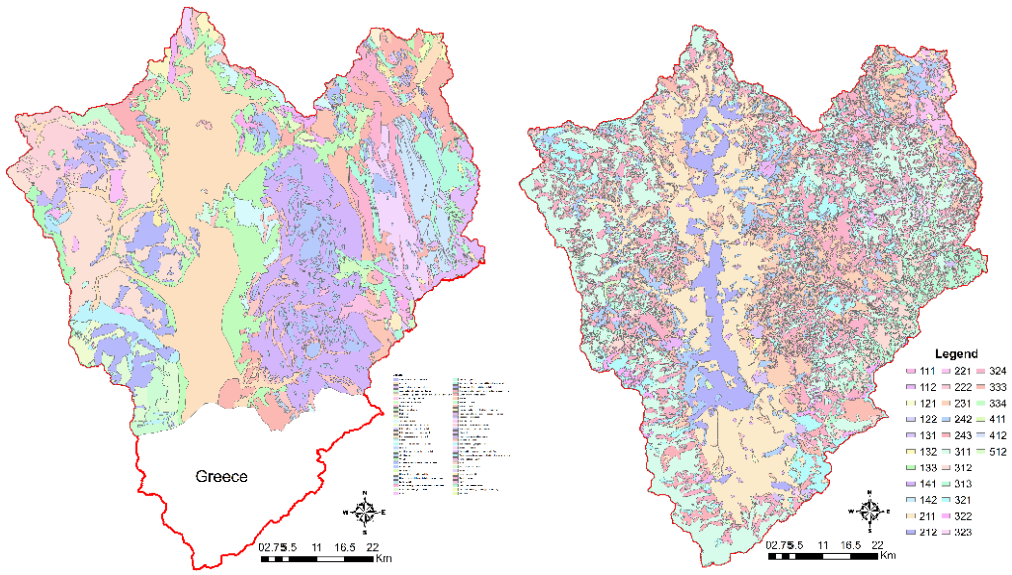


Figure 3. a – Geological map, b – CORINE Land Cover map

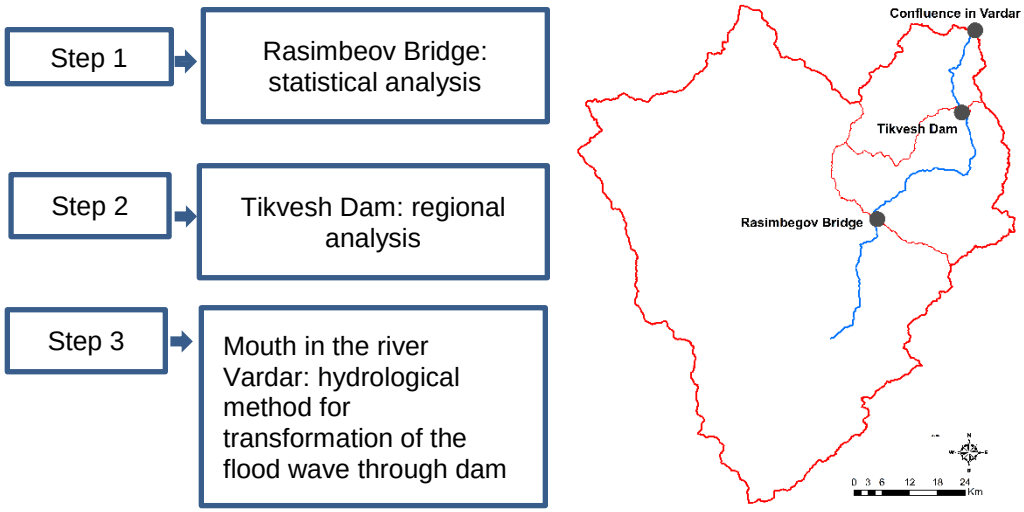


Figure 4. Algorithm for calculations of the maximum flood waters for the river basin of river Crna

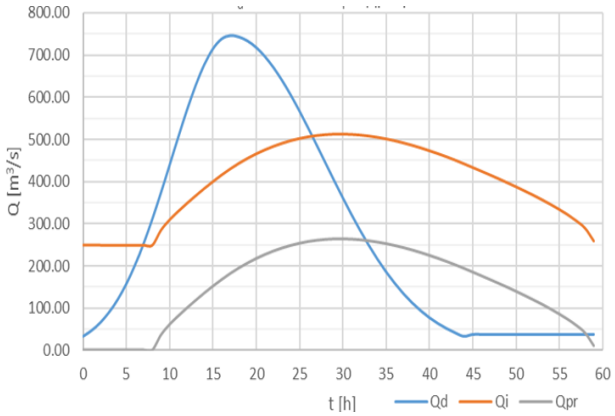


Figure 5. Input and output hydrograph at Tikvesh Dam

2.2. Hydraulic modeling

The hydraulic analysis were done for the riverbed of river Crna within the subject area from Bridge 3 (at the mouth in river Vardar) to Bridge 1 (at the bridge of E75 highway), with the software package HEC-RAS, made and developed by The Center for Hydraulic Engineering (HEC) of the US Army Corps of Engineers (USACE) [14]. For the purposes of this research, hydraulic analysis of the subject area were performed using a 1D model [15].

2.2.1. Input data

The hydraulic model for the analyzed section starts at the mouth of river Crna in the river Vardar and ends at the bridge of E75 higway with a total lenght of 813.45 meters, Figure 6. Geometrical data for the riverbed of river Crna was obtained from the 29 measured cross sections of the river Crna.



Figure 6. Analyzed section

Along the section there are modelled three bridges in the hydraulic model and was analyzes their influence. The characteristics of the bridges are given in Table 2.

Table 2. Characteristics of modeled bridges

Bridge	Type	Stationing data [km]	Number of bridge openings	Bridge top constr. [m.asl]	Bridge bottom constr. [m.asl]
B1 (at E75 higway)	Concrete	0+770.00	4	152.00	149.80
B2 (at regional road)	Steel	0+116.00	1	136.70	136.20
B3 (at mouth in river Vardar)	Concrete	0+080.00	3	137.40	136.00

2.2.2. Boundary conditions

Boundary conditions are defined at the downstream and upstream cross sections of the analyzed section as slope of the river bed, S_0 = 0.004 m/m for downstream and S_0 = 0.057 m/m for upstream, with the assumption that the flow in these profiles is stationary and uniform and with the given slope the normal depth in these boundary sections is defined.

The riverbed in the analyzed section is characterized by changes in the cross sections and the longitudinal profile, is overgrown with lush vegetation, big trees and erosion is apparent along the whole section. Given this state, the Manning's roughness coefficient for the river in the hydraulic model are 0.045 for the riverbed and 0.1 for the inundations.

Hydraulic analysis using the 1D model consists of simulating a flood wave propagation through the riverbed. The adopted maximum high water is $Q_{100years}$ = 585.99 m^3/s.

3. RESULTS

Hydrological modeling of the river basin of the river Crna was done to determine the hydrological characteristics needed for the calculations of the maximum flood waters in each sub-basin and the adopted maximum flood waters for the subject area used in the hydraulic modeling, Table 3.

Table 3. Results from the hydrological analysis

Sub-basin	$Q_{100years}$ [m^3/s]
Up to Rasimbegov Bridge	630.80
Rasimbegov Bridge to Tikvesh Dam	746.90
Mouth in river Vardar	**585.99**

With the hydraulic modeling of the river Crna a total number of 29 cross sections and the influence of the river on the bridges have been analyzed. The results of the hydraulic model of the water flow and flooded areas at the analyzed section are shown in the map of flooded areas for the analyzed return period of 100 years, Figure 7, the longitudinal profile of the riverbed, Figure 8, the influence of the river on the bridges, Figure 9 and the hydraulic parameters in Table 4 (Q – max. high water, Z_{min} – channel elevation, Z_{max} – max. water elevation, H – water depth, V – velocity, A -area , B –top width , Fr – Froude's number, τ – sheer stress).

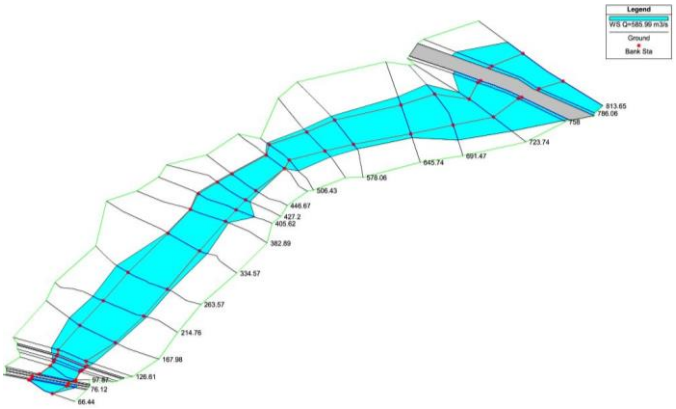


Figure 7. Map of flooded areas

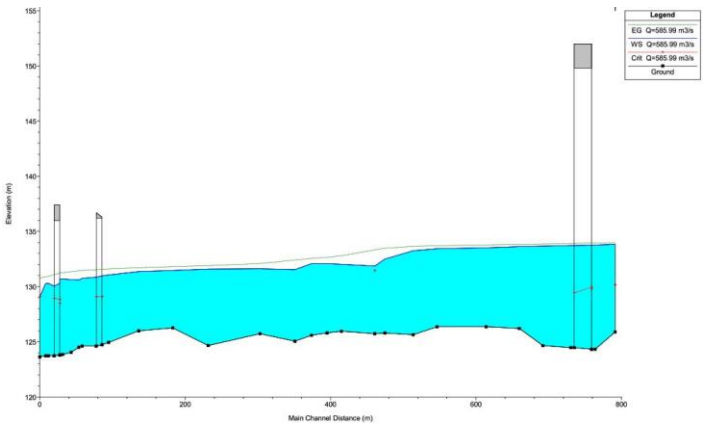


Figure 8. Longitudinal profile

Table 4. Hydraulic parameters

Prof.	Station	Q	Z_{min}	Z_{max}	H	V	A	B	Fr	τ
	(km)	(m^3/s)	(m)	(m)	(m)	(m/s)	(m^2)	(m)		(N/m^2)
1	0+813,65	585,99	125,90	133,83	7,93	1,76	416,73	139,34	0,24	20,42
2	0+786,06	585,99	124,33	133,78	9,45	1,93	393,09	128,91	0,25	20,49
3	0+782,00	585,99	124,33	133,77	9,44	1,93	392,61	128,89	0,25	20,52
	0+770,00	**Bridge 1 (at E75 highway)**								
4	0+758,00	585,99	124,48	133,73	9,25	1,94	358,65	123,17	0,24	18,67
5	0+723,74	585,99	124,66	133,67	9,01	1,94	328,27	92,36	0,24	22,25
6	0+691,47	585,99	126,21	133,63	7,42	2,02	315,78	87,78	0,27	29,52
7	0+645,74	585,99	126,37	133,52	7,15	2,28	269,64	64,00	0,31	45,58
8	0+578,06	585,99	126,37	133,43	7,06	2,30	260,90	56,82	0,30	46,38
9	0+545,52	585,99	125,64	133,25	7,61	2,79	225,04	50,85	0,36	66,11
10	0+506,43	585,99	125,80	132,49	6,69	4,41	139,53	47,90	0,65	150,93
11	0+492,54	585,99	125,74	131,87	6,13	5,34	109,80	29,01	0,86	361,09
12	0+446,67	585,99	125,95	132,02	6,07	3,89	151,62	41,45	0,61	167,56
13	0+427,20	585,99	125,81	132,08	6,27	3,37	176,61	46,88	0,52	123,36
14	0+405,62	585,99	125,59	132,09	6,50	3,03	198,46	70,80	0,48	79,27
15	0+382,89	585,99	125,06	131,55	6,49	4,12	143,26	44,98	0,71	210,13
16	0+334,57	585,99	125,74	131,62	5,88	3,05	198,80	53,19	0,46	94,92
17	0+263,57	585,99	124,67	131,60	6,93	2,46	257,76	67,93	0,36	56,52
18	0+214,76	585,99	126,26	131,46	5,20	2,63	234,73	64,68	0,40	67,86
19	0+167,98	585,99	126,00	131,37	5,37	2,65	238,32	63,64	0,39	65,18
20	0+126,61	585,99	124,95	131,06	6,11	3,32	198,10	49,73	0,47	100,60
21	0+119,88	585,99	124,73	130,98	6,25	3,44	176,09	43,28	0,50	120,84
	0+116,00	**Bridge 2 (at regional road P1102)**								
22	0+111,94	585,99	124,62	130,75	6,13	3,74	158,83	37,59	0,55	153,16
23	0+108,42	585.99	124,51	130,61	6,10	4,00	147,03	33,38	0,59	184,12
24	0+097,87	585.99	124,06	130,64	6,58	3,73	157,23	33,44	0,55	172,48
25	0+086,21	585,99	123,85	130,70	6,85	3,31	176,81	36,60	0,48	134,96
26	0+084,06	585.99	123,81	130,70	6,89	3,27	179,16	39,26	0,48	130,50
	0+080,00	**Bridge 3 (at mouth in river Vardar)**								
27	0+076,12	585,99	123,74	130,30	6,56	3,51	168,37	43,09	0,53	137,76
28	0+074,47	585.99	123,74	130,28	6,54	3,53	167,45	42,73	0,54	139,99
29	0+066,44	585.99	123,64	129,07	5,43	5,73	102,23	31,35	1,01	456,92

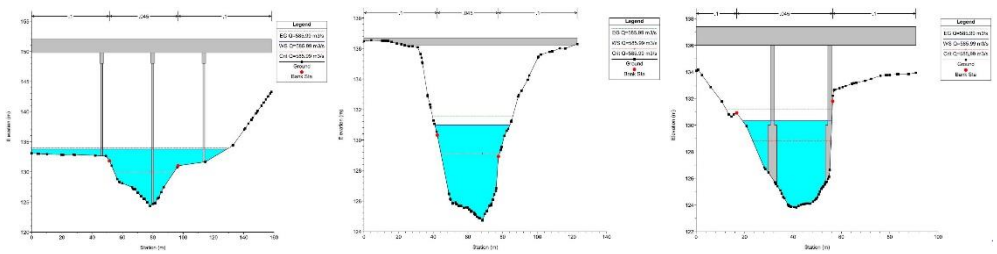


Figure 9. Influence of river Crna on bridges (a – Bridge 1, b – Bridge 2, c – Bridge 3)

4. DISCUSSION

Relevant and accurate data are required for quality hydrological analyses. Continuous and sufficiently long hydrological series of measured data play a major role in the quality of hydrological analysis. The insufficient number of measuring stations along the river Crna

imposes the use of multiple methods for determining the maximum flood waters, which is the basis for further hydraulic analysis. The outlet flow from Tikvesh Dam indicates the importance of the Dam for reducing high water levels downstream.

In this hydrological analysis, different methods of maximum flood waters calculations were used for different profiles. Any transfer of flow from one profile to another and the use of different methods is a basis for error in calculating the maximum flood waters, but in the absence of measured flow data for the appropriate location, with a certain degree of reserve, they can be used for the necessary analyses.

By analyzing the results of the hydraulic calculations, it can be concluded that there is a significant flooding at almost the whole analyzed section. Only part where there are no flooding areas are before the mouth in the river Vardar, mainly because the cross sections of the river Crna are expanding. The depth of the river and flooded zones ranges from 5 m to up to 9.5 m, the velocities in the river reach values of up to 5.73 m/s, and the sheer stress is greater than 456 N/m^2 resulting in the erosion in the river bed.

Bridge 1 is safely operating with a height of 15 meters above water level. Because the riverbed is natural, there is flooding around the bridge. The middle pillar of the bridge is located in the middle of the riverbed and is prone to erosion, so it is necessary to regulate the riverbed.

Bridge 2 is operating safely with a height of 4 meter above water level, but due to the narrow cross section at the bridge, the water has high velocity and sheer stress which results with occurrence of erosive processes. It is recommended that the riverbed be regulated to protect the bridge.

At the bridge on the Skopje-Thessaloniki railway, a deepening of the bottom, i.e. the presence of erosion, is observed, while one opening of the bridge is filled with material.

The bridges with its pillars are hydraulically unfavorable and increase flow resistance, which causes slowdown of the flow upstream of the bridges The flow regime is subcritical in the whole section and Froude numbers are below the critical value, Fr < 1.

The riverbed has a significantly reduced capacity and in the event of $Q_{100years}$ = 585.99 m3/s most of the section will be flooded.

River regulation can be carried out with technical measures first in the river basin, and then in the riverbed and banks. Measures that can be taken in the river basin are:

- Afforestation of the river basin enables retention of runoff, increasing of the runoff time, and significant reduction of flood waters.
- Control of the erosive areas of the river basin with technical-meliorative measures primarily intended for the reduction of surface runoff, reduction of erosion processes, creation of conditions and opportunities for biological works.
- Clearing the natural riverbed of dense low and tall-stemmed vegetation and its further maintanance.
- Operational plan for reservoir management.

In addition to measures in the river basin, for complete protection from the consequences of high water levels on the river Crna, it is necessary to foresee protective measures in the riverbed and on the banks. The most critical slopes that are subject to collapse need to be protected. Protection of the archarological site of Stobi from flooding can be done by building a parapet reinforced concrete wall, which will be founded on a layer of improved material.

5. CONCLUSION

With the help of the hydrological modeling the hydrological characteristics of the river basin of the river Crna were calculated and with the combination of statistical, regional and flood wave propagation analysis, the maximum flood waters at the profile of the mouth into the river Vardar was determined. The lack of sufficient measuring stations and the unavailability of continuous and high-quality input data (measured flows) imposes the use of multiple methods for determining the relevant flow, thereby complicating the analysis itself.

The hydraulic modeling of the river Crna at the analyzed section around the Stobi archaeological site, from the mouth in river Vardar to the bridge at the E75 highway was done in order to determine the effects of the river Crna on the bridges and determine the flooded areas. The results obtained from this research enable further research in this area with the aim of timely detection and prevention of hydraulic consequences. With the help of the results obtained from the analysis, a map of critical zones of flood areas can be created that will serve for the analysis of flood zones as well as preparation for prevention and management in the event of a large flood wave and also for the application and analysis of proposed restoration measures to prevent current and future hydraulic consequences.

In order to determine the best river basin restoration measures for the whole river basin of river Crna, a more thorough and bigger hydraulic analysis should be done for the whole basin and a more complex 2D model should be developed. Also, detailed pre-restoration data is required to prove the effects of the restoration.

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Research paper

ANALYSIS OF GNSS STATION SRJV00BIH AND SEISMIC ACTIVITY

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Abstract

This paper deals with the analysis of the time series of GNSS coordinates from station SRJV00BIH and their connection with seismic activity along key faults in Bosnia and Herzegovina. By using data on a time series of GNSS coordinates, the possibility of detecting tectonic movements in the context of specific earthquakes that occurred on a certain day was investigated. This seismic activity is linked to the data collected from the GNSS station. This involves the interaction of GNSS data with seismic events of intermediate magnitudes to identify potential deformations accompanying an earthquake. By monitoring these data, it is revealed whether there was a movement of the ground or deformations during the period of the earthquake. The methodology includes using the TSAnalyzer tool to analyse long-term trends and use of the Heaviside function, thereby identifying fluctuations potentially related to seismic activity. The results showed the existence of certain patterns in coordinate changes that coincide with seismic events on faults in the region, which suggests that GNSS stations can serve as an additional tool for monitoring geodynamic phenomena and improving the precision of seismic monitoring. Further research is proposed to improve the detection accuracy and integration of GNSS networks into regional early warning systems. The study aims to determine to what extent terrain deformations that precede significant seismic events can be detected and how GNSS data can help better understand fault activity.

Key words: *Global navigation satellite systems, Seismic activity, Time series, Ground deformation, Bosnia and Herzegovina, TSAnalyzer*

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1. INTRODUCTION

The advancement of geodetic measurement techniques and GNSS technology facilitates the recording of displacements and the precise determination of persistent movements of GNSS stations. Geodetic measurements in seismology are very demanding and of great importance for understanding processes at plate boundaries, because data on surface deformations help find new slip redistributions that can cause surface displacements. Tectonic geodesy is a branch of geodesy and geophysics that has significant applications in geoscience. It is an interdisciplinary field that studies the tectonic activity of the crust and its basic kinematics using geodetic measurement methods such as Global Navigation Satellite Systems (GNSS) and Satellite Laser Ranging (SLR).

Time series of GNSS coordinates allow a quantitative description of the movement of the GNSS station SRJV00BIH. By extracting geophysical signals from the time series of GNSS coordinates, clear insights into the movement of the GNSS station SRJV00BIH are obtained. In combination with seismological data, time series of GNSS coordinates are used to develop algorithms for earthquake modelling [1].

Time series of GNSS coordinates are most commonly used for geophysical research and have proven useful in investigating cycles of seismic deformations that relate to the entire seismic cycle.

The tectonic structure of Bosnia and Herzegovina is characterised by a complex geological structure that includes different tectonic units. Bosnia and Herzegovina is located within the Dinaric system, which is the result of the collision of the African and Eurasian tectonic plates. There are numerous faults in the territory of BiH as a result of tectonic processes. Faults are a factor that affects seismic activity in the country. In some areas, there is a folding of the lithosphere, that is, the deformation of the Earth's crust due to the action of tectonic forces, which leads to specific geomorphological characteristics of that area [2].

Seismic activity in Bosnia and Herzegovina is not evenly distributed throughout the country, but is concentrated in certain zones that are known for their greater activity. The southern part of BiH is known for its significant seismic activity. The area of Mostar, Čapljina and the surrounding areas are often affected by earthquakes. The fault that runs through the southern and northwestern part of BiH is known for its numerous earthquakes that have occurred in the past. The area around Sarajevo has often registered significant seismic events. The area around Banja Luka is also known for its registered seismic activity [2].

Based on data on the seismicity of BiH, it can be concluded that the highest frequency of earthquakes is in the area of Herzegovina, the border with Croatia, and the area of Banja Luka. In Banja Luka, Derventa and Tuzla, in recent years, there has been an increase in seismic activity. Earthquakes with the smallest depth were recorded in the Drina area (Prača, Višegrad, Srebrenica, Zvornik), and with the largest in the northwest and west of BiH [2].

Real-time global navigation systems and fault analysis play a key role in understanding geodynamic processes. The paper analyses the GNSS station SRJV00BIH and seismic activity on faults. The result of continuous GNSS measurements is a time series of GNSS coordinates. A connection has been established between the GNSS coordinates of the SRJV00BIH station and seismic activity on faults, with a special focus on the narrow area around the SRJV00BIH GNSS station.

GNSS time series analysis refers to the examination of data collected from GNSS stations that allow monitoring of changes in position in space over time [1]. The analysis is often used for geodetic, engineering and geophysical research. These researches also include

monitoring of the movement of the Earth's crust, landslides, seismic activity and similar phenomena.

GNSS time series represent the position of a GNSS station in certain time intervals and are made up of a series of coordinates (most often in three dimensions: east-west, north-south and vertical). Time series analysis aims to understand movement patterns, long-term trends, short-term events and seasonal changes. The analysis includes statistical and mathematical techniques for data processing, modelling, and interpretation of results to obtain the necessary information about geodynamic processes [1].

2. MATERIALS AND METHODOLOGY

2.1. Study of the area

Compared to other stations, the GNSS station SRJV00BIH, located at the Faculty of Civil Engineering building in Sarajevo, has the longest time series in the region, lasting about 24 years. Stronger earthquakes are rare for the area around Sarajevo, although the territory of Bosnia and Herzegovina falls into a seismically active zone. The hypocenter depth in this area ranges from 4 km to 30 km. Figure 1 shows the antenna of the GNSS station SRJV00BIH, while Figure 2 shows its location.



Figure 1. Antenna TRM57971 on the chimney of the Faculty of Civil Engineering in Sarajevo [3]

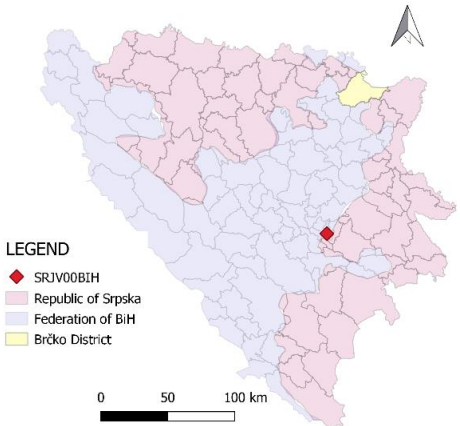


Figure 2. Location of GNSS station SRJV00BIH (drawing by author)

2.2. Input data

This work uses data downloaded from the Nevada Geodetic Laboratory (NGL) [4] website. NGL, through its MAGNET + Global GPS Network Map [4] service, provides access to a wide range of geodetic data and is known for its collection and analysis of geodetic data. These data were collected using a highly accurate GPS (Global Positioning System) receiver that is part of a global network that continuously records time series of data. The technology provides the ability to track surface ground motion with millimetre-level accuracy, which is important for geodetic and seismological studies. The data used are time series of GPS coordinates that refer to the IGS14 reference frame, which was established by the International GNSS Service (IGS) in 2014. The required earthquake data were retrieved from the U.S. Geological Survey (USGS) database [5], which collects and stores earthquake data worldwide. Access to the data and tools is open to researchers and scientists for research purposes. In this case, the Search Earthquake Catalog [6] was used to obtain the relevant data.

2.3. Time series analysis from GNSS station SRJV00BIH

Before applying a mathematical model, it is necessary to eliminate outliers, that is, it is necessary to carry out data cleaning. Outliers can arise due to various factors, such as temporary environmental anomalies or measurement errors and can significantly impair the accuracy of the model, especially if they are not removed from the data set or remain unidentified. For this reason, the application of algorithms for detecting and eliminating outliers is a key step in data preprocessing.

Using a robust algorithm based on the IQR (Interquartile Range) for identification and a rejection decision level of n = 3, outlier removal was implemented in a GPS time series of SPLT station coordinates [7].

$$\left|\hat{v}_i - median\left(\hat{v}_{i-w/2,}\hat{v}_{i+w/2}\right)\right| > 3 \cdot IQR\left(\hat{v}_{i-w/2,}\hat{v}_{i+w/2}\right) \quad (1)$$

For long-term trend analysis in GNSS time series, a linear model is most commonly applied, which is expressed as [8]:

$$y(t) = a + bt + \epsilon(t) \quad (2)$$

Where: $y\,(t)$ – GNSS station position at time t, a – initial value, b – trend coefficient (slope) showing the average change in position per unit time and $\epsilon\,(t)$ – residual component (error or noise) containing variability not explained by the linear model.

The coefficient b is a key parameter that indicates the existence of a long-term trend in the data. If b is positive, this indicates the existence of an upward trend (position increases over time), while a negative value of b indicates a downward trend (position decreases over time). When b is close to zero, which suggests that there is no significant long-term trend.

The Least Squares Method is most often used to estimate the parameters a and b. This method minimises the sum of the squares of the differences between the actual values of $y(t)$ and the estimated values from the model [8].

The model can be extended with sinusoidal components, if necessary, to include seasonal effects in the analysis [8]:

$$y(t) = a + bt + ccos\,(\omega t) + d\,sin(\omega t) + \epsilon(t) \quad (3)$$

Where c and d are the coefficients for the sinusoidal components, and ω is the frequency of seasonal oscillations.

These expressions allow for precise analysis of long-term trends and periodic variations in GNSS time series. The long-term trend is analysed without including seasonal variations that occur at specific time points t_0.

The Heaviside function can be useful when we want to include jumps in the time series. This function is used to model such discontinuities.

The Heaviside function, $H(t-t_0)$, is defined as [8]:

$$H(t-t_0)=\begin{cases}0, t<t_0\\1, t\geq t_0\end{cases} \quad (4)$$

The Heaviside function can be integrated into a time series model to simulate sudden changes or jumps in the series, such as earthquakes or other sudden changes in the position of GNSS stations.

The modified time series model with this function can be written as [8]:

$$y(t)=a+bt\ +\ \sum_{i=1}^{N}k_iH\ (t-t_i)+\ \epsilon(t) \quad (5)$$

Where: $y(t)$ – position of the GNSS station at time t, a – initial value (intercept), b – trend coefficient (slope), k_i – amplitude of the jump at time t_i, $\mathrm{H(t-t_i)}$ – Heaviside function that activates the jump at time t_i and $\epsilon(\mathrm{t})$ – residual component (error or noise).

The Heaviside function ensures that the jump becomes active only from time t_i onwards, while k_i determines the size of the jump in this model. This method allows for precise modelling of discontinuities that arise due to specific events such as earthquakes or technical changes in GNSS stations.

The weighted root mean square (WRMS) error is used to estimate the precision of a time series, which takes into account the different weights that may be assigned to different points in the series (e.g. due to different measurement reliability).

WRMS is defined as: $\hat{y}$

$$WRMS=\sqrt{\frac{\sum_{i=1}^{N}\omega_i(y_i-\hat{y}_i)^2}{\sum i{=}1^{N}\omega_i}} \quad (6)$$

Where: y_i – actual value of the time series at time *i*, $\hat{y}_i$ – predicted value at time *i* from the model, ω_i – weight assigned to the data at time i, and N – total number of points in the time series.

Implementation procedure:

1. Weight assignment: Based on the reliability of the data, weights ω_i are usually assigned (Points with higher measurement precision receive higher weights).
2. Calculation of residual error: The square of the difference between the actual value y_i and the predicted value $\hat{y}_i$ is calculated for each point i.
3. Summarisation with weights: Each square of the error is multiplied by the corresponding weight ω_i and summed for all points in the time series.
4. Normalisation: The sum of the weighted squared errors is divided by the sum of all weights $\sum_{i=1}^{N}\omega_i$.
5. Calculating WRMS: The square root of the expression gives WRMS.

WRMS takes into account the inhomogeneities in the precision of the measurements and allows a better understanding of the variability of the time series. For example, if some

measurements are more precise than others, WRMS will take them into account more when estimating the total error of the series. WRMS can help assess the quality of the model used to analyse trends and spikes in GNSS time series, allowing a more precise quantification of the remaining errors in the series.

3. RESULTS

In this paper, earthquakes in the vicinity of the GNSS station SRJV00BIH were analysed. TSAnalyzer was used for time series analysis. Figure 3 shows the location of the GNSS station SRJV00BIH, as well as earthquakes in its vicinity.

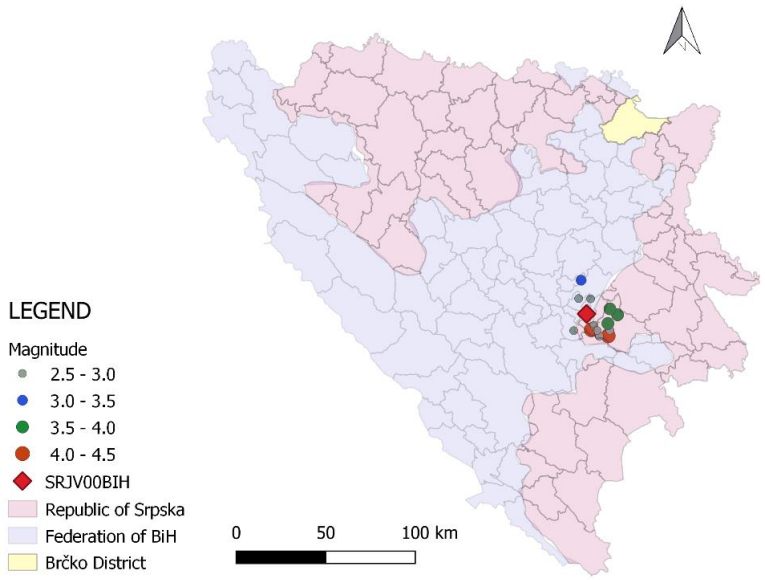


Figure 3. Earthquake report in the vicinity of the SRJV00BIH station (drawing by author)

Table 1 presents earthquakes in the vicinity of GNSS station SRJV00BIH. This table contains information on the depth, magnitude and distance from GNSS station SRJV00BIH for the listed seismic events. The earthquakes range in magnitude from 2.6 to 5.5 on the Richter scale. The depths of earthquakes range from 2 km to 13 km, indicating relatively shallow earthquakes. The distance from the station varies, with some earthquakes being more than 19 km away, while others are closer, e.g. SRJ8 (9,2 km).

Table 1. Depth, magnitude and distance from GNSS station SRJV00BIH for different seismic events

Seismic event	Date	N [°]	E [°]	Deep [km]	Magnitute	Distance from SRJV00BIH [km]
SRJ1	11.06.2000.	43.896	18.582	10.0	3.7	16.6
SRJ2	14.10.2000.	44.041	18.383	10.0	3.4	7.6
SRJ3	11.08.2001.	43.788	18.492	13.3	2.5	11.7
SRJ4	09.05.2003.	43.788	18.330	4.7	2.9	10.9

SRJ5	24.06.2003.	43.814	18.471	10.0	2.7	19.2
SRJ6	31.03.2004.	43.823	18.567	10.0	3.9	13.4
SRJ7	18.08.2005.	43.758	18.508	11.0	2.7	17.2
SRJ8	29.12.2007.	43.947	18.448	5.5	2.6	9.5
SRJ9	31.12.2007.	43.949	18.361	3.2	2.9	17.5
SRJ10	19.07.2008.	43.790	18.580	11.0	2.7	15.7
SRJ11	30.03.2009.	43.866	18.635	2.0	3.9	8.7
SRJ12	31.03.2009.	43.792	18.452	5.0	4.1	14.5
SRJ13	12.04.2015.	43.761	18.569	3.6	4.1	13.0
SRJ14	22.02.2019.	43.760	18.558	10.0	2.7	9.6

Table 2 shows the time intervals of the GNSS series, the number of epochs and WRMS before and after data cleaning. It can be seen that data cleaning reduces the WRMS values in all N (North), E (East) and Up (vertical) components, indicating an improvement in the measurement quality. There are gaps in series SRJ6 and SRJ10. Gaps in time series occur for several reasons and can significantly affect data analysis and modelling. One of the main causes is technical problems. If data is collected using sensors, power outages, equipment failures, or sensor calibration can lead to interruptions in data collection. Errors can occur during the transfer of data from the sensor to the database. If the connection is unstable or the data is stored incorrectly, this can lead to missing values. Sometimes data is intentionally filtered or deleted if it is considered invalid, which also creates gaps.

Gaps in time series can have a significant and often negative impact on data analysis and modelling. They have an important influence on statistical measures such as the mean, variance, and standard deviation. If data from periods with extreme values (peaks or troughs) are missing, these statistics will be incorrectly estimated. This can lead to incorrect conclusions about the underlying characteristics of the series. Understanding gaps is a key step in preparing data for analysis. Ignoring gaps can lead to wrong conclusions and ineffective models.

Table 2. Time series intervals, number of epochs and WRMS before and after data cleaning

Time series	Time series interval		No. of epochs	WRMS (contaminated)			No. of epochs after cleaning	WRMS (after cleaning)		
	From	To		N [mm]	E [mm]	Up [mm]		N [mm]	E [mm]	Up [mm]
SRJ1	15.06.1999.	11.06.2002.	620	2.7	3.2	20.5	599	2.3	2.9	7.7
SRJ2	15.06.1999.	14.10.2002.	743	2.6	2.7	18.9	727	2.4	2.5	6.8
SRJ3	16.02.2000.	19.07.2003.	921	2.5	2.6	7.2	893	2.4	2.5	5.9
SRJ4	08.12.2001.	27.09.2005.	840	1.6	1.8	6.8	811	1.5	1.6	5.5
SRJ5	08.12.2001.	27.09.2005.	840	1.6	1.8	6.8	810	1.5	1.6	5.5
SRJ7	22.02.2002.	29.03.2008.	1109	1.7	2.0	10.0	1078	1.5	1.8	5.7
SRJ8	20.05.2005.	28.04.2009.	625	1.6	2.0	12.1	605	1.4	1.8	6.3
SRJ9	20.05.2005	28.04.2009.	625	1.6	2.0	12.1	605	1.4	1.8	6.3
SR11	26.08.2005.	02.07.2010.	852	1.6	1.9	11.1	826	1.4	1.7	6.5
SR12	26.08.2005.	02.07.2010.	852	1.6	1.9	11.1	826	1.4	1.7	6.5
SR13	26.12.2013.	16.03.2020.	2178	1.6	1.9	12.3	2092	1.3	1.6	5.8
SR14	29.08.2017.	02.03.2021.	2178	1.6	1.9	12.3	1205	1.3	1.5	6.1

Table 3 presents the time series velocity by component N, E, Up and the component coseismic displacement (i.e., ground movement caused by earthquakes) for different time series. The velocity shows the changes in millimetres per year for each component. The coseismic displacement values represent sudden movements due to seismic events.

Table 3. Presentation of time series velocity by component and coseismic displacement by component

Time series	Velocity displacement by component			Coseismic displacement by component		
	N [mm/god]	E [mm/god]	Up [mm/god]	N [mm]	E [mm]	Up [mm]
SRJ1	27.4±0.4	12.0±0.5	4.2±1.4	16.1±0.9	-24.5±1.1	13.9±3.0
SRJ2	24.9±0.4	12.9±0.4	1.4±1.0	-1.8±0.8	-4.0±0.9	0.2±2.3
SRJ3	19.6±0.2	19.7±0.3	-3.6±0.6	-6.9±0.7	9.9±0.7	-1.1±1.7
SRJ4	22.9±0.2	16.3±0.2	-3.1±0.6	-1.9±0.6	-4.1±0.6	1.7±2.2
SRJ5	22.9±0.1	16.4±0.2	-3.0±0.5	-0.9±0.4	-3.0±0.4	2.2±1.5
SRJ7	23.4±0.1	16.1±0.1	-1.8±0.2	0.8±0.4	5.7±0.5	-9.3±1.7
SRJ8	22.8±0.1	15.2±0.2	1.0±0.6	-0.1±0.4	-3.2±0.5	-1.1±1.8
SRJ9	22.9±0.1	15.2±0.2	1.0±0.6	-0.1±0.4	-3.6±0.5	-0.8±1.9
SR11	22.9±0.1	14.9±0.1	2.1±0.2	1.8±0.4	0.4±0.5	4.2±2.0
SR12	22.9±0.0	14.9±0.1	2.1±0.2	1.9±0.4	0.2±0.5	4.5±2.0
SR13	22.2±0.0	14.9±0.0	0.0±0.2	-1.9±0.3	-2.1±0.4	-5.5±1.4
SR14	22.4±0.1	14.1±0.1	-0.6±0.5	-1.9±0.4	-3.2±0.4	1.3±1.6

The data indicate continuous motion, with significant horizontal and vertical displacements evident over long-term time series. Earthquakes in this area are relatively shallow but strong enough to cause coseismic displacements. GNSS data from the stations allow for precise tracking of these changes, which can help in better understanding seismic activity and its impact on the ground.

The correlation between the coseismic vertical displacement (Up) of the GNSS station and the earthquake magnitude (left graph in Figure 4) was performed, and it is -0.12, which indicates a very weak negative correlation. This means that there is no clear relationship in the data between the earthquake strength (magnitude) and the vertical ground displacement. It can be seen that earthquakes of smaller magnitude (below 4.0) as well as those of larger magnitude (above 4.0) can cause ground displacements that vary from positive to negative values. This indicates that the magnitude factor itself is not decisive for determining the vertical displacement. The correlation between the distance from the GNSS station and the coseismic vertical displacement (Up) is 0.23 (right graph in Figure 4), which also indicates a very weak positive correlation. The graph shows that vertical displacements are present in both earthquakes, closer to the station and those further away, but there is no clear trend indicating a significant effect of distance on ground motion.

The results of the analysis of horizontal displacement and the correlation between earthquake magnitude and horizontal coseismic displacement (N and E components) are -0.07, indicating a very weak negative correlation (left graph in Figure 5). This means that there is no clear relationship between earthquake strength (magnitude) and horizontal ground motion. Earthquakes of different magnitudes cause similar levels of horizontal displacement. The correlation between distance from the GNSS station and horizontal

coseismic displacement is 0.31, indicating a slightly positive correlation (right graph in Figure 5). Although not strong, this correlation is a little bit more pronounced compared to vertical displacements, suggesting that distance from the station may have a slightly greater impact on horizontal ground displacement.

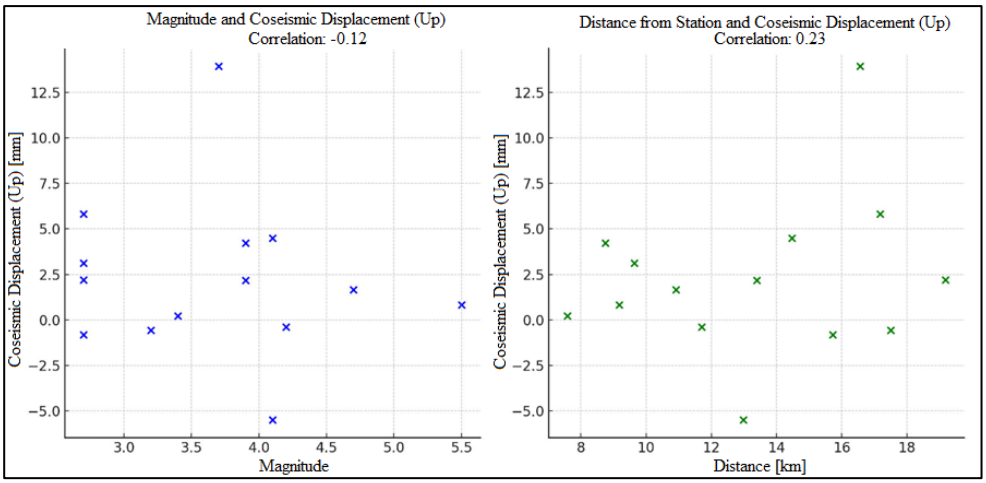


Figure 4. Display of weak correlation between the coseismic vertical displacement of the GNSS station and the earthquake magnitude, as well as the distance from the station (drawing by author)

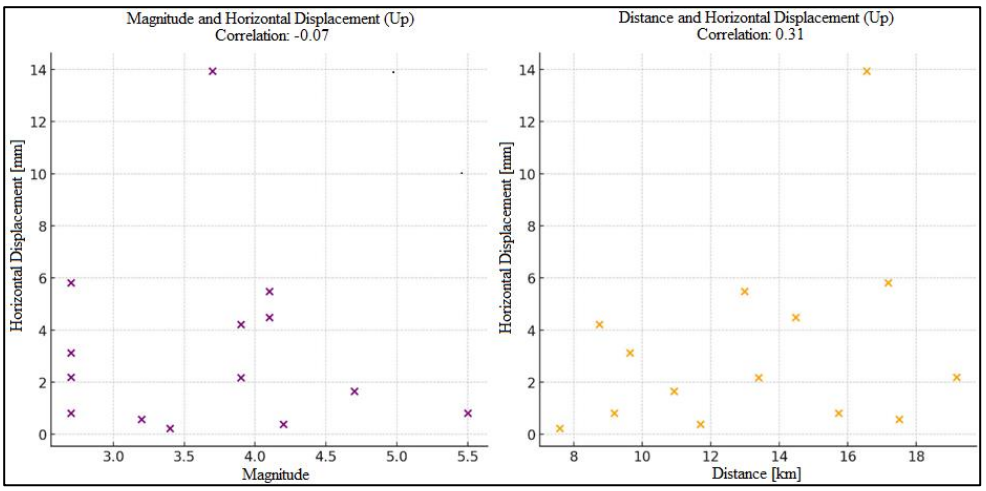


Figure 5. Display of the analysis of the relationship between the horizontal coseismic displacement of the GNSS station and the earthquake magnitude, as well as the distance from the station (drawing by author)

4. DISCUSSION

The WRMS values for the N, E and Up components were reduced after data cleaning in almost all time series. This shows that the data cleaning process significantly improves the measurement accuracy by reducing noise and eliminating contaminated data. Some series, such as SRJ1 and SRJ2, have a significant reduction in WRMS values, especially in the vertical component (Up), indicating that these series were significantly affected by noise or

irregularities before cleaning. For example, for SRJ1, the WRMS in the vertical component (Up) was reduced from 20,5 mm to 7,7 mm, which is a significant improvement. The vertical component (Up) generally shows higher WRMS values compared to the horizontal components (N and E). This is expected because GNSS measurements usually have higher imprecision in the vertical axis. After cleaning, the improvements in the N and E components are less pronounced than in the Up component, indicating that the vertical component was more affected by noise. Time series such as SRJ3, SRJ4 and SRJ5 show relatively small WRMS values even before cleaning, indicating a more stable measurement during that period. These series had less noise, which means that the GNSS data in those periods were less contaminated. Time series such as SRJ6 and SR10 have gaps, which can further affect the accuracy of the WRMS values. Gaps in the data can lead to larger errors in coordinate interpretation, especially during periods of increased seismic activity.

The movement speeds are expressed in mm/yr and represent the mean annual movement speed for each component (N-north, E-east, Up-vertical). The highest movement rates in the northern component were recorded for the SRJ1 series (27.4 mm/yr), while the lowest rates were recorded for the SRJ3 series (22.2 mm/yr). In the eastern component, the SRJ3 series shows a relatively high rate of 19.7 mm/yr, while the SRJ1 series has the lowest rate of 12.0 mm/yr. The vertical component (Up) shows significant deviations, with the SRJ1 series recording the highest movement rate of 4.2 mm/yr, while the SRJ3 series has a negative rate, indicating ground subsidence in that area. The coseismic displacement shows the total displacement by component in mm during the monitoring period. The SRJ1 series shows the highest coseismic displacement in the eastern component (24.5 mm), indicating a significant eastward shift. Also, the SRJ1 series shows relatively high coseismic displacement in the vertical component (13.9±3.0 mm), which indicates ground uplift in this area during the measurement period.

Negative values of coseismic displacement, such as those recorded in the SRJ7 series for the Up component (-9.3 mm), indicate ground subsidence during that period. Series with gaps in the time series (SRJ6 and SRJ10) may show larger fluctuations due to a lack of continuity in the data. The SRJ13 series shows more stable movement rates in all three components, which may indicate a more stable tectonic regime during the monitoring period. The vertical component shows larger oscillations compared to the horizontal components (N and E), which is expected because GNSS measurements are traditionally less precise in the vertical axis. Series with positive vertical displacement (e.g. SRJ1) indicate ground uplift, while series with negative displacement (e.g. SRJ7) indicate ground subsidence.

This analysis of velocities and coseismic displacement by component allows a deeper understanding of tectonic movements and ground deformations in the area monitored by GNSS stations. The data indicate significant changes in the horizontal and vertical components, which can be associated with tectonic activities and seismic events in the region.

5. CONCLUSION

Based on the conducted research and analysis of time series of coordinates from the GNSS station SRJV00BIH, it can be concluded that there is a significant potential for using GNSS data for monitoring seismic activity and detecting tectonic movements in Bosnia and Herzegovina. The analysis showed that changes in GNSS coordinates often coincide with

periods of increased seismic activity, especially near key faults in the region. This shows that GNSS stations have an important role in predicting seismic events and improving early warning of earthquakes.

Based on the WRMS analysis, it can be concluded that the cleaning process significantly contributes to improving the accuracy of GNSS data, especially in the vertical component. Data cleaning is crucial for ensuring reliability in monitoring tectonic movements and accurate monitoring of seismic activity. Based on the results, it can be concluded that neither earthquake magnitude nor distance from the GNSS station shows a significant relationship with horizontal or vertical coseismic displacements. However, distance from the station may have a slightly greater impact on horizontal displacements compared to vertical displacements. This indicates that for a deeper understanding of these displacements, other factors should be included, such as local geology, earthquake depth, tectonic faults and soil types, which can significantly affect the patterns of ground displacement during seismic events.

Coseismic displacements derived from the time series of the GNSS station SRJV00BIH indicate that vertical and horizontal ground changes are closely related to activities on local faults. Different values of movement velocities and coseismic displacements reflect how seismic activities affect deformations in certain periods.

The coverage of seismic sensors is poor. One century-old analogue and a few recently installed seismometers are insufficient for a region that exhibits mild to high seismic activity. Significant investments are needed to establish or improve GNSS, seismic and other sensor networks.

It is important to properly expand GNSS networks and integrate them with seismic sensors to obtain accurate and reliable data for seismic surveys and early warning systems. The combination of these two technologies allows for the measurement of both fast dynamic movements (seismic sensors) and slow, long-term ground movements (GNSS).

It is crucial to carefully select the locations of the stations to maximize coverage and accuracy. The stations should be placed on geologically stable ground (e.g. on rocks or stable foundations) to reduce the impact of noise from surface waves and human activities. A denser network is required for monitoring local seismic activity, while a sparser one can be used for regional studies. It is recommended to place the stations at 30-40 km for optimal monitoring, and this distance can be smaller in areas with high earthquake risk [9].

GNSS receivers and seismic sensors (accelerometers) must be installed at the same location, preferably on the same stable ground, to ensure accurate data correlation. Precise time synchronization between the GNSS receiver and the seismic sensors is essential. This is usually achieved by using the PPS (Pulse Per Second) signal from the GNSS receiver as a reference for the seismic sensors [10].

Complex algorithms, such as the Kalman filter, are used to process data, which combine dynamic data from the accelerometers (high frequency) with absolute displacements from the GNSS (lower frequency). This results in a wideband signal with high accuracy and no drift [11].

Improved methods of GNSS data analysis could significantly contribute to reducing the risk of natural disasters, especially in seismically active areas. In this way, GNSS technology can provide additional security and improve the ability to detect potentially destructive seismic events early.

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Review paper

NARRATIVE STRUCTURES IN ARCHITECTURE: CASE STUDY OF THE MUSEUM OF APOXYOMENOS

Petar Mitrović[1]

Abstract

Narrative architecture aims to communicate meanings through spatial qualities by actively engaging users as both readers and participants in storytelling. This paper investigates narrative structures in architecture through a case study of the Museum of Apoxyomenos in Mali Lošinj, Croatia, using a qualitative methodology that combines a short literature review with a single-case study analysis. The museum serves as an empirical model to examine how spatial design holds and transmits layered narratives in contemporary architectural practice, employing spatial reading, sequential spatial analysis, and the study of spatial experiences to deepen the understanding of architectural narratology within museum typology. Particular attention in the case study is given to the integration of outdoor areas, transitional thresholds, and framed views, which are recontextualized as distinct narrative scenes, emphasizing their role in generating emergent spatial meanings. The Museum of Apoxyomenos employs a hybrid narrative form that weaves multiple, overlapping stories into a unified spatial experience, presenting a broad background narrative encompassing diverse layers of meaning. The applied narrative structure positions visitors as active participants in the unfolding story, requiring interaction not only with the exhibition structure but also with the broader urban and cultural context. The findings of this study encourage a reevaluation of museum architecture, proposing that design should be understood not merely as a physical construct, but as an active communicative medium capable of shaping perception and conveying complex narratives.

Key words: *Narrative Architecture, Narrative Structures in Architecture, Museum Architecture, Phenomenology of Space*

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1. INTRODUCTION

Architecture can communicate meanings, histories, and cultural values through spatial experience. Interdisciplinary debates throughout the past decades have seen the notion of architecture as narrative medium increasingly explored, and by theories of narratology, spatial theory, and phenomenology. Narrative structures in architecture go beyond symbolic signification, and involve the structuring of spaces, articulation of in-between spaces, and orchestration of sensory experience to inform user perception. Understanding space through its narrative capabilities, primarily by interpreting “architecture as a text” and recognizing architecture as an active agent of space, he defines spatiality, materiality, and the transformation of spatial meanings.

This paper investigates how architectural form can integrate narrative structures in architecture to enhance experiential engagement, as analyzed in the case study that follows theoretical framework. It highlights the role of both sequential and symbolic aspects of space, viewing narrative architecture not as a simple translation of text into form, but as a dynamic space where practice, perception, and interpretation are constantly negotiated.

The research methodology integrates a short literature review of narrative architecture and narrative structures in architecture along with a single-case study analysis. The case study of the Museum of Apoxyomenos in Mali Lošinj, Croatia provides an empirical model to examine how spatial design holds and transmits layered narratives in contemporary architectural practice. Spatial reading of architecture, sequential spatial analysis, and spatial experiences have been used to analyze the architectural narrative structure of space. This approach aims to deepen the understanding of architectural narratology in museum typology as a key element in architectural design.

2. NARRATIVE ARCHITECTURE: FROM MEANING TO FORM

Narrative architecture aims to communicate meanings through its spatial qualities by actively engaging the users of the space, simultaneously as readers and participants in the narrative storytelling. As Željka Pješivac notes: “Narrative requires both a narrator and a reader in the same way that architecture requires both a design and an observer” [1]. Exploring this relationship between architecture and narrative, the built space plays a significant role, as “the connection between engaged storytelling and its culmination is found in the spatial articulation of architectural form” [2]. Various architectural theorists have explored narrative, both through their architectural practice and within architectural theory – Roland Barthes, Christian Norberg-Schulz, Peter Eisenman, Daniel Libeskind, Peter Zumthor, and Juhani Pallasmaa. Their works investigate how architecture, through its form, materiality, spatial organization, and ambiance, communicates with its users. Additionally, the integration of meaning, memory, and emotions can be read and interpreted in a way that space becomes a medium for architectural storytelling.

Marshall McLuhan states that “the medium is the message” [3] which characterizes architecture as a hot medium, delivering a direct and clear message, while Nigel Coates argues that architecture should instead be understood as a cool medium [4], due to its possibilities to layer meanings, to transform, and interpret them. According to Coates, “architecture operates through associations, continually reflecting and distinguishing spaces

in the observer's mind — such architectural space must therefore be returned to the human" [4].

From a semiotic point of view, one may regard architecture as signs within code systems that communicate meaning. As Umberto Eco would argue, such codes are not fixed but change through reinterpretation of its reading, understanding of complexities of different contexts, individual perceptions, and cultural backgrounds [5]. Architecture is in that way functioning within a semantic field, where meaning is not static but created in the process of interaction.

Contemporary architectural practice inherently involves engagement with architectural narratives. However, architecture narrative does not merely connote the physical realization of written texts. Commenting on the constraints of events and their underlying narrative, Bernard Tschumi compares and contrasts architectural form with the events housed within it [6]. These comparisons and contrasts are open to manipulation and reordering, the preliminary terms being established by the architect's spatial imagination. Therefore, space and time are sublimated into one structure, which is "defined by loose connections between them" [6].

Critical interpretation of narrative structures in architecture requires knowledge of the narrative itself. Although narrative can be treated as an objective entity, it is experienced subjectively through cognitive interpretation and spatial dissection. Lack of awareness of narrative may result in misinterpretation of spatial intention and reduced knowledge of the experienced architecture. Nevertheless, architectural design is fundamentally the spatial articulation of notions and concepts, producing complex spatial logics.

3. NARRATIVE STRUCTURES IN ARCHITECTURE

This research investigates the concept of architectural narrative through a cross-disciplinary approach, combining narratology, spatial theory, and architectural phenomenological discourse. While narrative models are well established in fields such as literary theory, film studies, and cultural analysis, their application to architectural theory is relatively under-explored. To address this knowledge gap, the research engages with theoretical models outside the mainstream architectural discourse, highlighting the need to conceptualize built environments as dynamic meaning conveyors. Within this framework, architecture is approached not merely as a physical construct but as a communicative medium through which social, historical, and ideological narratives are encoded and transmitted—thus enabling the reading of space as a form of narrative text. In this sense, narrative structures in architecture can be understood as a way to integrate both the tangible and the imagined layers of memory embedded in the ground, forming a new spatial motif that amplifies inherited values while simultaneously accommodating those that are speculative or absent [7].

In support of this view, Ryan, Foote, and Azaryahu argue that the concept of narrating space positions narrative as an object of representation, whereas spatializing narrative refers to the spatial context as the medium through which narrative is physically deployed [8]. This dual perspective further underscores the architectural potential to both embody and generate narrative, reinforcing the interpretive depth and communicative capacity of spatial design.

Narrative structures in architecture can be understood as the trajectory of sequential spatial experiences that unfold through movement, perception, and interaction within the built

environment. It refers to how architecture organizes and stages space over time, guiding users through a meaningful sequence that evokes interpretation, emotion, and reflection. As Roland Barthes posits, “to understand a narrative is not merely to follow the unfolding of the story, it is also to recognize its construction in 'storeys', to project the horizontal concatenations of the narrative 'thread' on to an implicitly vertical axis” [9]. This conceptualization of narrative as a multidimensional construct, both linear progression and vertical layering, offers a critical framework for reading spatialised narrative as architectural text in its phenomenological discourse. It invites a reading of space not only through its sequential experience, but also through the symbolic and structural depth embedded within its spatial composition. Adding to that, Susan Stanford Friedman’s “spatial reading” of narrative [10], an approach similar to Barthes of horizontal axis - the plot, and with different understanding of the vertical axis - consisting of other intertextual dimensions (author-reader, literary-historical considerations, and intertextual allusions). By bridging Barthes’ and Friedman’s frameworks, one can develop a methodological lens attuned to both the spatial and discursive dimensions through architectural narrative structures.

Tricia Austin's narrative environments theory addresses how space can be imagined to communicate stories through spatial, sensory, and material elements [11]. Spaces as interpretative active elements that create spatial meanings, Austin points out that material, physical, and sensory elements that are spatially designed have the capacity to add meaning and impact the experience of the person utilizing the space. This model is applicable to those spaces that have a strong cultural or historical background that needs to be conveyed to the users. Moving on from this, the Museum of Apoxyomenos illustrates how a designed spatial experience is created through the use of architectural narrative structures.

4. CASE STUDY: MUSEUM OF APOXYOMENOS

4.1. Conceptualisation and realisation of museum

In 1996, Belgian tourist René Wouters discovered a bronze statue of a young athlete on the seabed near the islet of Vele Orjule, close to the island of Lošinj. The discovery was reported to the Ministry of Culture of the Republic of Croatia in the autumn of 1998, and the statue was retrieved from the sea in 1999 [12]. It was named Apoxyomenos. The statue is one of the conventional subjects of ancient Greek votive sculpture; it represents an athlete caught in the familiar act of scraping sweat and dust from his body with the small curved instrument called a strigil. Apoxyomenos is a standing nude figure of an athlete in contrapposto, leaning on the right leg, the head and shoulders are slightly tilted, the left knee bent, and the leg slightly raised [13]. Following its discovery and restoration, it was decided that Apoxyomenos would be permanently exhibited to the public in a newly constructed museum in Mali Lošinj, housed in the former Kvarner Palace.

To design a proper house for the artifact, an architectural competition was held in 2009 and the Croatian architectural duo consisting of Idis Turato and Saša Randić emerged as winners of the competition. The authors posed the challenge - “how can such a perfect sculpture be presented in a space that exists outside any temporal or physical context, while also ensuring that the architecture is both engaging and educational” [14]? The spatial structure that allows a unique exhibition to be integrated within the existing museum is enabled by the concept of “house within a house” (Figure 1). Within this space, the authors

defined nine spatial scenes, guiding visitors through a spatial experience with a carefully constructed architectural narrative that follows the story of Apoxyomenos. The spatial elements integrated into the exhibition provide the historical context while also engaging visitors in the story. Through this layered narrative approach, architecture becomes a storytelling medium.

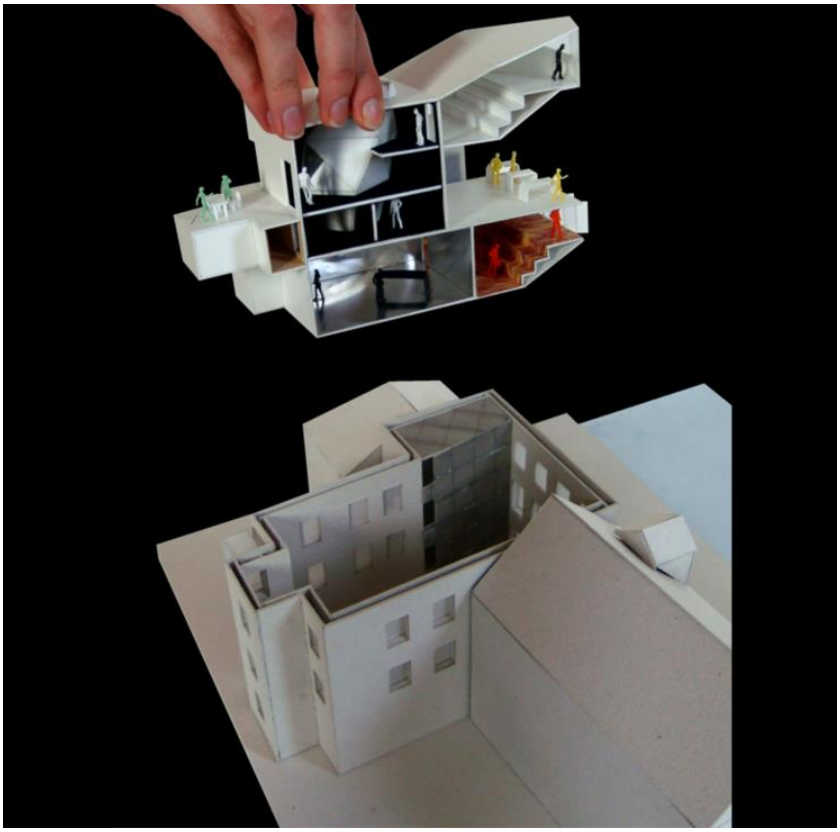


Figure 1. Architectural model illustrating the concept of "house within a house," designed by Turato & Randić for the 2009 competition project, source: https://www.idisturato.com/blog/project/muzej-apoksiomena/ (used with permission of the author)

While the core narrative and spatial intentions remained largely the same in the competition project from 2009, the realised 2016 project refined these elements, translating the original vision into a more tangible and accessible architectural experience. The competition proposal for the Museum of Apoxyomenos conceived a scenographic spatial story, realized by a distinct, autonomous architectural volume inserted within the historic Kvarner Palace. “The exhibition layout is composed as a fragmented, spatially complex structure that defines a curatorial scenario of passage through nine temporally and spatially differentiated scenes. Each scene is defined by a specific room, a space that narrates one of Apoxyomenos’s stories” [14]. However, while this vision was integral to the initial design, the realized 2016 project refined and materialized these conceptual ideas, introducing specific details and elements that transformed the experience of the space. These adjustments not only enhanced the sensory journey but also addressed practical concerns, such as accessibility, which were conceptually outlined in the competition proposal. Despite these

improvements, certain challenges persist in the realized project - such as spatial fragmentation, dominant architectural features that compete with the display, and limited accessibility for people with reduced mobility [15]. As a ship-like contrasting volume, the intervention emphasized tactile, acoustic, and olfactory properties to guide the visitors to the final encounter with the statue.

The ultimate 2016 project [16] maintained this conceptual strategy but grounded it down into a finished material and spatial existence creating an immersive museum environment that fulfills the original vision of its architectural narrative structure. It is important to highlight that the principles of universal design were addressed by ensuring accessibility for all through two elevators, as indicated in the initial competition documentation. However, the use of the elevator disrupts the intended spatial trajectory of the narrative journey. As a result, when elevators are used instead of the stairs as originally intended, the space is experienced as fragmented and incoherent, undermining the spatial experience that was meant to be emphasized by the seamless transitional zones between rooms.

The Museum of Apoxyomenos and its architectural design was recognized worldwide. Among the many nominations from 2017 up to today [17], “in 2019 the museum received the European Museum of the Year Award for the most creative and innovative exhibition design, specifically for the presentation of the sculpture. With its curatorial concept and architectural approach, it stands out as a unique museum institution not only in the Republic of Croatia but also across the Mediterranean” [15].

4.2. Architectural narrative structure of the museum

Azaryahu and Foote identify four strategies for configuring stories in space: (1) point, (2) sequential, (3) areal, and (4) hybrid narratives [18]. This paper focuses on the use of hybrid forms of narrative embodiment, explored through a case study. Such spatial storytelling emerges in contexts that serve as the locus of multiple, overlapping narratives - such as those examined in this case study. They define the sequential narratives as “linear arrangements of narrative content along trails or paths with chronological progression”, and areal narratives used “for stories extending over large areas or encompassing stories that involve long periods of time”.

The Museum of Apoxyomenos employs a hybrid narrative form that emphasizes multiple, overlapping stories. Presenting a broad background narrative that encompasses diverse layers of spatial meanings unified within a single museum structure, alongside the statue as a work of art, its discovery in the sea, and the search for a museum space, the subsequent architectural competition redefines urban space. Even though the exhibition itself is organized as a sequential narrative, moving through separate rooms with point-based storytelling and transitional spatial zones, the museum’s overall narrative embodiment extends beyond the building. It stretches from the sea, where the statue remained hidden for centuries, to the restored villa of significant cultural heritage that now houses the museum, and further to the architectural exhibition, which employs a striking and uniquely spatial form of storytelling. This complex layering represents the *diachronic metanarrative* of the site integrating historical depth, spatial transformation, and cultural reactivation. This complex layering represents what Mitrović and Kocić define as “the *diachronic metanarrative* is an autonomous, coherent, and self-reflective narrative structure, capturing the synthesis of layered narratives over time” [19].

Turato and Randić, in their 2009 competition project, defined nine scenes that narrate the story of Apoxyomenos, referring to the future museum as a “central event generator for the town of Mali Lošinj” [14]. The complex use of narrative in architectural practice necessitates an analysis of all components that spatially construct an architectural narrative structure. However, the authors did not address the surrounding context of the Palace Kvarner, which houses the Museum of Apoxyomenos. They articulated the nine scenes integral with its transitional zones (Figure 2).

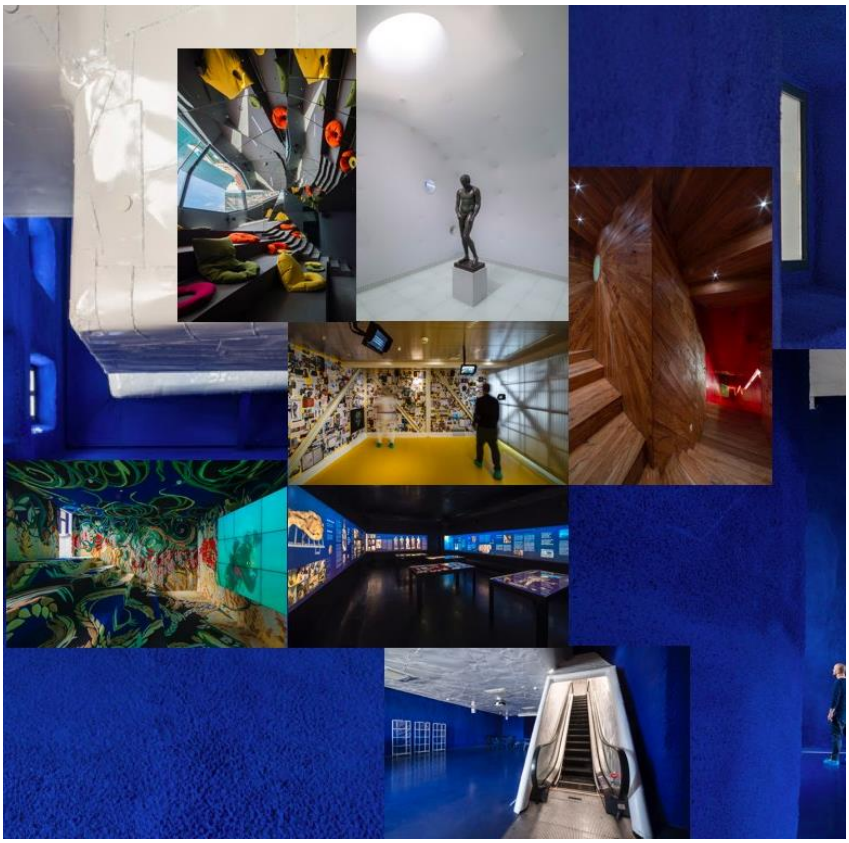


Figure 2. Spatial collage of the main scenes structurally arranged for the Museum of Apoxyomenos, 2016, source: https://www.idisturato.com/blog/project/muzej-apoksiomena-2016/ (used with permission of the author)

For the purpose of analyzing narrative structures in architecture, these transitional elements should be considered distinct spatial statements within the museum’s overall narrative. Rather than being treated as integrated components, they should be viewed as separate sequences, due to their capacity to generate and convey new meanings in the spatial experience.

This study identifies and articulates the key components of architectural narrative structures, situating them within the framework of architectural phenomenology discourse, in the following order:

1. **Urban Surrounding:** Villa Kvarner and its immediate urban surroundings serve as the starting point before entering the museum. The transitional entrance space, defined by the villa’s first-floor terrace, acts as an intermediate zone between the street front and the museum interior. This marks a Roland Barthes’ idea of projecting

a horizontal narrative onto a vertical axis of symbolic meaning [9]. The villa's reconstruction was preserved almost entirely, with one notable change: the embedded blue eyes above the museum entrance, embracing Umberto Eco's semiotic codes that function as visual mnemonic device.

2. **Room 0:** Visitors enter the museum through an open, public ground floor that welcomes them. The inserted white exhibition structure appears to float within the blue interior space, symbolizing the seabed where the statue of Apoxyomenos was once lost. The foyer space acts as a "cool medium" [4] that invites interpretation where the user, now a narrative participant, begins decoding this layered visual and symbolic contrast.
3. **Transition 1:** The escalator marks the first transitional zone. A white tube, integrated into the inserted museum structure within Villa Kvarner, leads visitors to the first exhibition room. According to Tricia Austin, narrative environments rely on sensory cues to convey meaning [11]. The escalator narrows focus, slows movement, and heightens bodily awareness, a spatial equivalent of a narrative prologue.
4. **Room 1:** The black rubber room presents the statue's historical narrative on display tables, accompanied by an informational image strip along the walls. A distinct spatial-acoustic atmosphere emerges from the echoing sounds of both the speakers and the visitors within the space. It materializes horizontal axis (plot development) of architecture narrative structure while creating vertical atmospheric depth via sensory disorientation.
5. **Room 2:** The following rooms are arranged in an enfilade sequence: a small amphitheater covered with a handwoven merino wool carpet, patterned like the sea floor, where a film about the history of the Apoxyomenos statue is projected.
6. **Transition 2:** The next transitional zone, extending from the amphitheater, is a narrow red staircase with integrated water sound effects, leading visitors to the next room. Dramatic change in color signifies a shift in narrative tone, while the ascent physically mirrors Barthes' narrative acceleration. Material contrast reinforces a moment of narrative tension and bodily reorientation.
7. **Room 3:** The "media room" presents a space where the story of Apoxyomenos is conveyed through collaged media reports on the walls. Additionally, through a frog's-eye view via an opening in the ceiling, visitors catch their first glimpse of a segment of the statue.
8. **Transition 3:** The following space is a transitional stair zone, lined with wooden-clad walls and featuring another opening that frames a portion of the statue—from torso to head. These transitional spaces, previously marked by red and wooden finishes, are connected to the entrance of the media room. A demarcation line, defined through a shift in materiality, separates the spaces according to their distinct narrative roles.
9. **Room 4 (Narrative Climax):** An airy space with rounded white walls and a skylight follows, where filtered light subtly illuminates the statue of Apoxyomenos. This moment marks the narrative climax of the Azaryahu and Foote's sequential narrative [18].
10. **Room 5:** After visiting the statue room, visitors enter the "town's kaleidoscope room," which features an amphitheater and a reflective ceiling. Here, mirrors function as spatial devices that reintroduce the context of Villa Kvarner into the interior through

immaterial means. In this nuanced way, the space of Mali Lošinj once again becomes an integral part of the exhibition. The triadic visual presentation of the statue is complitet with the opening in the wall offering a bird's-eye view of the statue's head.

11. **Transition 4:** The staircase connecting the amphitheater in the "town's kaleidoscope room" (Room 5) includes a window that symbolically and representationally frames the sea. As Eco suggests, meaning shifts through context: the sea here is not just origin but reinvention. This spatial moment completes the *diachronic metanarrative* arc [19].
12. **Room 6:** Visitors exit the "town's kaleidoscope room" and enter the vertical circulation area leading back to the ground floor. The bifurcated staircase and elevator, clad in coarse black materials, stand in stark contrast to the blue-white palette of the ground floor, symbolizing the conclusion. The space marks the transition from story to reflection, from immersion to exit.

The key distinction between the Turato and Randić's architectural narrative structure of the Museum of Apoxyomenos (9 scenes) [14], and the structure proposed by the author of this paper (12 scenes) lies in the treatment of the museum's internal and external spaces. Here, the outdoor zones, transitional thresholds, and framed sea views are redefined as distinct scenes due to their narrative significance and the generation of new spatial meanings. This revised reading demonstrates how the Museum of Apoxyomenos activates spatial narrative not only through its rooms, but through their sequencing, material shifts, and symbolic resonance. Certain scenes act as narrative nodes that guide the visitor's perception and emotional progression, such as the blue-white entry contrast, the red staircase, or the mirrored amphitheater, each contributing to the dynamic unfolding of meaning. These spaces are not isolated moments but integrated components of a broader narrative strategy that elevates the visitor from observer to participant. The museum thus exemplifies a hybrid narrative form that integrates sequential, point-based, and areal storytelling [18], structured as a diachronic metanarrative that fuses history, memory, and embodied experience.

5. CONCLUSION

The contribution of this paper lies in understanding the complexity of narrative structures in architecture as a tool for spatial storytelling. Furthermore, it offers insight into the exhibition design of the Museum of Apoxyomenos, where transitional spatial zones and representational spaces of narrative are recognized as equally valuable spatial units as the areas containing exhibited artifacts. The broader theoretical focus of this paper is "the space occupied by the text itself, and, especially, the spatial form of the text, as its core concerns" [9].

Building on the theoretical overview that follows, narrative architecture and narrative structures in architecture both represent the possibility of integrating narrative into space through spatial sequencing, along with the integration of spatial meanings. This spatial constellation results in the transmission of cultural meanings, collective memory, and ideological frameworks to the users of the space through an experiential encounter. Analyzing the narrative structure in architecture in the case study of the Museum of Apoxyomenos provides a simpler way to understand the complex spatial meanings. These

meanings have developed over time, as demonstrated in the case study. The Museum of Apoxyomenos employs a hybrid narrative form that emphasizes multiple, overlapping stories, presenting a broad background narrative that encompasses diverse layers of spatial meanings unified within a single museum. Alongside the statue as a work of art, its discovery in the sea, and the search for a museum space, the subsequent architectural competition redefined the urban narrative of the town of Mali Lošinj, Croatia. Even though the exhibition itself is organized as a sequential narrative, moving through separate rooms with point-based storytelling and transitional spatial zones, the museum's overall narrative embodiment, through the user's perception and interpretation, extends beyond the exhibition's space.

The primary difference between the architectural narrative structure defined by Turato and Randić and the proposed structure in this paper lies in the treatment of the museum's internal and external spaces to convey a story. This paper demonstrates that the integration of outdoor areas, transitional thresholds, and framed views are recontextualized as separate scenes, emphasizing their narrative importance and the creation of emergent spatial meanings. The applied narrative structure at the Museum of Apoxyomenos positions visitors as active participants in the unfolding story, where interaction with both the exhibition structure in the interior and the museum's broader context is essential. The findings of this study encourage a reevaluation of architectural design within museum typology, viewing it not merely as a physical construction, but as a communicative medium for its audience.

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Review paper

LEGISLATIVE IMPACT ON BIOCLIMATIC ARCHITECTURE IN THE EUROPEAN UNION: CURRENT STATUS IN SERBIA

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Abstract

The goal of this paper is to underscore the importance of synergizing legal norms, energy standards and urban planning strategies to advance the principles of bioclimatic architecture for its broader practical application. Contemporary climate changes and the growing imperative to preserve the environment, inevitably calls for a paradigm shift in construction and architectural practices. Bioclimatic architecture constitutes one of the key approaches in achieving energy efficiency and sustainable construction. It involves designing buildings that are intrinsically responsive to the prevailing natural environment encompassing local climate, topography and other ecological parameters in order to minimize the ecological footprint. For the successful promotion of bioclimatic principles, it must be codified within a nation's regulatory framework. The term bioclimatic architecture does not explicitly appear in legal documents, but its fundamental principles as passive solar optimization, using renewable energy sources, natural ventilation, and the adaptation of buildings to local climatic conditions are inherent in legal regulations. Therefore, particular attention will be devoted to Directives 2010/31 and 2024/1275 of the European Union, along with the statutory regulations of the Republic of Serbia, as well as the current state of bioclimatic architecture in practice.

Key words: *climate, energy efficiency, regulatory framework, European Union, Republic of Serbia, practices*

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1. INTRODUCTION

The contemporary era is increasingly defined by rapid climate change, accelerated urbanization and escalating environmental challenges, positioning architectural practice and the construction sector as pivotal domains for advancing societal sustainability. Conventional design and building methodologies typically driven by cost-efficiency and the imperative for rapid implementation are now subject to mounting pressures to undergo transformation and align with emerging ecological imperatives [1]. In this context bioclimatic architecture is a design concept aimed at utilizing natural environmental conditions to reduce energy consumption and support sustainable construction. The goal is to achieve an optimal balance between indoor comfort and ecological sustainability. Successful implementation of this approach involves the use of passive solar techniques and renewable energy sources, which contribute to minimizing negative environmental impacts [2].

This paper examines the extent to which the legislative instruments of the European Union, as well as relevant national regulations, incorporate the principles of bioclimatic architecture. Special emphasis is placed on identifying the areas that are comprehensively regulated within the legal framework, as well as those that remain insufficiently regulated. In addition to the normative analysis, the paper assesses the current state of bioclimatic architecture in practice, in order to highlight the gap between regulatory intentions and actual implementation, and accordingly proposes targeted recommendations for enhancing the legislative framework to support truly integrated bioclimatic design practices.

2. BIOCLIMATIC ARCHITECTURE - LEGISLATIVE FRAMEWORK OF THE EUROPEAN UNION

The legislative framework of bioclimatic architectural principles across the European Union is characterized by a dual structure of binding instruments and complementary non-binding measures, each contributing uniquely to the overarching goal of enhanced energy efficiency and sustainable development in the built environment.

2.1. Binding Legal Acts

The regulatory structure is primarily defined by binding legislative acts, in particular Directive 2010/31/EU, Energy Performance of Buildings Directive – EPBD [3] and Directive 2012/27/EU, Energy Efficiency Directive – EED [4]. Recognizing the differences across EU countries in factors such as the existing building stock, geography and climate, the directive allows governments to decide on some measures (*i.e.* renovation measures) best-suited to their specific national context. In order to ensure an adequate living comfort from the perspective of energy requirements, a significant amount of energy consumption is necessary. This energy demand inevitably leads to a negative ecological footprint. The importance of bioclimatic architecture lies in its ability to reduce energy use through exploitation of natural resources such as sunlight and airflow. This approach not only helps protect the environment but also enables energy savings, which is crucial for the future of sustainable housing. Given that the majority of existing residential buildings especially in this region are energy inefficient, it is imperative to implement comprehensive energy retrofitting measures to revitalize their performance and align them with contemporary

sustainability standards. Buildings are the single largest energy consumer in Europe. Also, CO_2 emissions are directly linked to energy consumption in buildings, with the impact being particularly pronounced in the residential sector. Heating and cooling of buildings is one of the largest sources of greenhouse gas emissions in Europe. The building sector is therefore crucial to achieving the EU's energy and climate goals. To boost the energy performance of buildings, the EU has established a legislative framework that includes the revised Energy Performance of Buildings Directive (EU/2024/1275) [5] and the revised Energy Efficiency Directive (EU/2023/1791) [6].

When we talk about energy standards, Directive EU/2024/1275 provides that all new buildings should be zero-emission buildings by 2030, while all new public buildings must be zero-emission from 1 January 2028 and existing buildings should be transformed into zero-emission buildings by 2050. The advent of Directive 2024/1275/EU signifies a progressive evolution in this regulatory landscape. [5]

Energy Efficiency Directive codifies a set of ambitious targets that resonate strongly with bioclimatic principles. This target sets the goal of reducing EU final energy consumption by 11.7% by 2030, compared to the projected energy use for 2030. It translates into a primary energy consumption target of 992.5 million tonnes of oil equivalent (Mtoe) and a final energy consumption target of 763 Mtoe by 2030. [6]

The latest index reveals that the EU buildings sector is significantly off track to meet its 2030 and 2050 climate goals. Final energy consumption in buildings has dropped by only 2.8%, while the target was a 6.5% reduction. The reduction is happening at less than half of the required pace. [7]

2.2. Non-binding Legal Acts

Complementing these binding directives are a range of non-binding instruments comprising guidelines, recommendations, and strategic frameworks that further articulate the rationale behind bioclimatic architecture. The most important is European Green Deal where bioclimatic architecture is promoted through several initiatives under the European Green Deal:

1. Renovation Wave Strategy: Aims to at least double the annual energy renovation rate of residential and non-residential buildings by 2030, targeting the renovation of 35 million building units. This strategy emphasizes deep energy renovations, incorporating passive design principles and renewable energy integration [8].
2. Circular Economy Action Plan: Promotes the use of sustainable materials and circular design in the construction sector, aligning with bioclimatic architecture's emphasis on resource efficiency and environmental harmony [9].

3. ENERGY EFFICIENCY IN BIOCLIMATIC ARCHITECTURE - LEGISLATIVE FRAMEWORK OF THE SERBIA

Republic of Serbia, as a candidate for EU membership is currently engaged in the harmonization of its legislation with European standards, but the principles of bioclimatic architecture are only partially regulated in the national legislative framework. The primary focus is placed on energy efficiency as most important, while broader bioclimatic aspects, as green infrastructure, the integration of water resources (rainwater harvesting and

infiltration systems), use of local and recycled materials and advanced passive systems, remain insufficiently or entirely unregulated.

Considering that bioclimatic principles play a crucial role in enhancing the energy efficiency of buildings, energy efficiency is the most comprehensively regulated aspect within the Serbian legal framework in bioclimatic fields. Its include the following legal instruments: The Law on Planning and Construction [10], The Rulebook on the Energy Efficiency of Buildings [11], The Rulebook on the Conditions, Content, The Procedure for Issuing Energy Performance Certificates for Buildings [12], and the Integrated National Energy and Climate Plan of the Republic of Serbia for the period up to 2030, with projections extending to 2050 (INECP) [13].

These instruments collectively aim to infuse sustainable principles into construction practice while aligning Serbia with the European Union's ambitious standards in energy efficiency and environmental protection. At the domestic level, the Law on Planning and Construction serves as the cornerstone of Serbia's regulatory apparatus, establishing the procedural and substantive prerequisites for urban development. This legislative act, in tandem with the Rulebook on Energy Efficiency of Buildings, emphasizes the integration of energy performance criteria into construction activities [10,11]. They stipulate that the energy performance of a building shall be determined by issuing an Energy Performance Certificate, which is issued and governed through CREP database by the Ministry for construction, traffic and infrastructure. All new buildings must obtain this certificate in order to be granted an occupancy permit and energy class of a new building, must be at least class "C" or higher. Owners of existing residential buildings are required to obtain an Energy Performance Certificate within ten years from the date this law enters into force, and the energy class must be improved by at least one level of existing buildings, following reconstruction, extension, renovation, adaptation, rehabilitation, or energy refurbishment works. [12] On the other side, INECP further reinforces this regulatory paradigm by delineating strategic goals and timelines for reducing energy consumption in buildings and incorporating innovative, energy-saving technologies. The improvement of energy efficiency constitutes a key priority. In 2022, the total energy consumption amounted to 16.4 Mtoe, and the share of households in electricity consumption was 46.17%. [9] The goal of INECP is for final energy consumption in 2030 to amount to no more than 9.6 Mtoe. [14] By signing the Sofia Declaration on the 'Green Agenda' for the Western Balkans (WB), Serbia formally acknowledged and committed to aligning with the European Green Deal, including the adaptation to local climatic attributes to enhance building performance.

The effective implementation of these standards is hampered by economic barriers inherent in the transition toward energy-efficient construction, particularly the substantial initial capital investments required for innovative technologies. Such economic impediments delay the widespread adoption of sustainable practices and, by extension, impede the transposition of robust EU norms into the domestic regulatory framework.

4. BIOCLIMATIC ARCHITECTURE – CURRENT STATUS IN SERBIA

The formal adoption of relevant statutory instruments should be followed by the effective mechanisms for integration of bioclimatic principles into practical application. The current situation in Serbia reveals a noticeable gap between regulatory intentions and actual implementation. One of the key issues is that the existing methodology for calculating and

certifying the energy performance of buildings excludes cooling load assessments, a critical omission that predisposes design outcomes toward suboptimal thermal management solutions and thereby undermines the adoption of passive cooling and natural ventilation strategies. Moreover, bioclimatic principles are neglected in the early stages of development, particularly during the urban planning phase of an area. As a result, the application of bioclimatic architecture is more common in rural than in urban areas.

Examples in rural areas are the traditional houses of Stara Planina in Senokos are largely integrated into the natural environment, incorporating significant elements and components of bioclimatic design and passive solar architecture. The traditional vernacular architecture of Stara Planina is, to a considerable extent, aligned with the principles of bioclimatic architecture [15]. Behind that, we have traditional rural houses in Vojvodina, which are largely harmonized with their natural surroundings and incorporate significant elements of bioclimatic design and passive solar architecture [16].

For Serbia to fully capitalize on the benefits of bioclimatic architecture, a multidimensional strategy is required one that aligns legislative modifications, economic incentives, and institutional capacity building with the robust models already in place within the European Union. To create a legal environment that fosters bioclimatic architecture, Serbia is required to amendment the existing legislation with:

1. Explicit definition and integration: Amend national planning and building codes to provide a clear, legally binding definition of “bioclimatic architecture.” This definition should encompass not only the principles of passive solar design, natural ventilation, and optimized thermal mass but also mandate their consideration in the permitting process. By embedding these concepts into core statutes, the regulatory framework will encourage consistency and uniformity in application;
2. Integration of bioclimatic standards into the early stages of planning, specifically the phases of urban planning and technical design, which enables the systematic implementation of measures that maximize the use of renewable/natural resources (such as solar energy, natural ventilation, building orientation, shading, etc.) with the aim of reducing the overall energy consumption of buildings.
3. Inclusion of green clauses in land lease and sale agreements;

Also, a comprehensive economic strategy is essential to overcome the initial cost barriers and foster widespread adoption, and author recommend:

1. 30% reduction in land development fees, contingent upon the implementation of bioclimatic design solutions;
2. Targeted grants for the installation of passive solar equipment, high-performance thermal insulation, and natural ventilation systems, up to 40% of the investment value;
3. Gradual introduction of a national carbon tax ranging from €20 to €50 per ton of CO_2, aligned with the EU legislative, with partial revenue recycling through subsidies for bioclimatic projects.

Establish legal frameworks that couple mandatory standards with economic incentives, as introducing accelerated depreciation, tax relief, or subsidies for new and rehabilitated projects that achieve certified bioclimatic performance levels can transform regulatory obligations into commercially viable opportunities. These mechanisms have to show that investments in energy efficiency and environmental protection generate multiple returns, and that investing in such solutions is not economically unjustified but rather part of a modern trend.

5. CONCLUSION

The analysis shows that the legislative framework of the European Union exerts a significant influence on the promotion and development of bioclimatic architecture, particularly through the progressive alignment of national regulations with the principles enshrined in the EPBD and the broader objectives of the European Green Deal.

In the Republic of Serbia, the process of transposing these directives is still ongoing. However, Serbian construction legislation is progressively aligning with European standards, with particular emphasis on reducing energy consumption and enhancing the technical quality of buildings. This evolving legal framework supports the development and adoption of technologies that improve energy efficiency in the building sector.

While Serbia's current regulations focus on optimizing energy use in construction, there remains considerable potential for further progress by integrating a wider range of bioclimatic principles. Such integration would not only help lower costs but also promote environmental sustainability more effectively. Creating a strong synergy between legal regulations and the practical measures proposed in this study is essential to establish stable conditions and incentives for their successful implementation. Moreover, incorporating bioclimatic principles in the planning of new urban developments is especially important. This includes considerations related to urban design, spatial geometry, maximizing passive solar gains, and encouraging natural ventilation. By embracing these improvements, Serbia can enhance the practical application of bioclimatic architecture, thereby making a significant contribution to Europe's energy efficiency and climate resilience goals.

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Review paper

RECYCLED BRICK POWDER AS SUSTAINABLE SUPPLEMENTARY CEMENTITIOUS MATERIAL: A REVIEW

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Abstract

This paper investigates the potential of recycled brick powder as a sustainable alternative for partial replacement of Portland cement in cement composites. Given the significant impact of the cement industry on global CO2 emissions, finding environmentally friendly solutions has become a key goal in the construction industry. Recycled brick powder, as a secondary material, demonstrates considerable pozzolanic activity and the potential to reduce the environmental footprint of cement production. A systematic literature review indicates that replacing cement with recycled brick powder in the range of 10–20% improves the mechanical properties, reduces shrinkage and water absorption, and also improves chloride and carbonation resistance of cement-based composites, due to the pozzolanic activity and filler effect of recycled brick powder. This paper provides insights into the various aspects of using recycled brick powder in cement-based composites, contributing to waste reduction and enhancing the sustainability of construction materials.

Key words: *Recycled brick powder, Cement-based composites, Fresh properties, Mechanical properties, Chloride resistance, Carbonation resistance.*

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1. INTRODUCTION

The cement industry is one of the most significant sources of carbon dioxide (CO_2) emissions, a greenhouse gas with the most pronounced impact on global warming. In fact, 8% of total global CO_2 emissions come from the cement industry, which is responsible for 27% of total direct CO_2 emissions from industrial sectors, making it the second-largest CO_2-source among industries [1]. According to the International Energy Agency (IEA) [2], annual cement production is expected to reach 4.4 billion tons by 2050.

There are several effective approaches to reducing CO_2 emissions caused by the cement industry. Some of the main strategies include: (i) increasing reliance on renewable energy sources to reduce emissions associated with energy consumption, (ii) improving clinker production processes to lower emissions generated by chemical reactions, and (iii) implementing carbon capture, utilization, and storage (CCUS) technologies [3, 4].

In addition, partial cement replacement with alternative binding materials, such as industrial by-products, and adequately treated some of the construction and demolition (C&D) wastes, can further reduce greenhouse gas emissions, as these materials have a lower carbon footprint [5].

Bricks are considered the second most common construction material after concrete and are treated as waste in cases of damage during manufacturing, building, or demolition processes (Fig. 1). During the firing process in brick production, the crystalline structure of clay-based raw materials undergoes dehydroxylation, forming a reactive amorphous structure that results in pozzolanic activity [6]. After the waste brick is ground into a powder with an appropriate particle size distribution this powder can be used as a supplementary cementitious material (SCM) in mortars or concrete [7-11].



Figure 1. Brick waste generated during construction and demolition activities [12].

Kolawole et al. [13] determined that the total content of main oxides (SiO_2, Al_2O_3, and Fe_2O_3) in RBP exceeds 70%, leading to the classification of RBP as a Class N pozzolan according to ASTM C618 [14]. Its mineralogical composition mainly consists of crystalline SiO_2 (quartz), Fe_2O_3 (hematite), and Al_2O_3 + SiO_2 (mullite). Similar results were reported by He et al. [15] as well as Aliabdo et al. [16]. Shao et al. [6] showed that the amorphous phase in RBP is 20.1%, while quartz represents the main crystalline phase. Lam et al. [17] and Abib et al. [18] also found that RBP contains a high percentage of silica and alumina, and stated that the main crystalline phase is quartz.

Ouyang et al. [19] investigated the particle morphology of RBP and found that the particles resemble quartz dust, while Lam et al. [17] determined that RBP particles have angular shapes and rougher surfaces compared to cement particles. Increased grinding of the powder leads to the removal of irregular edges, making RBP particles more spherical, as demonstrated by Zhao et al. [20]. Finally, Kolawole et al. [13] reported that RBP particles are wide, with a slightly amorphous band, and flattened as a result of the milling process.

This review aims to collect and analyze the latest research related to the use of RBP, as an environmentally friendly alternative to cement in cement-based composites, with regard to the selected fresh and hardened properties.

2. PROPERTIES OF CEMENT-BASED COMPOSITES WITH RBP

2.1. Fresh Properties

2.1.1. Water Demand

Although the use of RBP leads to a decrease in the workability of cement-based materials, compared to other types of waste particles, such as granite, marble and ceramic powder, RBP has the least impact on increasing water demand [21]. Nas et al. [22] demonstrated that mortar with a 5% RBP replacement had the same water absorption rate as the reference sample, suggesting that lower replacement ratios may not significantly affect mixture properties. However, the general trend shows that higher RBP content in the mix leads to increased water demand, with particle size and cement replacement level playing key roles. This is mainly attributed to the irregular shape and porous surfaces of RBP [23]. Chen et al. [24] emphasized that RBP particles smaller than 10 μm exhibit a higher specific surface area, which results in stronger water absorption and increased inter-particle friction, thereby raising the water demand in cement-based mortars. Zhao et al. [20] investigated the effect of varying RBP particle sizes on the water demand required to achieve standard consistency with 30% cement replacement. Their results showed that while the inclusion of 30% RBP increased water demand, this effect diminished with smaller particle sizes. The explanation lies in the smoother surface and more regular shape of finer RBP particles, which enhances the lubrication effect and mitigates the influence of increased surface area [25].

2.1.2. Rheological Properties

The presence of RBP as SCM in cement-based materials can significantly affect their rheological behavior, particularly by increasing the yield stress [26]. This effect is attributed to the irregular and porous structure of RBP particles, which, compared to cement particles, absorb more water and increase inter-particle friction. Their porosity allows water to be retained within the pores, reducing the thickness of the water film in the mix, while the rough particle surfaces further contribute to inter-particle friction [21]. Additionally, the particle size of RBP plays a role in determining the yield stress. When RBP particles with larger diameters are used to replace cement, yield stress tends to increase; conversely, smaller RBP particles lead to a reduction in yield stress. Finer RBP provides better volume distribution, more efficient void filling, and thicker water films around particles, all of which reduce friction and improve workability [21].

Nevertheless, cement pastes with RBP contents between 10% and 40% exhibit shear-thinning behavior-viscosity decreases with increased shear rate. This phenomenon is

attributed to the breakdown of particle flocs at higher shear rates, which releases additional free water into the mix and lowers the viscosity [27-29]. Despite the shear-thinning effect, the overall impact of RBP on increasing yield stress remains evident, especially when coarser and rougher particles with higher water absorption capacity are used.

2.1.3. Flowability

The flowability of cement composites containing RBP is influenced by several factors. Primarily, RBP has a higher water absorption capacity compared to cement, which reduces the amount of free water in the mixture and increases overall water demand [30]. The rough and irregular surface of RBP particles can also increase friction and hinder the flow of the mix [31-33]. However, prolonged grinding of RBP helps break down larger pores, reducing its water absorption ability. Simultaneously, the particles become finer and more rounded, which may reduce friction and improve flowability. RBP may also contribute to better dispersion of cement particles during the early stages of hydration, and accelerate the transformation of free water into gel water. The relative slump of concrete is determined by comparing the slump value of the mix with RBP to that of the control mix. Most studies have reported a decrease in the flowability of fresh mixtures with increased RBP content [34,35]. For example, Kırgız [36] observed slump reductions by 4.60%, 19.07%, and 46.77% for 5%, 7%, and 10% RBP replacement, respectively, compared to the reference concrete. Similar conclusions were drawn in the study by Senol et al. [37], where the addition of 20% RBP negatively affected the filling capacity of the self-compacting concrete in both V-funnel and L-box tests. These results were also confirmed by Liu et al. [38] and Ge et al. [39].

Nevertheless, some studies indicate the opposite trend. Arif et al. [40] recorded an increase in slump values by 10.6% and 29.8% for 5% and 10% cement replacement with RBP, respectively, compared to control samples. Additionally, research by Ma et al. [41] showed that for the same cement replacement level, with a decrease in RBP particle size, there was an increase in the cement paste slump, although in no case did the slump exceed that of the control mixture.

2.2. Hardened properties

2.2.1. Compressive Strength

The inclusion of RBP as SCM in cement-based composites can, under specific conditions, lead to improved compressive strength. For instance, Olofinnade et al. [42] found that concrete with 10% RBP as SCM exhibited higher 28-day compressive strength compared to reference. However, they also noted that increasing the RBP content beyond this point led to a reduction in strength, recommending a maximum replacement level of 15%. Similar recommendations were made by Letelier et al. [43] and Liu et al. [44], while Toledo Filho et al. [45] and Kirgiz et al. [36] suggested an optimal replacement of cement with 10–20% RBP. Ge et al. [46] demonstrated that concrete with 25% RBP could reach up to 50 MPa in compressive strength, provided that an optimized mix design is used: a water-to-binder ratio of 0.26, 33% sand content, and RBP particle size of 0.06 mm. According to Zheng [47], mortars with 20% and 30% RBP as SCM showed 7.6% and 21.6% lower strength, respectively, compared to those with 10% RBP after 14 days of curing, while Ortega et al. [11] observed that mortars containing 10% RBP exhibited higher compressive strength after 400 days compared to the control sample.

In addition to the level of cement replacement, the fineness of the RBP also plays a crucial role. Irki et al. [48] evaluated different Blaine fineness levels (390, 430, and 520 kg/m²) and demonstrated that increased fineness positively affects compressive strength of self-compacting mortar up to a certain threshold beyond which the strength decreases. Finer particles yielded higher strength at the same replacement level. Similarly, Ma et al. [23] found that the 28-day compressive strength of mortar was improved when using RBP with D50 = 6 μm and 12 μm, but only for replacement levels below 15%.

2.2.2. Flexural and Tensile Strength

The mechanical properties of cement-based composites incorporating RBP are strongly influenced by RBP fineness and the level of cement subtitution with it. Studies have shown that when these parameters are properly optimized, RBP can enhance both flexural and tensile strength due to RBP's pozzolanic activity and filler effect. For example, Usha Rani et al. [49] found that concrete with 10% and 20% RBP exhibited higher flexural strength after 28 days compared to the control sample, while at 30% RBP, a slight decrease was observed but still within a range of the reference value. Similarly, Duan et al. [25] reported a slight reduction in flexural strength with increasing RBP content, though even at 30% replacement the values remained similar to those of the control mortar. Zheng [47] confirmed that flexural strength values for concretes with 10%, 20%, and 30% RBP did not significantly differ from that of mix without RBP, while similar conclusions were made about the tensile strength of concrete with RBP. Consistently, Ge et al. and Ortega et al. [46,11] concluded that RBP does not have a major adverse effect on the tensile and flexural strength of cement-based composites. Furthermore, Naceri et al. [50] observed improvements in flexural strength for mortars with 5% and 10% RBP after 90 days of curing, while higher RBP contents led to a gradual decline.

However, not all studies present consistent findings. Olofinnade et al. [42] noted that even with less than 10% RBP, a slight drop in tensile strength was detected, with more pronounced reductions at higher contents. Similar trends were observed by Ma et al. [41], who reported a continuous decrease in flexural strength with increased level of RBP as SCM.

Apart from the dosage, RBP fineness also plays a key role. Ma et al. [41] showed that finer particles sizes enhance flexural strength compared to larger ones at the same replacement level. Irki et al. [48] also highlighted the positive influence of Blaine fineness, i.e. their tests showed that mortars containing RBP with Blaine values of 390, 430, and 520 kg/m², at replacement levels between 5% and 20%, exhibited improved tensile strength compared to the control samples, both after 28 and 90 days of curing. Based on the overall analysis, it can be concluded that the addition of RBP as SCM may positively impact the tensile and flexural strength of cement-based composites-but only if the cement replacement level and RBP's particle fineness are carefully optimized.

2.2.3. Shrinkage Properties

Cracking due to shrinkage in cement composites represents an increasingly relevant issue due to their widespread use. This highlights the importance of a deeper understanding of the shrinkage behavior of cementitious materials containing RBP. According to various studies, RBP as SCM can significantly reduce shrinkage, though many factors influence this effect. Ge et al. [39] observed a substantial reduction (about 35.9%) in autogenous shrinkage with the use of 10% RBP. This shrinkage-reducing effect can be attributed to several

mechanisms. First, the usage of RBP as SCM leads to a reduction in the early hydration products formation, which results in a reduced formation of small pores and thereby limiting autogenous shrinkage of cementitious material. Second, due to its high water absorption capacity, RBP acts as an internal water reservoir, while gradually releases moisture, which helps saturate capillary pores and mitigates shrinkage [51]. Furthermore, Ma et al. [41] reported that cement-based composites, containing 7.5%, 15%, and 30% RBP as SCM, exhibited lower 42-day drying shrinkage by 3.6%, 6.3%, and 11.6%, respectively, compared to a control value.

Additionally, RBP particle size plays a significant role in the shrinkage behavior of cement-based composites. Liu et al. [38] found that fine RBP particles help reduce total mortar shrinkage, whereas larger particles can lead to an increase in shrinkage by 2-3%. Finer RBP improves the pore structure by acting as both a filler and a pozzolanic material, ultimately lowering shrinkage [52]. However, some negative effects have also been reported. Naceri et al. [50] and Rovnaník et al. [53] observed that excessive water absorption by RBP can accelerate evaporation, potentially increasing shrinkage in cement-based materials. In summary, RBP as a SCM has a significant effect on the shrinkage of cementitious materials, particularly on its reduction. Nonetheless, to fully utilize its potential, further research is needed, especially in optimizing the level of cement substitution and fineness of RBP in concrete and mortar mixtures.

2.2.4. Water Absorption

Studies have shown that increasing the content of RBP up to a certain level can reduce water absorption in cement-based composites. Ortega et al. [11] found that the capillary absorption coefficient of concrete containing 20% RBP as SCM, with diameter about 8.5 μm, was 19.2% lower than that of control. Ma et al. [41] found that the use of fine RBP had a more pronounced effect on reducing water absorption compared to coarser particles. However, excessive use of low-fineness RBP may increase water uptake, indicating the importance of carefully balancing both fineness and level of cement substitution. Similar findings were reported by Schackow et al. [9], who tested mortars with average RBP particles smaller than 5 μm. After 28 days of curing, the mortars containing RBP as SCM (up to 40%) had lower water absorption and reduced porosity compared to the control one. A nearly linear relationship was observed between RBP content and porosity reduction - higher RBP levels led to lower porosity, up to a certain threshold. Furthermore, Schackow et al. [9] compared the water absorption coefficients of mortars with and without RBP after 90 days of curing. While there were no significant differences in water absorption within the first 10 minutes, samples containing RBP exhibited a clear reduction in the absorption coefficient after 90 minutes. This effect was attributed to a combination of the filler effect and pozzolanic activity of RBP, which reduced capillary channels and hindered fluid transport. Interestingly, at 40% RBP content, a slight increase in absorption coefficient was observed, suggesting that there is an optimal dosage of RBP, beyond which the benefits may be reversed due to changes in the microstructure.

2.2.5. Chloride Resistance

Chloride ions from the environment pose a continuous threat to reinforced concrete structures due to the risk of steel bar corrosion, which severely compromises concrete durability [54]. Therefore, evaluating the resistance of cement-based composites with RBP

to chloride penetration is of growing importance. Gonçalves et al. [55] found that mortars containing 10% and 20% RBP as SCM showed improved resistance to chloride ingress, which they attributed to the pore refinement in cement-based matrix. Similar results were reported by Ortega et al. [11], who observed that chloride migration coefficients in mortars with 10% and 20% RBP were reduced by 31.70% and 48.15%, respectively, compared to the control. They concluded that the synergy between the pozzolanic activity and filler effect of RBP contributes to a denser, less permeable microstructure. However, not all findings are consistent. Ge et al. [46], who tested concrete with 10%, 20%, and 30% RBP, found that the sample with 30% RBP had the lowest chloride resistance.

2.2.6. Carbonation Resistance

Concrete's resistance to carbonation depends on the composition and density of the cement matrix, as CO_2 penetration reduces pH and accelerates steel corrosion [56,57]. The process involves diffusion of CO_2 through the pore structure, dissolution in pore water, and reaction with hydration products to form calcium carbonate [57,58]. According to Shao [59], the depth of carbonation in mortar increased with higher RBP content during accelerated testing-reaching a maximum of 13.8 mm at 40% RBP as SCM after 28 days of carbonation. Conversely, under natural carbonation conditions, Schackow et al. [9] observed the carbonation depths under natural conditions after 28 and 90 days for mortars with and without the addition of RBP. The addition of RBP did not significantly affect the degree of carbonation after 28 days, but differences in behavior were noted after 90 days. Mortars containing 10% and 25% RBP showed lower carbonation rates compared to the control value. Moderate RBP content can enhance matrix density and reduce permeability, thereby slowing down carbonation process. However, excessive RBP reduces the content of calcium hydroxide, while lowering alkalinity and increasing vulnerability to carbonation [9,59].

3. CONCLUSION

The incorporation of RBP into cement-based materials significantly affects both fresh and hardened properties, with outcomes depending on both the replacement level and the fineness of the used RBP as SCM.

In the fresh state, with increasing the presence of RBP as SCM in mix there is an increase in water demand due to the irregular shape and porous surfaces of coarser RBP particles. However, this effect decreases with smaller RBP particle sizes due to their smoother surface and more regular shape, which improves the lubrication effect and mitigates the impact of the increased surface area. Rheological properties such as yield stress and viscosity tend to deteriorate with higher RBP content and coarser grading, although these effects can be mitigated through the use of finer particles. Regarding flowability, most studies report a reduction in slump and flow diameter with increasing RBP content, although some findings indicate the opposite trend - highlighting the importance of controlling particle size and optimizing mix design.

When it comes to the mechanical properties of the hardened composite, results indicate that small amounts of RBP as SCM (up to 15%) can even enhance compressive strength, especially when finely ground particles are used. In contrast, higher levels of cement replacement with RBP lead to strength reduction. A similar trend is observed in terms of

flexural and tensile strength, i.e. with careful adjustment of fineness and level of cement substitution, RBP can maintain or even improve these properties.

In a term of shrinkage, RBP has proven beneficial by significantly reducing both autogenous and drying shrinkage of cementitious materials. The usage of fine RBP particles as SCM helps reduce total shrinkage, while cement replacement up to 30% with RBP (with optimal fineness) results in the decreasing of drying shrinkage of the cement-based composites.

The addition of RBP as SCM in the optimum range, as well with optimal fineness, can lead to the refinement in pore structure and reduction of the permeability of the cement-based matrix. Therefore, the use of RBP up to 40% as SCM can lower water absorpiton of cement-based composites. Moderate amounts of RBC (10–20%) can improve the resistance of the cement-based materials to chloride penetration, while RBP in the range of 10-25% as SCM reduces the carbonation rate.

A systematic literature review indicates that replacing cement with RBP (with optimal fineness) in the range of 10–20% improves the mechanical properties, reduces shrinkage and water absorption, and also improves some durability properties such as chloride and carbonation resistance of cement-based composites, while contributing to the reduction of C&D waste disposal.

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Research paper

SEISMIC DESIGN APROACH FOR TORSIONAL EFECTS ON RC DUCTILE BUILDINGS

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Abstract

This study investigates the influence of torsional effects on the seismic performance of reinforced concrete (RC) ductile buildings and provides a framework for their analysis and design. Key considerations include the relative positions of the center of mass (CM) and center of stiffness (CS), stiffness distribution, and the control of lateral displacements and inelastic rotations. Equations for determining total forces, torsional stiffness, radius of rotation, and system displacements under eccentric seismic loading are presented, along with methods to constrain inelastic twist in asymmetrical systems. The research adopts Paulay's classification of torsional systems into torsionally unrestrained and restrained categories, highlighting design strategies to limit torsional rotations while maintaining ductility. A numerical example illustrates the application of these concepts, demonstrating the design of a system with limited twist through optimal placement of vertical walls and consideration of ductility capacities. The findings emphasize the critical role of torsional considerations in modern seismic design, providing engineers with analytical tools to enhance structural resilience and prevent excessive damage during strong earthquakes.

Key words: *Ductility, Stiffness, Strength, Capacity, Torsional, Displacement, Inelastic, Response*

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1. INTRODUCTION

Structures with an asymmetric distribution of stiffness and strength in plan experience combined torsional and translational seismic responses (shown in Figure 1).

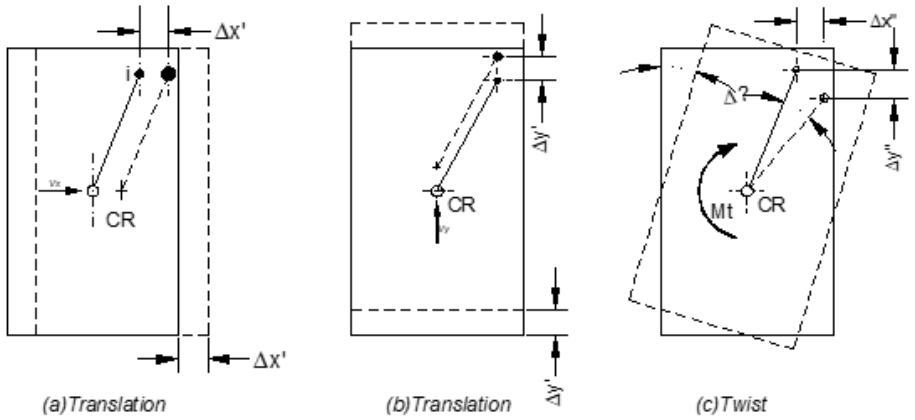


Figure 1. Combined torsional and translational responses

Plan irregularities often arise from non-uniform mass distribution, causing rotational motions of the floor slab even in systems where stiffness and strength are symmetric. A crucial step during the conceptual design phase is selecting an appropriate stiffness distribution for the structure. In systems expected to behave in a ductile manner, seismic design must consider the influence of torsional effects on inelastic deformations. Although this consideration is strongly recommended, it remains optional in most current design codes. However, recent developments emphasize their role in improving structural performance and reducing damage during strong earthquakes [1].

2. SEISMIC DESIGN CONSIDERATIONS ON THE DUCTILE BEHAVIOR OF STRUCTURES

In reinforced concrete (RC) ductile buildings, torsional effects arise due to irregularities in mass, stiffness, or geometry. In most building models, seismic forces are considered to act at the center of mass (CM) of the floor, while the lateral resistance is provided at the center of rigidity (CR), which is determined by the configuration and stiffness of the lateral force resisting elements. When the CM and CR do not coincide, eccentricity arises, generating torsional moments in addition to translational demands.

Figure 2 illustrates two plan views of a building subjected to lateral seismic forces:

- In (a), the Center of Rigidity (C_R) and Center of Mass (C_M) are offset, causing torsional rotation under earthquake loading (E), resulting in unequal lateral displacements (Δ) across the width.
- In (b), the Center of Base Shear (C_B) and Center of Mass (C_M) are aligned, resulting in pure translation without torsion.

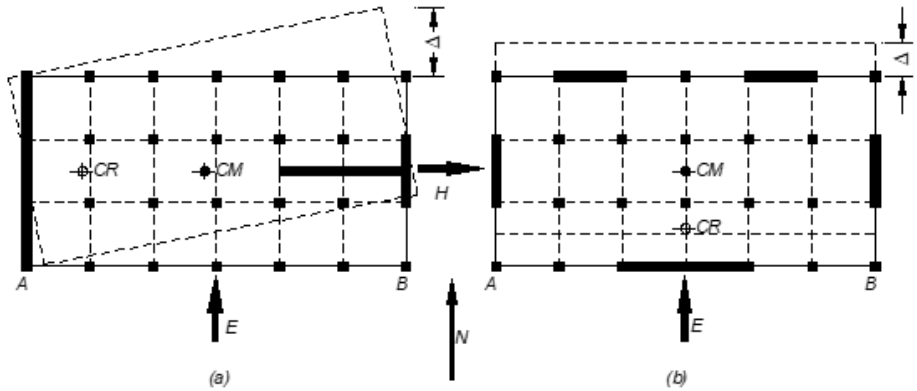


Figure 2. Typical distribution of vertical elements resisting lateral forces

This torsional response can significantly amplify the displacement and damage in certain structural elements, especially those located at the perimeter of the building. Seismic design must address these effects by ensuring that torsion-induced displacements remain within the ductility limits of structural elements. Key strategies include balancing stiffness distribution, controlling lateral displacements at points far from the center of stiffness, and detailing elements to accommodate inelastic torsional deformations. Since most structures are expected to respond inelastically, their design relies on ductile behavior characterized by controlled displacements and rotations. Assessing torsional effects during design is important to avoid unexpected failures. Including torsion in analysis helps ensure all critical elements perform safely under earthquakes [2].

For structures prone to torsional effects, the following performance criteria are generally adopted:

- Earthquake-induced deformations, including twisting, must not exceed the ductility capacity of structural elements.
- Maximum displacements, especially at points farthest from the C_S, should remain within specified limits, typically expressed as a percentage of the story height.

These provisions acknowledge the role of ductility in accommodating controlled inelastic deformations while maintaining overall stability and integrity. By ensuring displacement limits are respected, seismic design allows structures to withstand both translational and torsional demands without incurring excessive damage [3].

2.1. Determining Total Force and Torsional Stiffness in Structural Systems

In the analysis of a simplified structure with a few structural walls the forces acting on each element are divided into translational components and torque-related components [4].

The total force acting on an element in the x and y directions is the sum of the translational and torque-induced components:

$$V_{ix} = V'_{ix} + V''_{ix} \qquad V_{iy} = V'_{iy} + V''_{iy} \tag{1a,b}$$

The translational force components V'_{ix} and V'_{iy} are calculated as:

$$V_{ix}^{'} = (k_{ix}/\sum k_{ix})V_{Ex} \qquad V_{iy}^{'} = \left(k_{iy}/\sum k_{iy}\right)V_{Ey} \tag{2a,b}$$

Where: V_{Ex} and V_{Ey} are the external forces acting in the x and y directions.

The forces due to torque V_{ix}", V_{iy}" are defined by:

$$V_{ix}^{"} = y_i k_{ix} M_t/K_t \qquad V_{iy}^{"} = x_i k_{iy} M_t/K_t \tag{3a,b}$$

Where: Mt is the torque, and K_t is the torsional stiffness, defined as:

$$K_t = y_i^2 k_{ix} + x_i^2 k_{iy} \tag{4}$$

Where, x_i and y_i are the distances of the element from the center of twist and the k_{ix} and k_{iy} are the stiffness values in the x and y directions, respectively.

The radius of rotation relating to the torsional stiffness of the system can be defined as:

$$r_{kx}^2 = K_t/\sum k_{ix} \qquad r_{ky}^2 = K_t/\sum k_{iy} \tag{5a,b}$$

Where: $\sum k_{ix}$ and $\sum k_{iy}$, are the sum of the stiffness values of all elements in the structure.

2.2. Effect of Eccentricity on Displacement and Stiffness in Seismic Design

The displacement of structure Δ_m is defined by:

$$\Delta_m = \Delta_m^{'} + \Delta_m^{"} = V/\sum k_i + \theta_t e_s \tag{6}$$

Where: Δ'_m and $\Delta"_m$ are the translational and rotational components of displacement of mass and θ_t is the angle of twist, defined as:

$$\theta_t = M_t/K_t = V\, e_r\, /K_t \tag{7}$$

With these equations, the displacement of structure Δ_m can be established by the equation:

$$\Delta_m = V[1/\sum k_i + \ e_r^2/K_t] \tag{8}$$

Then, the stiffness of the system K_S is determined by the equation:

$$K_s = V/\Delta_m = \sum k_i /(1 + \ e_r^2/K_t) \tag{9}$$

It shows that, whenever the eccentricity of inertia exists, the inertia of the system is smaller than the sum of the weights of the elements. Therefore, the displacement at the yield point of the system is:

$$\Delta_y = V_E/K_s \tag{10}$$

2.3. Constrain against Twisting

An important aspect of the inelastic behaviour of an asymmetrical structural system is the consideration of the level of control over the inelastic twist. However, one of the design goals is to constrain the system against unlimited inelastic twist. The system in this way, during the development of the translational displacement expected for the ductility capacity, μ_Δ, preserves a certain amount of stiffness in the twist and is determined with the relation:

$$K_{tr} = \lambda_t K_t \tag{11}$$

Where: $\lambda_t \leq 1.0$

The parameter λt, in equation (11), expresses the degree of restriction of the twist:

$$\lambda_{tx} = \sum (x_i^2 k_{iy})/K_t \qquad \lambda_{ty} = \sum (y_i^2 k_{ix})/K_t \qquad (12a,b)$$

In the ultimate limit state, the twisting moment that must be accepted can be determined by the equation:

$$M_{tu} = e_v V_E \qquad (14)$$

Where: e_V is the eccentricity, and it should satisfy $e_v \leq e_r$, where e_r is the design (or strength-based) eccentricity.

These equations and classifications provide a framework for analysing and designing ductile structures about torsional response, considering factors such as stiffness, displacements, and restriction of twist.

3. A CLASSIFICATION OF TORSIONAL DUCTILE SYSTEMS

The classification of torsional systems proposed by Paulay differentiates between torsionally unrestrained and torsionally restrained systems based on their ability to control torsional rotation during seismic activity in the principal directions of a building These classifications are particularly important for ductile structures, which are designed to withstand seismic forces. Thus, according to Paulay, the systems of ductile structures for torsional response are classified into two categories:

1. Torsional unrestrained systems with unlimited twist, where λt =0 and
2. Torsional restrained systems with limited twist, where λt >0.15.

3.1. Torsional Unrestrained Systems

Systems with λ_t values above this threshold are deemed to have sufficient torsional resistance to qualify as torsionally restrained systems. The simplest structure (Paualy) (shown in Figure 3) with transverse elements serves as an example of a torsionally unrestrained system.

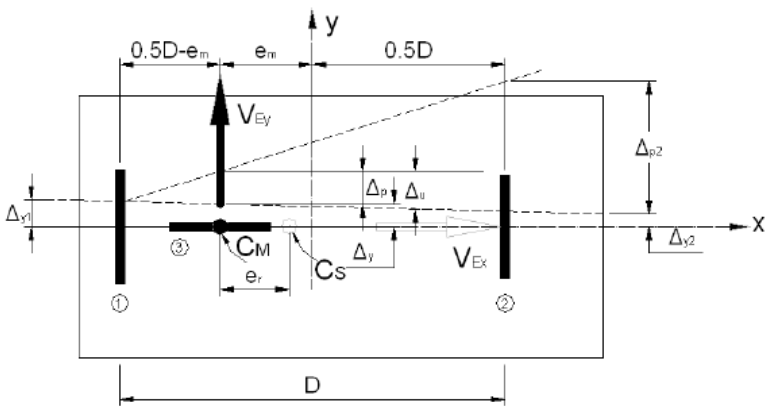


Figure 3. Characteristics of torsional unrestrained system

The yield displacement of the system which considers the contributions of both elements will be:

$$\Delta_y = (V_1/k_1)(0{,}5 + e_m/D) + (V_2/k_2)\,(0{,}5 - e_m/D) \quad (15)$$

The displacement ductility applicable to the system can be defined by the expression given by Paulay:

$$\mu_\Delta = \Delta_u/\Delta_y = 1 + \Delta_p/\Delta_y = [(\mu_{max} - 1)/(1 + \omega_0)] + 1 \le \mu_{max} \quad (16)$$

Where:

$$\omega_0 = [V_1 k_2\,(0{,}5 + e_m/D)]/[\,V_2 k_1 (0{,}5 - e_m/D)] \quad (17)$$

Therefore, the maximum necessary requirement of the system ductility should be limited, and it may be shown that (Eq.17) is also valid when more than two elements are positioned to resist the force V_{Ey}. The force V_{Ey} can be established by the equilibrium of the cutting force components, $V_{Ey} = V_1 + V_2$.

3.2. Torsional Restrained Systems

The value λ_t > 0.15 represents a threshold limit proposed by Paulay, indicating the minimum level of torsional restraint required for a system to be considered torsionally restrained (shown in Figure 4).

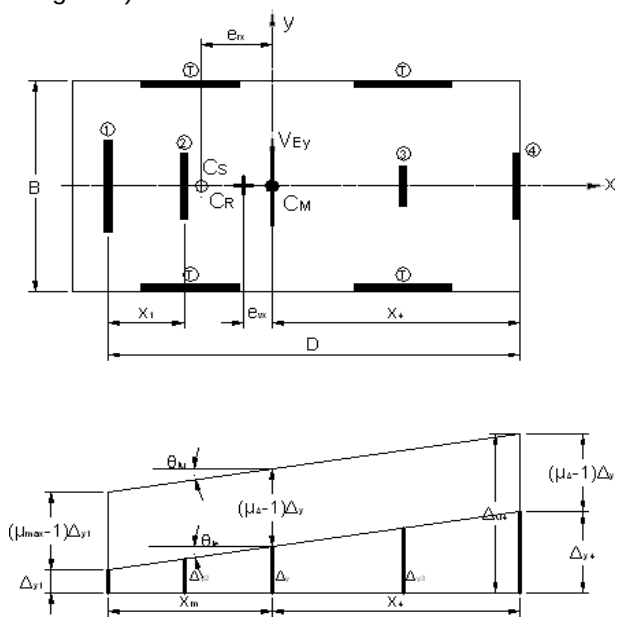


Figure 4. Characteristics of torsional restrained system

The maximum acceptable requirement of ductile displacement of the system is limited:

$$\mu_\Delta = [(\mu_{max} - 1)/(1 + \omega_{tr})] + 1 \quad (18)$$

Where: the factor ω, applicable to strained torsional systems:

$$\omega_{tr} = [V_{Ey} k_1/V_1 K_{sy}] - 1 \quad (19)$$

Overall, this classification and the associated equations provide a framework for designing ductile structures with a focus on limiting torsional rotations and ensuring the inelastic response of the system remains within acceptable limits [5].

4. DETERMINATION OF LIMITED TORSION, CAPACITY AND DISPLACEMENT IN DUCTILE SYSTEMS

In the numerical example, the torsional response of ductile systems is analyzed. This principle is based on the deformation capacity and the corresponding demand of the system, especially of its critical elements, more precisely on the torsional force. The analysis determines the inelastic displacements of the elements depending on the inelastic motion of the system [4].

On this basis, the critical elements are provided with lateral force resistance, especially in the length of the plane, against the demand of inelastic deformations. For the determination of the displacements, the ductility factor is used for known displacements. By focusing on controlling the inelastic displacements of the elements, possible torsional effects are not considered by the distribution of masses, which affects the instantaneous position of the center of mass [6].

4.1. Numerical Example

In the provided example, the proposed steps for designing a system with limited twist are illustrated using (Figure 5). The system in the example meets the criteria for limited twisting, which is important in building design. The figure shows a shaded area covering 16 floors and an unshaded area with 3 floors. The relative stiffness values (ki) were chosen to limit twisting in the top 13 floors and the whole structure. Vertical walls are used to resist lateral forces.

The results focus on the 1st and 4th floors, assuming all elements have a displacement ductility capacity of $\mu_{max}=5$. This example emphasizes the importance of limiting twist through the smart placement of vertical walls and considering ductility in the design.

4.1.1. Input Data

The input data considered in this research paper are summarized in the form of table. The data are given in the direction of axes x and y of the building.

Table 1. General input data of the considered building

Direction:	x	y
Building floor plane: [m]	$L_X=24$	$L_y=24$
Walls lengths: [m]	$l_{4x}=5$, $l_{5x}=6.3$, $l_{6x}=5$	$l_{1y}=5$, $l_{2y}=6.3$, $l_{3y}=5$
Wall thickness: [mm]	d=200	
Module of the building: [m]	B=6.0	
Moment of inertia: [m^4]	$I_{4x}=2.08$, $I_{5x}=4.16$, $I_{6x}=2.08$	$I_{1y}=2.08$, $I_{2y}=4.16$, $I_{3y}=2.08$
Stiffness: [m^4]	$k_{4x}=2.08$, $k_{5x}=4.16$, $k_{6x}=2.08$	$k_{1y}=2.08$, $k_{2y}=4.16$,$k_{3y}=2.08$

4.1.2. Input Data for the First Floor

The positions of the centers C_M and C_S and the corresponding eccentricities are shown as a function of the horizontal platform dimension B=6.0 m in (Figure 5b).

Table 2. Input data for the first floor

Direction:	x	y
Centre of Mass:	$x_M = 1.422$	$y_M = -3.726$
Stiffness:	$\sum k_{ix} = 8.32$	$\sum k_{iy} = 8.32$
Centre of Stiffness:	$x_s = 12$	$y_s = 12$
Torsional stiffness:	$K_t = 1198.08$	
Radius of rotation:	$r_{kx} = 12$	$r_{ky} = 12$
Ecctrencity:	$e_{rx} = 1.422$	$e_{ry} = 3.726$
Troques:	$M_{tx} = 3.726V_{Ex}$	$M_{ty} = 1.422V_{Ey}$
Parameter of degree of torsional restraint:	$\lambda_{ix} = 0.5$	$\lambda_{iy} = 0.5$
Strengths of Elements:	$V_{4x} = 0.328V_{Ex}$ $V_{5x} = 0.5V_{Ex}$ $V_{6x} = 0.172V_{Ex}$	$V_{1y} = 0.22V_{Ey}$ $V_{3y} = 0.28V_{Ey}$ $V_{2y} = 0.5V_{Ey}$
The smallest force for the walls:	$V_{6x} = 0.172V_{Ex}$	$V_{1y} = 0.22V_{Ey}$

4.1.3. Input Data for the Fourth Floor

The positions of the centers C_M and C_S and the corresponding eccentricities are shown as a function of the horizontal platform dimension B=6.0 m in (Figure 5c).

Table 3. Input data for the fourth floor

Direction:	x	y
Centre of Mass:	$x_M = -1.0$	$y_M = -0.8$
Stiffness:	$\sum k_{ix} = 6.24$	$\sum k_{iy} = 6.24$
Centre of Stiffness:	$x_s = 10$	$y_s = 8$
Torsional stiffness:	$K_t = 399.36$	
Radius of rotation:	$r_{kx} = 6.93$	$r_{ky} = 6.93$
Ecctrencity:	$e_{rx} = 1.0$	$e_{ry} = 0.8$
Troques:	$M_{tx} = 0.8\,V_{Ex}$	$M_{ty} = 1.0\,V_{Ey}$
Strengths of Elements:	$V_{4x} = 0.366V_{Ex}$ $V_{5x} = 0.634V_{Ex}$	$V_{2y} = 0.709V_{Ey}$ $V_{3y} = 0.291V_{Ey}$
The smallest force for the walls:	$V_{4x} = 0.366V_{Ex}$	$V_{3y} = 0.291V_{Ey}$

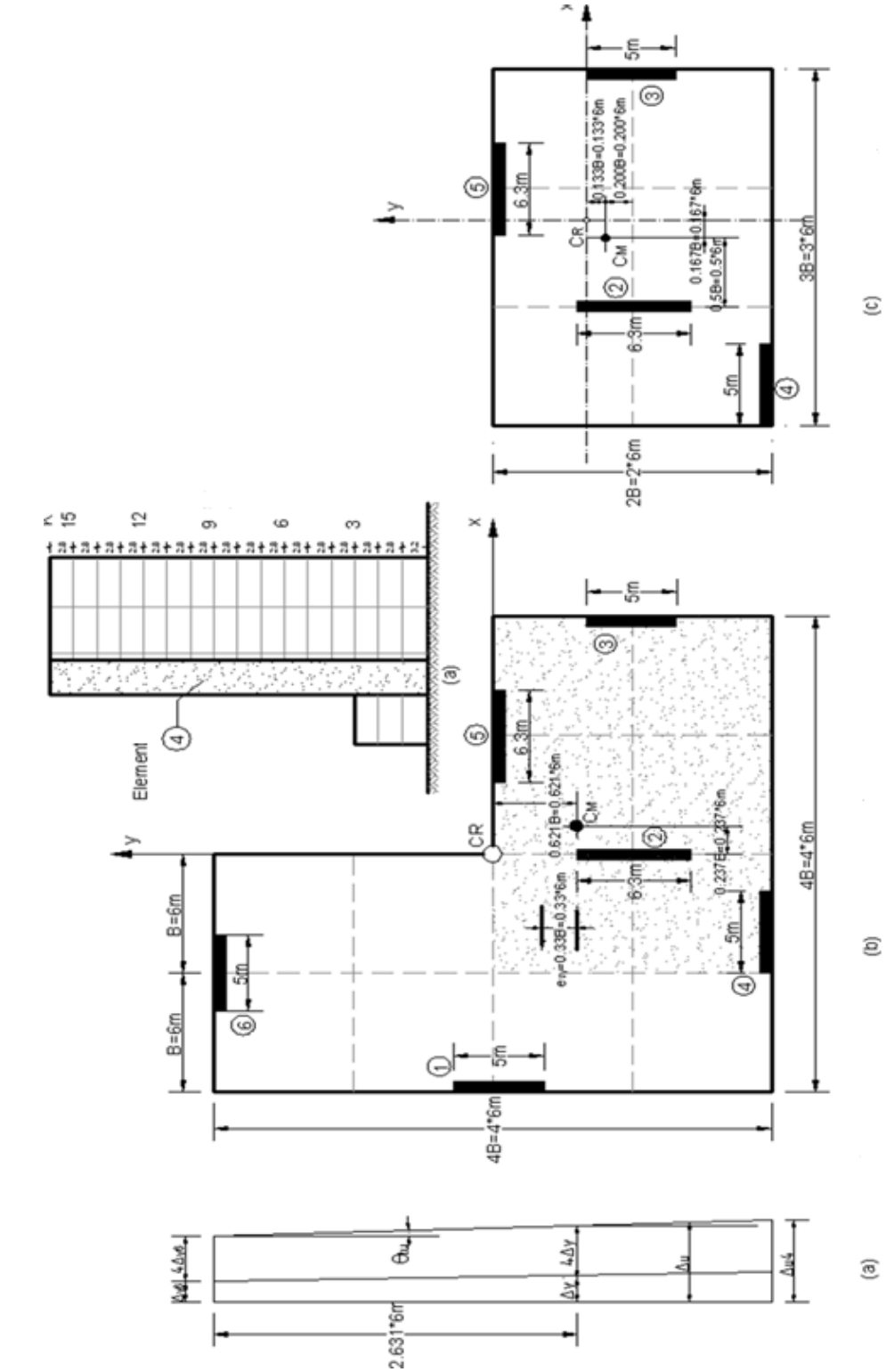


Figure 5. Example of torsionally restrained building, a) displacements, b,c) layout of the first and fourth floor (adapted from reference: [3])

5. DISCUSSIONS

The numerical example highlights the effectiveness of torsional restraint in seismic design through a focused analysis of a ductile structural system. By strategically distributing stiffness and using vertical walls to resist lateral forces, the design meets the criteria for limited torsional response, particularly on the 1st and 4th floors.

The results demonstrate that controlling inelastic displacements and ensuring the ductility of critical elements especially walls with lower yield strength is crucial to achieving seismic resilience. In both examined floors, eccentricities between the center of mass and the center of stiffness introduced torsional moments, yet the resulting displacements remained within acceptable ductility limits ($\mu_{\Delta x}$ and $\mu_{\Delta y}$ below the capacity μ_{max}=5). This indicates that the system can undergo significant inelastic deformation without compromising structural integrity.

Moreover, the analysis shows that the placement and stiffness of structural walls directly influence torsional stiffness (K_t), radius of rotation (r_k), and eccentricity-induced torques (M_t). The values of the torsional restraint parameters (λ_i and ω_{rt}) further confirm that the system is effectively restrained against excessive twist.

In summary, the example validates the importance of:

- Optimizing wall locations and stiffness distribution.
- Evaluating torsional effects through eccentricity and torque parameters.
- Ensuring that critical elements have sufficient ductility.
- Controlling inelastic displacements to avoid structural failure.

This design approach ensures seismic performance while reducing the risk of torsional amplification, particularly in irregular structures or those with asymmetric mass and stiffness distribution.

6. CONCLUSIONS

Torsion is a critical factor in the seismic design of buildings, particularly in ductile systems intended to withstand significant lateral forces. It refers to the twisting or rotational response of a structure when subjected to seismic-induced moments, which can lead to uneven displacement demands on structural elements.

- For the first floor, seismic analysis identifies walls 1 and 6 as the critical elements due to their relatively low yield strength. The combined stiffness in the x- and y-directions, along with torsional factors (ω_{rtx} = 0.593, ω_{rty} = 0.154), indicates moderate torsional restraint. The calculated displacement ductility factors ($\mu_{\Delta x}$ = 3.51, $\mu_{\Delta y}$ = 4.47) confirm that the system can accommodate inelastic deformations within acceptable limits, maintaining controlled torsional behavior.
- For the fourth floor, walls 3 and 5 are identified as critical due to their lower yield strength. The measured stiffness values (K_{sx} = 6.158, K_{sy} = 6.115) and torsional factors (ω_{rtx} = 0.062, ω_{rty} = 0.167) reflect adequate torsional restraint. Displacement ductility factors ($\mu_{\Delta x}$ = 4.77, $\mu_{\Delta y}$ = 4.43) demonstrate that the system can sustain significant inelastic deformations while ensuring a stable torsional response.

Overall, the results highlight the importance of strategically locating and sizing critical walls, combined with explicit consideration of torsional effects, to maintain structural performance and safety under seismic loading.

In summary, considering the torsion effect in the design of buildings is essential for ductile systems intended to withstand seismic activities. Designers should account for the inelastic displacement caused by torsion in certain elements and take measures to limit the effects of unlimited inelastic torsion.

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Research paper

INDUSTRIAL HERITAGE AND ITS PRESENCE IN THE CONTEMPORARY LIFE OF SMALL TOWN CITIZENS IN BULGARIA: CASE STUDY TRYAVNA

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Abstract

Bulgaria's industrial heritage, encompassing both tangible and intangible aspects, forms an integral part of the nation's historical legacy. However, the discourse surrounding this heritage remains divisive, primarily owing to two transformative events in its history: nationalization and privatization. Although its place in the current reality is often debated, these discussions rarely focus on smaller settlements. This article is part of a broader research project centered on exploring and promoting industrial legacy of small settlements in Bulgaria.

The subject of this study is the municipality of Tryavna, which is one of the four municipalities of Gabrovo province, Bulgaria. Methods employed in conducting the research include a literature review, interviews with local citizens and experts, as well as field research. A brief history of industrial development of Tryavna is provided, within the context of the broader regional history. Plachkovtsi, a nearby small settlement with rich mining and railway history is also examined. Notable industrial buildings from machine building, textile, furniture and mining industry are presented. It has been observed that industrial heritage constitutes a significant element of local historical narratives, yet it is relatively underrepresented in discussions regarding future development. Today, despite its rich industrial history, to its citizens, Tryavna remains primarily recognized as a center for tourism and traditional crafts and Plachkovtsi is rarely perceived as a mining town. Regardless, historical industrial development in this municipality remains an important element of the national industrial heritage.

Key words: *industrial heritage, small town, local identity, disappearance of historic industrial sites, mining town, railway history, Tryavna*

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1. INTRODUCTION

Industrial sites symbolize technological progress and modernity while simultaneously standing as monuments to decline, evoking the sense of loss and nostalgia. Protecting them helps in preserving cultural memory, strengthens regional identities and fosters a sense of place, yet many face neglect or redevelopment pressures. In recent decades, the preservation and repurposing of industrial buildings have grown to be a major theme in heritage studies, reflecting broader discussions on sustainable urban planning and collective memory. However, despite growing interest in industrial heritage, research on the mechanisms of transformation - how spaces evolve and how communities engage with them - is still lacking. This issue is particularly evident in Bulgaria, where industrial heritage is under-researched, especially in small settlements. Nationalization and privatization created gaps in historical documentation, with some aspects of industrial history intentionally erased from the official narratives in the second half of the 20th century. Following privatization, most industrial enterprises became private property. This shift, coupled with the wave of deindustrialization across Europe, led many to cease production and ultimately shut down. Some industrial complexes were demolished due to a lack of protection, as they were not recognized as historically significant. As a result, all historical layers were treated indiscriminately, leading to the loss of valuable heritage. Another issue is the absence of living witnesses from the years preceding nationalization, as firsthand accounts continue to fade into history.

Eastern Europe has a distinct industrialization trajectory. Due to a shared communist heritage, Eastern European countries display common patterns in industrial development and heritage interpretation. Existing heritage theories provide useful perspectives, but their application to Eastern Europe must account for its unique industrial and political history. One particularly relevant framework is Tunbridge and Ashworth's concept of **dissonant heritage** [1], which explores conflicting narratives surrounding historical sites. Industrial heritage itself is dissonant, as it carries elements of trauma, stemming from harsh working conditions, environmental degradation, labor strikes, alienation, and the societal upheaval caused by rapid industrialization. These challenges contribute to a complex legacy, where industrial sites evoke both nostalgia and struggle. Another theme within dissonant heritage is its ideological burden - heritage is inherently political. Given Eastern Europe's regional history - where industrialization was deeply tied to state-driven policies - it is only natural that industrial heritage sites remain ideologically charged. Similarly, Smith's **Authorised Heritage Discourse** (AHD) [2] highlights **top-down heritage control**, which socialist regimes reinforced by limiting alternative narratives. As Sucala notes, post-socialist contexts react against AHD, with grassroots movements emerging despite official rejection of Communist heritage [3]. Sucala's discussion on AHD [3] contrasts top-down heritage control with grassroots movements, aligning with Robertson's **Heritage from Below** [4], which explores community-driven heritage engagement. These civic initiatives often reflect *the instability of identity in contemporary society* [5] as local communities seek ways to redefine their heritage in response to political and economic shifts. A particularly relevant expression of this identity negotiation is **nostalgia for industrial labor** [6], which offers a unique lens through which Eastern European industrial heritage can be analyzed.

This paper examines the industrial heritage of **Tryavna municipality**, a region that, to the author's knowledge, lacks a contemporary comprehensive study of its industrial development. Its history has likely been overshadowed by the nearby town of Gabrovo, often referred to as the "Bulgarian Manchester" due to its prominent industrial legacy. While

existing local studies [7, 8, 9, 10] in Tryavna focus on individual factories or industry branches, they rarely address the buildings in their present form, leaving gaps in the broader narrative of industrial heritage. Since **heritage and memory are spatial** in character [1,5] preserving the materiality of these sites is important. This study seeks to construct an integrated account of Tryavna municipality's industrialization, linking historical developments with the physical sites that remain today. Additionally, it explores how local citizens perceive this industrial legacy, asking: *what is its place in the rapidly changing contemporary reality?* Through firsthand observations and documented sources, this research contributes to discussions on industrial heritage and its evolving significance in community identity.

A brief overview of Tryavna municipality follows in the next section, providing essential context for the analysis.

2. BRIEF OVERVIEW OF TRYAVNA MUNICIPALITY

Tryavna is one of the four municipalities of Gabrovo province, situated in the North-Central region of Bulgaria. Nestled on the northern flanks of the Balkan Mountain, the town of Tryavna is renowned for its preserved Revival architecture, rich cultural heritage and picturesque natural landscapes. It is the administrative center of the Tryavna municipality, as well as the cultural and economic center. Tryavna town has a population of around 8000 citizens [11]. During the Revival period, it was a cultural and education center serving as a meeting point for intellectuals, artists and socially conscious people. Tryavna art school (Trevnenska shkola) is popular Bulgarian art school, emerged in the XVI century, famous for its woodcarving, icon painting and building crafts. At the beginning of the 20th century, some crafts gradually developed into a flourishing industry, which was further expanded after World War II.

Eight kilometers south of Tryavna lies Plachkovtsi, a small settlement with a population of approximately 1,500 [11]. Situated at the foot of Tryavna Mountain - a nature reserve - Plachkovtsi is located at the convergence of three small creeks that merge to form the Tryavna River. Due to the proximity of the two settlements, they can be perceived as one continuous urbanized area, despite some notable differences in the character of their built environments. Railway line 4, a key factor in Plachkovtsi's development, passes through both settlements, connecting them to North and South Bulgaria [12]. Historically, Tryavna region hosted industries such as coal mining, textiles, machine building and woodworking, alongside a strong tourism sector.

Tryavna Municipality was selected for this study due to its limited representation in discussions on industrial heritage, despite its significant role in Bulgaria's industrial history. While the region's historical industrial narrative remains relatively preserved, the physical sites associated with it are largely unknown. Some of these buildings and industrial landmarks are embedded in the daily lives of local residents, yet they lack formal protection and are rarely acknowledged in conversations about the town's future development. Additionally, unlike other mining regions in Bulgaria, which are primarily defined by their industrial identity, Tryavna has a more complex character shaped by both its industrial heritage and its strong presence in the tourism and cultural sectors. This multifaceted context adds layers of complexity to the issue, requiring a nuanced approach to understanding its development and heritage.

3. METHODS

This study employs ethnographic fieldwork, focusing on direct observation of industrial heritage sites and their contemporary use. Sites were selected based on their historical importance, significance in the town's industrial development, and accessibility, ensuring a representative analysis of the local industrial legacy. Data were gathered through site visits and architectural assessments, including evaluation of physical condition, historical significance and stylistic features. Additionally, the research examined patterns of continued operation, reduced functionality, abandonment, or (partial) demolition. Informal interactions with locals provided insights into public perceptions of industrial heritage. Conversations with former workers, journalists, municipal administrators, and cultural institution employees, provided additional perspectives on the significance of industrial heritage. Field notes and photographic documentation captured details and spatial transformations.

Library research complemented the fieldwork, drawing on archival materials, historical records, and scholarly works related to industrial heritage and urban development. By integrating observational analysis with documented sources, this study offers a comprehensive perspective on industrial sites within their historical and social contexts. Furthermore, comparative analysis positions this case study within the broader framework of the country's industrial heritage preservation efforts, highlighting regional challenges.

4. RESULTS

4.1. Tryavna town: from crafts to industry

4.1.1. Textiles

Entrepreneurial initiative has played an important role in shaping industrial development across the region. The nearby town of Gabrovo is renowned for the entrepreneurial spirit of its citizens, who transformed it into an industrial center. Similarly, the people of Tryavna are known for their strong entrepreneurial drive. Many of the town's early manufacturing enterprises emerged from the innovative thinking of notable local figures. The first industry to develop naturally was **wool production**. The first factory in Tryavna was built around 1881 by local entrepreneurs in the nearby settlement Dimiev han (now neighborhood of Tryavna). Establishing this enterprise was a difficult task, as there was no efficient transportation structure to Western Europe at the time - except for possible transport via the Danube. One industrialist had to travel to England personally to purchase machinery and hire technicians. Transporting the machines back was equally challenging due to logistical hurdles, further complicating the process. It was innovative yet complex undertaking for the time - although the one industrialist did not speak a single word of any language other than Bulgarian, the initiative was successful and they manage to build the factory, which was known colloquially as "the English woman". Initially, the English specialists operated the machines and trained local workers, laying the foundation for industrial development. Although initially successful, leading to the construction of three additional factories in Tryavna and the surrounding villages, by 1896 the enterprise went bankrupt [13]. The biggest factory, located near the train station in Tryavna, was bought by "St. George" Company[2] and refurbished around 1902 [14].

[2] St. George Company was a part of "Badeshtnost" JSC, that is described in next section

Under this leadership, the property gradually turned into a very successful enterprise. The old factory building, measuring 13 by 70 meters [14] and likely constructed around 1891 [15], was soon joined by a new two-story structure built parallel to the original. The 22,000 m² property also housed three shops, three two-story residential buildings for workers and personnel, and two prominent buildings - one serving as the director's residence and the other designated for administrative functions [14]. Positioned at the intersection of two streets bordering the property, the two buildings served as focal points of the site. Around the mid-1930s, another factory, called "Cotton Yarn" - was built on the same site. It was a modern reinforced concrete two-story building of impressive size, measuring 36 by 36 meters with a height of 15 meters [16]. The complex was located on the riverbank and had picturesque appearance at first but progressively evolved and in 1930s, the site had taken on the appearance of a fully developed industrial complex, especially after 1931, when a thermal power plant – "Bedek" - was built. It used the low-quality coal from the nearby mines and had 51 meters-high chimney and two cooling towers, approximately 22-meters-high, which dominated the town's silhouette [17]. These were demolished in the second half of the century. Most of the buildings of this industrial site were demolished in the first years of the 21st century and to this day, the plot is empty. The only remnants are the two buildings at the intersection. The location of the complex can be seen in Fig 1, site 1.

Alongside this enterprise, another textile factory - focused on silk products - helped shape the local industrial landscape. **Silk farming and weaving** had long been practiced in Tryavna, forming a unique local craft [15]. Building on this tradition, a factory was established before the turn of the 20th century. It was a small workshop, founded in 1876 but it gradually developed some new machinery and forged commercial ties with customers in Italy, France, Vienna and Russia. This proto-industrial enterprise remained a family-run business until a pivotal moment in 1927, when the oldest son sought to modernize the factory despite his father's objections. Seizing an opportunity, he sent his father on holiday and, during his absence, demolished the family house, repurposing its space (and some of the materials) to construct a new, reinforced concrete factory - 6-meter-high and covering approximately 350 m² [8,18]. The factory was a very successful and well-known establishment based on the region's traditional craft. It produced horse tackle for the police force and was the only one in Bulgaria to produce surgical threads. However, following nationalization, the factory ceased to exist in its original form, as its operations were relocated to Rousse and its machinery was transferred there [8]. Thus, the new regime abruptly halted the operations of a once-thriving factory. Over the years, the building underwent many transformations and today hosts a nightclub. It is located on the riverbank, near craftsmen's street and the Museum for Woodcarving and Iconpainting, as shown in Fig 1, site 2. Although the factory's history has been well researched, the building itself does not appear to hold significant importance.

Another **textile factory** (that also produced apparel), called „Lotus" (presented in Fig 1. site 3), was established in 1938 [19]. It was located at the center of the settlement, where a small stream flows through the site. The complex is an eclectic mix of buildings from different eras, creating a somewhat disorganized yet historically layered architectural landscape. One striking peculiarity is its proximity to the town's cemetery - due to the steep terrain, some graves are directly visible from the higher levels of the factory. Although the company has ceased production, all buildings remain standing, and plans are underway for their adaptive reuse, with proposals to transform some of them into a residential complex.

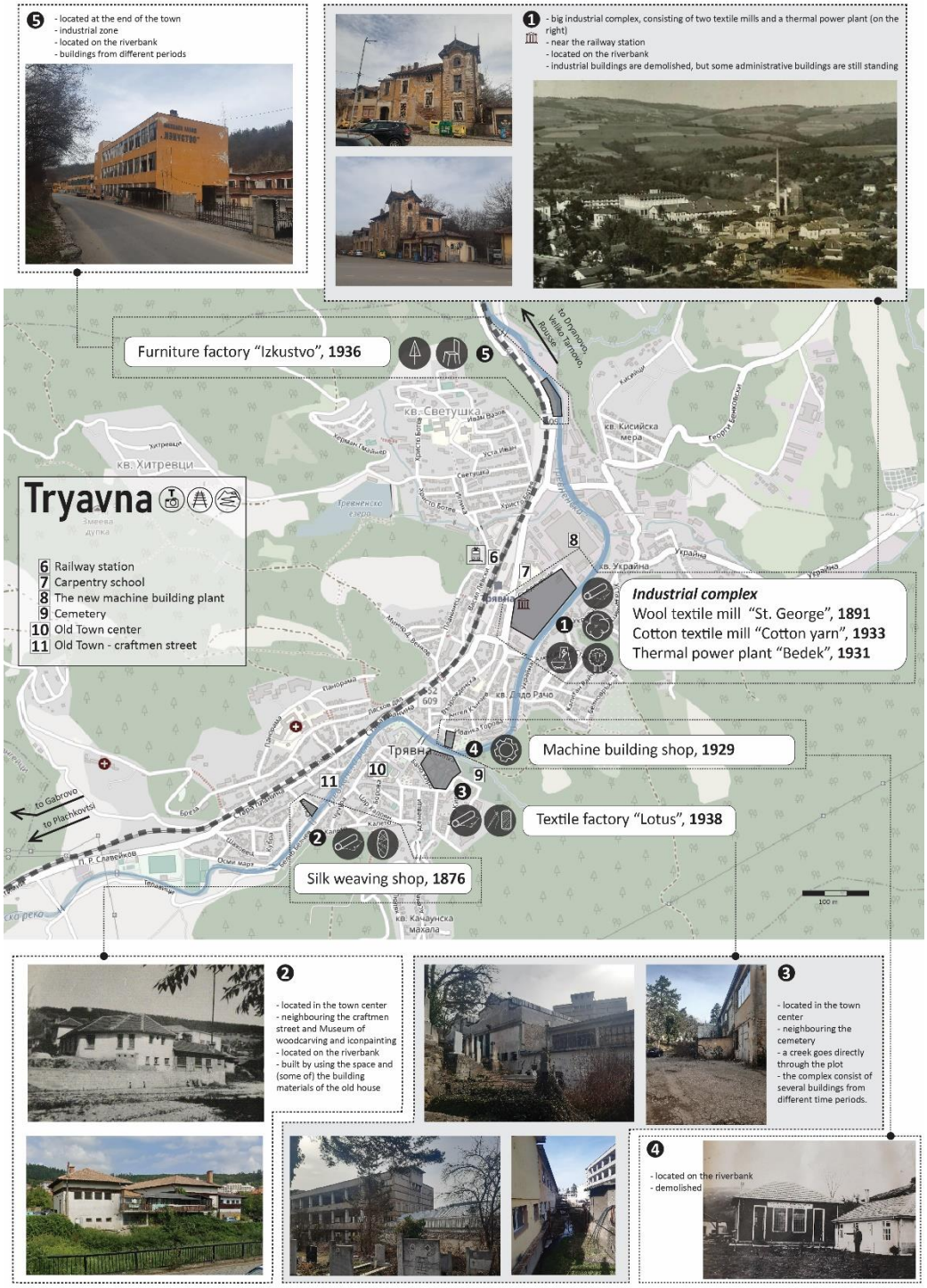


Figure 1. Map of Tryavna territory with industrial sites; source: author's own work; photos - author, archival photos: provided by Galina Ivanova, map: ©Open Street Maps

4.1.2. Railway and machine building

While textiles formed the region's industrial foundation, the arrival of the **railway** in the early 20th century was equally transformative, connecting Tryavna to the rest of the country. Its arrival necessitated the construction of new infrastructure and buildings to support its operations, while also bringing skilled railway workers whose expertise contributed to the training and education of the local population. That, in addition to the mining activities in nearby Plachkovtsi region, helped establish new interest for the machines. In Tryavna, one industrial branch that evolved organically was **machine building**. It was initiated by a single person who was self-taught but gained prominence over the years. He was formerly trained as a technician in Gabrovo and in Gorna Oryahovitsa - which is a marshaling yard - and wanted to become train driver but couldn't obtain a formal education. A skilled technician with a natural love for machines, he opened a small machine-building shop in 1929 and gave a start to a very successful machine building complex that is still operating today. The small shop held broader importance, as it was serving the factories in the whole region. After WWII, the factory was moved to a different site (marked in Fig. 1. as site 8). [7]

The original shop - shown in Fig. 1, site 4 - has not survived as it fell to neglect and was demolished less than 10 years ago. Buildings like this - with historical significance but less architectural distinction - are particularly difficult to preserve, as their history is often overshadowed or obscured by the communist narrative. The founder – Boris Hadzhisemkov - was a significant figure in Tryavna's history, similar to famous local craftsmen.

4.1.3. Furniture building

While textiles, railways, and machine building shaped the region's industrial growth, another branch emerged - one deeply rooted in local traditions and reflecting the area's unique history – **furniture building**. It is believed that many well-educated members of the ruling class made Gabrovo Province their home after the fall of the Second Bulgarian Empire in the late 1300s. These individuals not only held political influence but also had access to sophisticated art and culture, shaping the intellectual and artistic landscape of the region. Their dedication to preserving tradition and their pursuit of beauty became the foundation of Tryavna art school (Trevnenska shkola). It is a unique and known in Bulgaria school that includes woodcarving, icon painting and building crafts. At the beginning of the 20th century, a carpentry school was established, inheriting and advancing these woodcarving traditions. [20] With the first graduated class in 1924, a small-scale furniture workshop was created, expanding the craft into industrial production. In the early 1930s, the shop developed into a factory, situated on a 1000 m^2 plot with a two-story building measuring 40 by 12 meters [21]. The factory specialized in furniture construction, millwork, wood carving, upholstery, and lathe work, some of them in traditional Revival style [21]. After World War II, it evolved in "Izkustvo" factory (illustrated as site 5 in Fig.1) that produced luxurious furniture and interior millwork for export. Though it no longer operates at full capacity, the legacy remains - a complex of buildings from various periods, picturesquely situated along the river's bends in the northern part of the town.

4.1.4. Industrial heritage in Tryavna: legacy and future

Tryavna has always been and remains a city of artistic crafts. The development of industry, especially in the earlier period, is an expression of this shared pursuit of beauty among Tryavna residents and of their entrepreneurial spirit. The industrialization of Tryavna

in the 20th century reflects global economic and production trends, aligning with broader patterns of modern industrial development. Despite this, factories remain a large part of the lives of several generations of Tryavna residents and an integral part of the historical development of the town. Several in-depth local research works were conducted on the history of the town's industries with a focus on the key figures interwoven into their development. However, less attention is given to the remaining factory buildings and complexes - a material expression of this period. A natural question emerges: *how can these historical sites be integrated into the town's modern landscape, and what role should they play in shaping its future?* Yet another question lingers: *why are these buildings not important in a town renowned for its builders?*

4.2. Plachkovtsi town, Trans-Balkan railway and "black gold" deposits

4.2.1. Black coal

A key reason for Plachkovtsi's development is the ***black coal deposits*** located nearby in the mountain. First records about the exploitation of the deposits are from 1860 – before the Liberation of Bulgaria and under the Ottoman rule, here opened the first coal mine on the Bulgarian territory – state mine Belnovrah. Coal was essential for powering river vessels on the Danube. The black coal found in this region was particularly valuable for producing coke - an indispensable material for metal smelting - drawing keen interest from the army for its potential extraction. Some small-scale industrialists - particularly from the nearby towns of Veliko Tarnovo and Gabrovo, where Bulgaria's first industrial enterprises were emerging - attempted to explore coal deposits, as the growing industries naturally required energy sources. One major problem was the impassable terrain and the absence of modern roads leading to the mountain. Following the Liberation, several European companies sought concessions in Bulgaria. Among them, a company backed by Belgian and French capital became the first to explore the region's „black gold". Around 1899 this company created a mine called "Prince Boris" which was located southward Plachkovtsi, near Radevtsi village. Gradually, a **miners' village**, called Grabchevo, was developed around the mine. Other miners' villages were also created high up in the mountain notably the mining settlement around "Lev" mine (1900). [9,10]

Grabchevo - marked in Fig. 2 as site 1- emerged as the most significant industrial center, primarily due to substantial financial investments. Initially, foreign capital fueled its development, followed by a surge in domestic investments around World War I, particularly from one of Bulgaria's most influential financial institutions at the time - Bulgarian Commercial Bank. This Bank was connected to the influential Burov and Gubidelnikov families, whose significant contributions to Bulgarian industry include the mining complex. The bank's shareholders established a new joint-stock company, '"Badeshtnost" (meaning in Bulgarian - "future"), that controlled many mines in the region. This allowed Grabchevo to expand with superior architectural and engineering advancements compared to other industrial sites in the area. It facilitated the flow of not only capital but also know-how and technology, initially imported from abroad and later fostering a close-knit professional community around the mines [10]. The material legacy of this development includes Muller's villa (residential building form the French company period), Burov's villa, the main administration building, and various industrial facilities. At the turn of the twentieth century, the first experimental coke ovens in

Bulgaria were built in the village, alongside small-scale coal washing plant [10]. Following the mine's closure in the mid-twentieth century, a children's camp was established on the site. Today, however, the settlement stands abandoned.

The first official **industrial coke ovens** (shown in Fig. 2 as site 3) were built in Plachkovtsi around 1930 by "Badeshtnost". As at that point, the "Badeshtnost" company owned many mines from Tryavna to Burgas, they needed a central administration and decided to place it in Plachkovtsi [10]. That building still exist and has a similar style as the administration buildings of St. George complex in Tryavna, which had the same owners. The coke plant gradually developed into a big industrial complex which operated until the beginning of the 60s when coal deposits were depleted and coke ovens operations were moved to the site of the newly built metallurgical giant Kremikovtsi, near Sofia. After the 60s, it was decided a new type of industry to be created on the premise of the former coke ovens - one that was innovative and rare – **petrurgy** - production of basalt pipes, floor tiles and other products. Basalt products are acid-resistant, among other qualities, so they play an important role in chemical, textile (dyeing works) and certain food factories like breweries and sugar refineries. Their durability and resistance made them an essential and cost-effective choice for these industries, ensuring longevity and efficiency in production. As petrurgy was this tangential and innovative branch of metallurgy, an R&D program was launched, necessitating the construction of a new research and development center. Today, the new administration and R&D center are still standing, but the enterprise closed at the beginning of the 21st century. [9,10]

As mining operations began in the mid-19th century, after a century of extraction, many deposits were depleted. The last one working was Lev mine situated high up in the mountain near Krastets railway station, as can be seen on Fig. 2, site 2. It was not part of the „Badeshtnost" company [9], so it has a different development path. Mining operations continued after World War II, leading to the further development of the miners' village. It was closed at the beginning of the 21st century but most of the buildings are still standing, including miners' dormitories, cantine, administration, and transport facilities near the railway station.

4.2.2. The Railway

The ***railway*** was integral to the region's history. Plachkovtsi was as much defined by its railway heritage as by its identity as a mining town. At the turn of the 20th century, Plachkovtsi found itself at the center of major events of national significance, which unfolded as follows. There was a need for a Trans-Balkan railway. The railway was important for upholding the territorial integrity of Bulgaria after the Unification (1885), but a difficult choice had to be made between three possible routes. One route, located far to the east of Plachkovtsi, followed easy terrain, allowing for quicker and more cost-effective construction. The second proposed option involved a tunnel near Gabrovo, which was strongly supported by Gabrovo's industrialist community. The third and ultimately chosen route crossed the Balkan Mountains near the newly established mines in the Plachkovtsi region. On the one hand, having a railway leading up to the mines meant easier access and granted further development and exploitation of this important resource. On the other hand, the terrain posed significant challenges and constructing a railway included complex engineering work to overcome numerous steep slopes. There were heated debates, but at the end, the miner companies lobby prevailed, and a decision was made for the Trans-Balkan railway to cross the mountains via Tryavna and Plachkovtsi. The line was finished in 1913. [10]

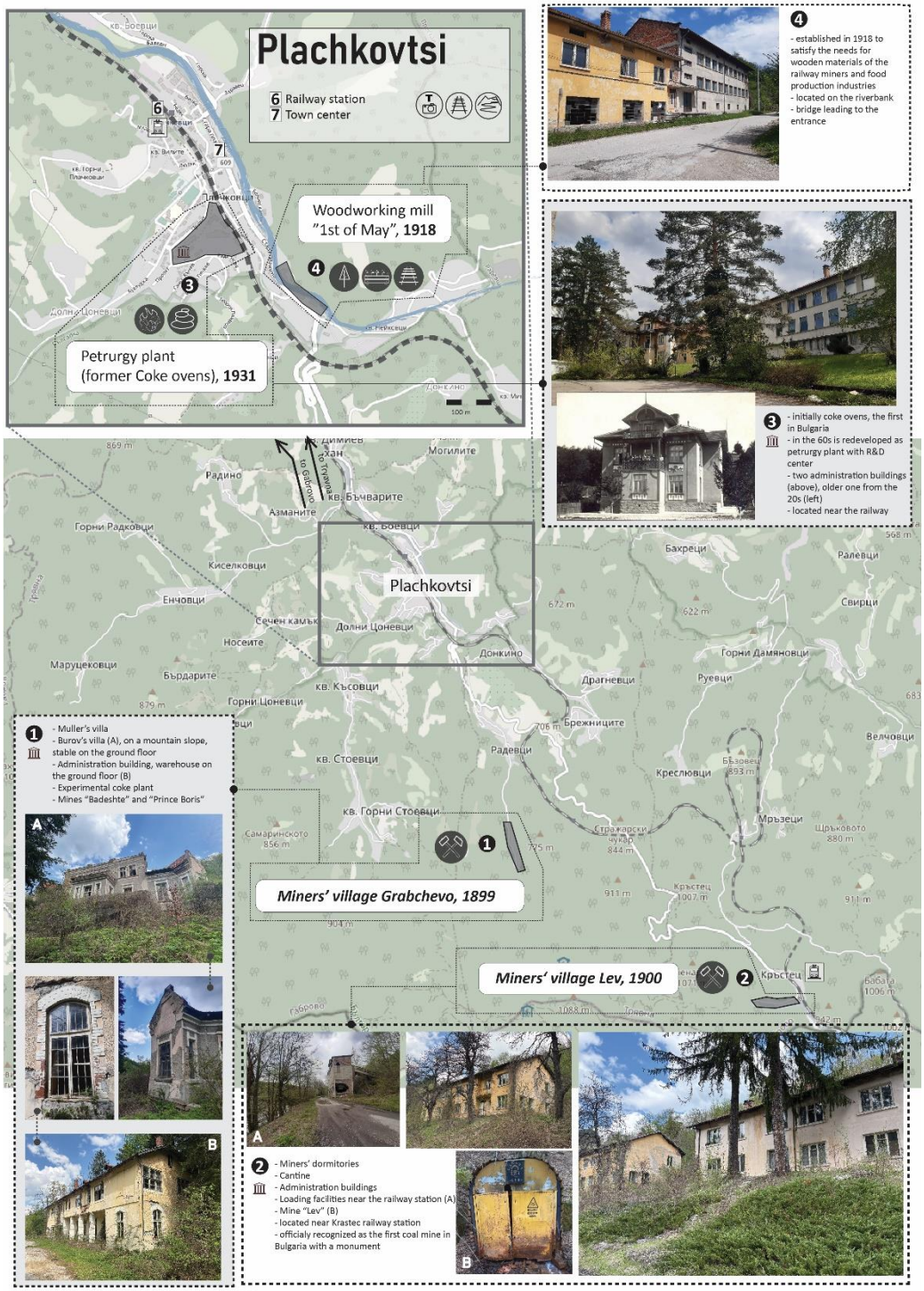


Figure 2. Map of Plachkovtsi territory with industrial sites; source: author's own work, photos - author, archival photo: Plachkovtsi municipality, map: ©Open Street Maps;

The one advantage of the unusual terrain was the creation of a remarkably picturesque route. The train winds its way up steep mountain ridges, navigating countless curves and tunnels that unveil breathtaking views. Today, this route stands as one of the most scenic railways in Bulgaria and a popular tourist attraction. However, it was much more for Plachkovtsi – it gave it access to the Danube, as well as to the southern part of Bulgaria and the small mountain town transformed into a lively center of transportation and mining activity [10]. With railroad workers and miners in need of services and entertainment, a range of new activities emerged. Additionally, the beautiful nature suggested the development of the region as a resort and soon that activity flourished, which resulted in the construction of many hotels and villas, some of which are still used. With the end of mining operations in the beginning of the 21st century, tourism retains its importance in the region.

4.2.3. Woodworking

One additional industrial branch that developed for the needs of the mining and railway industry was **woodworking.** A demand arouse for wood products and wooden building materials – ranging from railway sleepers to structural elements for construction of bridges and tunnels. Additionally, wooden frames were needed to fortify the mineshafts. Furthermore, the manufacturing of crates and barrels, needed for packing of fruit and pulps, became important in the 1930s when Bulgaria was exporting various food products. Wooden material was abundant in the vast Balkan forests, and the problem that laid ahead was its extracting and processing. Three separate wood mills were created in Plachkovtsi and the surrounding villages. The first mill was created in the village of Neykovtsi (now a neighborhood of Plachkovtsi) in 1918 and was called “Progress”. It was a stonewall building. The largest one called „Predela“, was established in Plachkovtsi in 1940 and included a wood mill and a furniture production facility. [9,22] Strategically located along the riverbank, its entrance, accessible via a bridge, lent it a distinctive and picturesque quality that combines functionality with aesthetics. These factories were the foundation on which a wood-processing plant - “1st of May” - was developed in the second half of 20th century. The buildings still exist today, and the plant is operational. The plant location is shown in Fig. 2, site 4.

4.2.4. Industrial heritage in Plachkovtsi: fading national legacy

The last coal mining activities ended nearly 20 years ago. The remaining buildings stand in silence, and despite their historical significance, some have succumbed to neglect. The mountainous terrain, which was a major obstacle 120 years ago, still constrains the adaptive reuse of these structures, as mining villages are located in remote areas - though some lie along mountaineering routes. Almost all of the properties were privatized, and ownership is another obstacle to the process of adaptive reuse. Their history is slowly being forgotten – an art installation at the center of Plachkovtsi focuses on the story of the railway, but not of the mines. A lonely monument up in the mountain, near the Lev mine says that this is the place where the first coal in Bulgaria was being extracted. Today, Plachkovtsi takes pride in its past while steadily evolving into a tourist destination. Miners’ villages of Grabchevo and Lev are still standing, as is the Coke plant (Basalt casting factory). No conservation efforts are known to the author and some of the history is obscured due to the involvement of entrepreneurs and industrialists which were viewed negatively by the socialist state. Local citizens confide with frustration and nostalgia that *“Mines are no more”.* They also proudly share that in the previous years the town has won prizes for the best mountain resort. It is

true that tourist activities are an integral part of Plachkovtsi's identity, but the question of the disappearing industrial heritage remains.

5. DISCUSSION

One objective of this study was to examine how people engage with industrial heritage in their daily lives. The findings highlight the complex relationship between industrial heritage and local perceptions in Tryavna municipality. Some of these sites hold **national significance** - most notably, the first coal mines in Bulgaria - playing a key role in the country's industrial development. Yet, their heritage status remains largely undervalued. Many industrial sites have fallen into neglect, influenced by the broader process of deindustrialization and the shift to privatized ownership; however, other factors also contribute to their fading relevance in contemporary life. These include *the lack of official protective status for the buildings and sites, the absence of established traditions for reinterpreting and preserving industrial heritage, and the absence of a coherent narrative that integrates multiple perspectives.* In some cases, *historical distance* plays a role, as some mines closed in the 1960s, while certain factories shut down only two decades ago. Additionally, a growing emphasis on *tourism as a priority* has led to industrial heritage being overlooked.

For many local communities, *industrial sites are not something to preserve but something to revive*. The focus is often on rebuilding industry, restoring jobs, and ensuring economic stability, with sites seen more as remnants of lost industries rather than historical monuments. At the same time, **nostalgia for industrial labor** [6] persists, shaping how people engage with these sites and influencing attitudes toward their future. Conversely, some locals view industrial heritage as purely historical, treating it as a relic of the past. This view aligns with Smith's Authorized Heritage Discourse [2], which privileges expert-driven narratives that emphasize preservation and monumentality over community-driven interpretations.

These results highlight the tension between nostalgia for lost industries and the practical challenges of preserving historically significant sites, raising questions about the role of industrial heritage in contemporary urban landscapes. The tension aligns with the concept of **dissonant heritage** [1], which emphasizes how heritage can be contested, particularly when different groups assign conflicting meanings to industrial sites. However, as many industrial legacy sites in Tryavna municipality retain their architectural integrity, they present valuable opportunities for adaptive reuse and reintegration into the urban environment. *How should their interpretation evolve to ensure relevance in the present?* While some authors emphasize grassroots perspectives [4], others argue that only external experts can provide interpretations that effectively shape future development strategies [23].

Tryavna's industrial narrative is likely overshadowed by the nearby city of **Gabrovo**, the administrative center of the province. Gabrovo – a much bigger town than Tryavna - is renowned for the entrepreneurial spirit of its citizens and has long been recognized as a historic industrial center. One of the earliest factories in Bulgaria emerged here, gradually expanding the town into a thriving industrial center by the 1930s. Following World War II, the city experienced another major wave of industrialization, particularly in textiles, machine building, and chemicals, with large industrial complexes shaping its economic landscape. Despite economic shifts, Gabrovo continues to embrace its identity as a historic industrial center, maintaining a strong workers' spirit among its population. Industrial heritage is actively

researched, interpreted, and preserved, notably through the local **Industrial Heritage Museum** [24]. While some factories were demolished, others have been protected, refurbished, or repurposed for new uses.

Gabrovo remains recognized as a textile center, but when considering mining heritage, notable Bulgarian examples include Pernik, located near Sofia, and Madan, in the Rhodope Mountains. A summary table, comparing key characteristics of Pernik, Madan and Plachkovtsi is presented in Table 1.

Table 1. Comparison of sites with mining industrial heritage in Bulgaria

	PERNIK	**MADAN and RUDOZEM**	**PLACHKOVTSI and TRYAVNA**
Location	Pernik province	Smolyan province	Gabrovo province
Size	~70 000	Madan ~5000 Rudozem ~3000	Plachkovtsi ~1500 citizens Tryavna ~8000 citizens
Industry type	Brown coal deposits Metallurgy, various industries	Lead-zinc deposits, Flotation factories	Black coal deposits, Coke ovens
Year of establishment	Late 1870s	Late 1920s	Late 1850s
Type of property	Mostly state property, until the beginning of XXI century	Mixed, but state property for most of the time	Mixed - private and state
Heritage status	Some facilities have heritage status; an underground museum is established in the 80s in one of the oldest mines (1891)	An underground museum is established in 2023	None

Pernik is a renowned coal mining and metallurgical center. The discovery of coal shortly after the Liberation spurred the development of various industries, most notably the rise of the metallurgical giant “Steel” (formerly “Lenin”), that is still operational. In the 1980s, in one of the oldest mines (1891), an underground *Museum of Mining* was established, contributing to the town’s evolving identity as a historical industrial center. Pernik has successfully cultivated its industrial heritage through numerous initiatives, including a digital platform [25] that provides extensive information on its industrial history and a map of the mines.

Unlike the mines in Plachkovtsi, which initially operated under private ownership, Pernik’s mines were always state-controlled and developed accordingly. Another factor contributing to Pernik’s greater recognition is the larger size of the town (approximately 70 000 citizens [5]) and its proximity to Sofia, making it more accessible and historically prominent.

Madan (~5000 citizens [11]) is a center for mining activity in the Rhodope Mountains, where lead-zinc deposits have been extracted since the late 1920s. Alongside the nearby town of Rudozem (~3000 citizens [11]), Madan has developed a strong industrial history and a distinct miners' identity, as both towns largely grew around mining operations. Their early 1950s urban design and architecture, set against the mountainous landscape, create a unique and recognizable image. Efforts to preserve the region’s industrial heritage have been ongoing and supported by the local municipalities and the mining companies. Initiative began

in the 1980s, with the establishment of a “Rhodope’s Crystal” hall – a museum of crystals found in the mines. More recent projects include opening of *"Museum of Mining and Ore Extraction"* with artefacts and photographs donated by the biggest mining company of the region and repurposing of a mine shaft – Spoluka – into a tourist attraction and underground museum [26]. However, the continued presence of active mining operations makes it challenging to view some industrial sites as heritage landmarks. The mountainous terrain and the region’s remoteness also pose difficulties for wider heritage recognition. Additionally, while evidence of ancient and medieval activity exists, large-scale resource exploitation only began with the onset of World War II, meaning the historical distance may not yet feel sufficient for some buildings and infrastructure to be perceived as monuments.

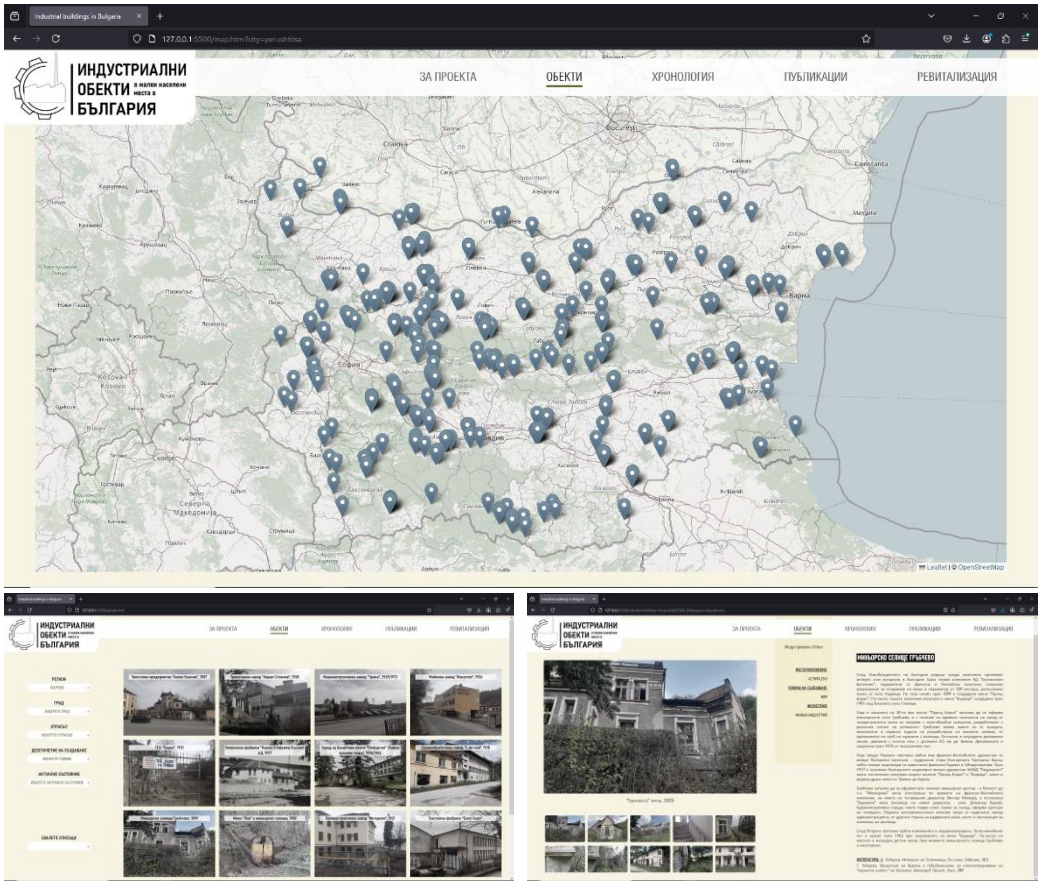


Figure 3. Screenshots from the interactive platform on Bulgaria’s industrial heritage. First: map of Bulgaria with industrial sites. Second: list of industrial sites in Gabrovo region. Third: Information on an individual industrial site (Grabchevo);.Source: author’s own work.

A common challenge across all cases of industrial heritage in small towns is the lack of information and awareness regarding how industrial heritage fits into a broader historical context and what are the possible ways to preserve it - through adaptive reuse, conservation efforts, etc. One initiative to address this issue is the creation of an online database for sharing knowledge on the subject. Such platforms foster collaboration, enabling joint efforts in gathering data on historic industrial sites and exploring strategies for their preservation.

Examples for such platforms include a platform [27] created by Research Centre for Industrial Heritage FA CTU Prague, Czech Republic and a platform [28] created by the civil non-profit organization V.I.D.A. in Greece. Such platforms can also create an invaluable collection of case studies that can be used as a starting point in preliminary research for preservation projects. Based on the ongoing research of the author, a platform on industrial legacy in Bulgaria (Fig.3) is currently under development. The platform seeks to not only gather information but popularize the existing efforts for preserving industrial heritage in Bulgaria [29] and to collect existing Bulgarian works on adaptive reuse approaches [30,31,32].

For Bulgaria, case study research from the broader region is also relevant and applicable. Researching the successful restoration of Senjski rudnik [33,34], the difficult divisive debate and civic initiatives around Petrila's industrial heritage [35] and the rebranding of Lavrion's mines [36,37] can serve as a starting point for creating sustainable restoration plan and for deeper understanding of the conflict surrounding the contemporary industrial heritage debate.

6. CONCLUSION

This paper aimed to examine the industrial heritage in Tryavna region by placing it against the broader context of the town's historical development and the industrial development of the state. It highlights the complexities surrounding industrial heritage, revealing how factors such as privatization, deindustrialization, and historical distance shape public perceptions. While some communities in Bulgaria actively reinterpret these sites through adaptive reuse and preservation initiatives, others struggle to recognize them as heritage landmarks. Comparative analysis underscores the role of town size, local initiatives, policy support, ownership and accessibility in shaping the future of industrial heritage. Efforts to bridge knowledge gaps, such as industrial heritage platforms, demonstrate the potential of digital resources in fostering collaboration. Ultimately, fostering awareness and integrating industrial heritage into urban and cultural narratives can ensure these sites remain a meaningful part of contemporary life.

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Review paper

EXPERIENCES AND LESSONS LEARNED IN THE IMPLEMENTATION OF THE SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION – 10 YEARS SINCE ADOPTION

Ana Stojanovic[1], Dejan Vasovic[2]

Abstract

On March 18, 2015, the Member States of the United Nations (UN) adopted the Sendai Framework for Disaster Risk Reduction 2015–2030 in Sendai, Japan. As the first major global agreement of the post-2015 development agenda, the Sendai Framework provides a comprehensive set of principles, strategic priorities, and actionable measures designed to guide national and local efforts toward reducing disaster risks and enhancing disaster preparedness. It aims not only to mitigate the direct impacts of hazards but also to safeguard developmental gains, promote sustainability, and protect human lives and livelihoods from both existing and emerging risks. A key aspect of the Sendai Framework is its emphasis on building disaster-resilient communities and systems, particularly in urban settings where vulnerability is often strengthen by rapid population growth, aging infrastructure, and socio-economic inequalities. Resilience, in this context, refers to the capacity of individuals, communities, institutions, and infrastructure systems to anticipate, withstand, adapt to, and recover from the adverse effects of disasters. Enhancing resilience requires an integrated, multi-sectoral approach that aligns risk reduction strategies with sustainable development and climate adaptation efforts. This paper aims to critically examine the current status, progress, and challenges associated with the implementation of the Sendai Framework across diverse national contexts, ten years after its adoption. Particular emphasis is placed on Priority for Action D, which focuses on the substantial reduction of disaster-related damage to critical infrastructure and the minimization of disruption to essential services. These services including health care, education, water and electricity supply, sanitation, and transportation serve as the backbone of societal functioning and play a vital role in enabling swift recovery and continuity during and after disaster events. The resilience of such infrastructure is, therefore, a determining factor in the overall ability of communities to absorb shocks and maintain essential services, particularly in times of crisis. The paper further explores the extent to which countries have operationalized this priority and identifies emerging practices and policy innovations that contribute to enhanced systemic resilience.

Key words: *Sendai Framework, Disaster Risk Reduction, Resilience, Critical Infrastructure*

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1. INTRODUCTION

Disaster Risk Reduction (DRR) represents one of the key challenges of contemporary society, particularly in light of the increasing frequency and severity of both natural and anthropogenic hazards. Over the past few decades, the international community has developed a range of strategies and frameworks aimed at enhancing community resilience to various risks. However, despite clear guidelines and growing awareness of the importance of DRR, the number of recorded disasters has increased nearly fivefold over the past fifty years [1]. These trends indicate that risks continue to escalate globally, while people, their property, and critical infrastructure remain increasingly vulnerable and exposed to their impacts [2].

Over the past thirty years, the international community has established a number of key normative documents that form the foundation for action in the field of DRR. The first major milestone was reached in 1994 with the adoption of the Yokohama Strategy and Plan of Action for a Safer World, which laid out fundamental principles for building community resilience [3]. Building on this foundation, the Hyogo Framework for Action 2005–2015 marked a significant step forward by defining concrete priorities, including the institutional strengthening of DRR capacities and the integration of risk management into development policies [4]. A pivotal moment in the evolution of the international DRR approach occurred during the Third United Nations World Conference on Disaster Risk Reduction, with the adoption of the Sendai Framework for Disaster Risk Reduction 2015–2030 [5]. Unlike the Yokohama Strategy and the Hyogo Framework, the Sendai Framework introduces measurable targets (e.g., percentage reduction in losses) and shifts the focus from disaster management to risk management. It also places greater emphasis on resilient systems and proactive prevention, while recognizing the human, social, and economic dimensions of risk.

In parallel with the development of specific DRR frameworks, the international community has also adopted a series of broader global documents that incorporate disaster risk reduction as a key component of sustainable development and climate resilience. With the adoption of the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs) in 2015, DRR was recognized as a prerequisite for achieving multiple goals, including the eradication of poverty (SDG 1), the development of sustainable cities (SDG 11), climate action (SDG 13), and the strengthening of institutions and capacities for crisis response (SDG 16) [6]. That same year, the Paris Agreement on Climate Change placed additional emphasis on adaptation and resilience, highlighting the importance of anticipatory approaches to climate-related risks [7]. Furthermore, the New Urban Agenda, adopted in 2016 at the Habitat III Conference, promotes the integration of DRR into urban development planning through strengthened infrastructure, participatory risk governance, and the reduction of vulnerabilities in urban areas [8]. These documents, together with the Sendai Framework, constitute a normative foundation for synergistic action at the global, national, and local levels.

In light of the tenth anniversary of the adoption of the Sendai Framework, now regarded as the most important global framework in the field of DRR, it is essential to assess the extent to which the aforementioned international and national strategies have contributed to reducing damage and losses, particularly in relation to critical infrastructure. At the same time, there is a growing need to identify the obstacles that have hindered more effective implementation, as well as to extract lessons learned that can inform the next phase of global efforts.

This paper aims to provide an overview of the experiences gained thus far in the implementation of the Sendai Framework, with a particular focus on the achievement of Target D, through the analysis of available documents, reports, and examples of good practice. The focus is placed on identifying key challenges and opportunities for strengthening the resilience of critical systems, as well as exploring potential pathways for enhancing global and local cooperation in the coming period.

2. METODOLOGY

For the purposes of this study, a qualitative content analysis was conducted on key international documents related to DRR, with a particular focus on the Sendai Framework for Disaster Risk Reduction 2015–2030. This approach enables a deeper understanding of the normative and implementation aspects of global DRR policies through the systematic interpretation of document content [9].

The analysis included primary sources, such as reports and databases of the United Nations Office for Disaster Risk Reduction (UNDRR), as well as secondary sources, such as relevant academic literature, evaluation reports, thematic analyses, and official statistical data at both global and national levels. Special attention was given to the implementation of Target D of the Sendai Framework, which focuses on reducing damage to critical infrastructure and minimizing disruption to essential services such as health, education, water supply, and electricity.

The criteria for analysis included explicit references to Target D, identification of barriers and challenges in its implementation, documented examples of good practice and availability of quantitative data enabling comparison across different national and regional contexts.

The analytical framework was based on thematic analysis [10], which allowed for the identification and categorization of key themes and patterns within the collected documentation. This approach makes it possible to observe broader trends in the implementation of the Sendai Framework, as well as specific regional differences.

The results of the analysis are presented in the following section, structured around key obstacles and examples of good practice in the implementation of the Sendai Framework, with an emphasis on progress toward achieving Target D.

3. RESULTS AND DISCUSSION

According to official data from the UNDRR monitoring system on the implementation of the Sendai Framework, published in October 2024, a total of 163 countries, representing approximately 84% of all United Nations Member States, have submitted national progress reports on the implementation of the Sendai Framework's objectives [11].

However, despite the growing number of reports and formal national strategies, countries working on the implementation of the Sendai Framework face a range of structural and systemic barriers that significantly limit the effectiveness of implementation. Based on the analysis of reports, evaluations, and available literature, several key challenges have been identified, which are recurring across different geographical and institutional contexts.

The main challenges in the implementation of the Sendai Framework are as follows:

1. Insufficient political commitment and weak coordination among levels of government often hinder the effective implementation of DRR strategies. While many countries adopt formal strategies, political will for their implementation varies. Moreover, the lack of alignment between national, regional, and local institutions results in a fragmented approach that diminishes the effectiveness of measures [12].
2. Limited financial resources – the lack of funding is one of the most serious challenges, particularly in low- and middle-income countries. Instead of investing in prevention and risk reduction, budgets are still predominantly focused on emergency response and post-disaster recovery. This imbalance further exacerbates long-term vulnerability [13].
3. Lack of data and knowledge on risks – effective risk management requires reliable, up-to-date, and spatially disaggregated data. In many regions, both basic data and the capacity to analyze them are lacking, making it impossible to plan and prioritize interventions accurately [12].
4. Inadequate integration into development planning – DRR is often viewed as an isolated activity rather than as an integral part of the development agenda. Consequently, plans for urban development, infrastructure, and land use rarely include resilience elements, missing the opportunity for long-term prevention and adaptation [8, 12, 14].
5. Capacity limitations – many local governments, especially in rural and less developed areas, lack sufficient technical and institutional capacities to implement DRR measures. Additionally, community-level capacity-building programs are often underdeveloped or neglected [15, 16].
6. Weak engagement of the private sector – although the private sector can play a key role in building resilient infrastructure, its involvement in DRR strategies is often limited and unstrategic. The lack of regulatory incentives and partnerships between the public and private sectors further reduces the scope of collaboration [17, 18].
7. Climate change and emerging risks – the increasingly severe consequences of climate change, such as extreme weather events, droughts, and floods, complicate risk management. Additionally, new forms of risk, such as pandemics and cyber threats, were insufficiently addressed in the initial Sendai Framework, necessitating its update and expansion [19, 20].
8. Underdeveloped monitoring and accountability systems – countries face challenges in reporting on Sendai Framework indicators due to weak monitoring and evaluation systems. Responsibility for DRR outcomes is often dispersed among various stakeholders, making it difficult to identify weak points and respond in a timely manner [21, 22].

Although the challenges mentioned above pertain to the implementation of the Sendai Framework as a whole, their cumulative impact is particularly evident in the context of Target D. Protecting critical infrastructure and ensuring the continuity of essential services require a high level of coordination, capacity, funding, and data, all of which, as the analysis has shown, are often limited or fragmented. Therefore, the achievement of Target D can be seen as a mirror of the overall system's ability to shift from a reactive to an anticipatory risk management model.

The degree of achievement of Target D of the Sendai Framework varies significantly among countries and regions, but a common denominator remains the high level of exposure

and vulnerability of critical infrastructure to the consequences of disasters. According to data from UNDRR published in 2024, between 2015 and 2023, an average of more than 94,000 damaged critical infrastructure assets were recorded annually, while over 1.6 million disruptions in the provision of essential services, including healthcare, education, water supply, and electricity, were documented [23]. The most affected are low- and middle-income countries, particularly those classified as least developed countries and landlocked states, where institutional and technical capacities for prevention remain limited.

The analysis of national reports shows that the challenges in achieving Target D are multilayered and deeply rooted in the broader context of risk management systems. The most commonly identified barriers include insufficient integration of DRR principles into spatial and infrastructure planning, outdated or non-resilient buildings, lack of investment in preventive measures such as seismic reinforcement, early detection systems, and decentralized energy sources, as well as weak coordination among sectors responsible for infrastructure and risk management [24].

Despite these challenges, there are examples of countries that have made visible progress in infrastructure protection. Notably, Japan stands out, having developed robust technical standards, pre-defined protocols, and continuous investment in prevention based on lessons learned from past disasters. As a result of these measures, Japan experiences a relatively low number of disruptions in the provision of essential services, even during major natural disasters, making it a model of good practice in achieving Target D [25].

These global trends find both parallels and contrasts in the regional context of the Western Balkans, where DRR efforts are still evolving. In recent years, Serbia has made significant progress in aligning its disaster risk reduction strategies with international frameworks, particularly the Sendai Framework for Disaster Risk Reduction 2015–2030. The adoption of the Law on Disaster Risk Reduction and Emergency Management marked a key step toward institutionalizing DRR at the national level [26]. This legal framework introduced obligations for local-level risk assessment and planning, as well as mechanisms for cross-sectoral coordination and the inclusion of vulnerable groups in risk governance processes.

One of the critical challenges facing Serbia's DRR and emergency management system is the fragmentation of its institutional framework and procedures, along with limited capacities at both central and local levels [27]. As a result, practical implementation remains uneven, with substantial differences in technical capacity, financial resources, and access to up-to-date risk data. While some local authorities have developed DRR action plans and early warning systems, others continue to operate with outdated emergency protocols and limited integration of climate risks into development planning. Additional challenges include insufficient investment in the resilience of critical infrastructure and gaps in monitoring and evaluation mechanisms for DRR targets, particularly Target D.

In the broader context of the Western Balkans, DRR remains a growing priority, but countries vary considerably in terms of institutional maturity and political coherence. Countries such as North Macedonia, Montenegro, and Albania have also adopted DRR strategies aligned with the Sendai Framework, often with support from European Union projects and regional initiatives, such as the Disaster Preparedness and Prevention Initiative for South Eastern Europe (DPPI-SEE) [28]. However, regional cooperation is still limited, and the exchange of good practices tends to be informal and project-based rather than institutionalized.

Compared to broader European and global DRR trends [29], Western Balkan countries are largely in a transitional phase, shifting from a reactive to a more preventive and risk-informed approach. Although policy-level alignment with the Sendai Framework is evident, full implementation, particularly in areas such as infrastructure protection, community resilience, and data transparency, remains under development. Unlike many EU Member States, countries in the Western Balkans often lack the financial and technical resources needed for the consistent operationalization of DRR goals.

Therefore, incorporating the regional context into DRR assessments is essential for understanding both the progress and the existing gaps in the implementation of Target D. It also highlights the need for stronger regional cooperation, capacity building, and sustainable investment in critical systems to ensure that national efforts are not only aligned with global strategies, but also adaptable to local realities.

4. CONCLUSION

A decade after the adoption of the Sendai Framework for Disaster Risk Reduction 2015–2030, the achievement of its targets particularly Target D remains a significant global challenge. Evidence indicates that, despite increasing formal commitments and the integration of DRR principles into policy discourse, the practical implementation of measures aimed at safeguarding critical infrastructure and ensuring the continuity of essential services continues to be impeded by a range of systemic obstacles. These include institutional fragmentation, inadequate financial and technical resources, and limited risk-informed planning. As a result, many countries continue to report substantial damage to infrastructure systems and recurring disruptions in service delivery during disaster events, which, in turn, prolong recovery periods and amplify the long-term vulnerability and exposure of affected communities.

In the context of the Republic of Serbia, notable progress has been achieved in terms of regulatory development and the establishment of institutional frameworks. However, the national approach to critical infrastructure protection remains largely fragmented. Preventive investment remains insufficient, and inter-institutional coordination mechanisms are underdeveloped, limiting the effectiveness of DRR initiatives.

This issue acquires additional significance in light of Serbia's ongoing European integration process. Strengthening the resilience of infrastructure systems and harmonizing national policies with EU DRR standards is increasingly recognized as a vital component of the EU accession agenda. In particular, this agenda is reflected in Cluster 4 – Green Agenda and Sustainable Connectivity, which encompasses key policy areas such as energy, environmental protection, and climate change mitigation. Within this context, Target D of the Sendai Framework assumes heightened strategic relevance, functioning as a vital linkage between Serbia’s international obligations and its European aspirations. It also presents an opportunity to advance policy and institutional reforms that simultaneously contribute to enhanced societal security, systemic resilience, and sustainable development.

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Preliminary report

THE MINERAL BATH BUILDING IN BANKYA - SYNTHESIS OF ARTS AND PRESERVATION OF ARCHITECTURAL HERITAGE

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Abstract

One of the architectural jewels of the 20th century in Bulgaria - the Mineral Bath in Bankya - is located in the immediate vicinity of Sofia. It was designed by the Bavarian architect Karl (Carl) Hocheder and opened for visitors in 1911. The architect's overall intention to merge the function of a spa, equipped with the most modern technical facilities of its time, and to achieve a unique aesthetic consonance of artistic and architectural ingredients, ranked the building among the first of its type in terms of beauty and facilities in Europe. The study examines in parallel the historical background to the origin and functioning of the Mineral Bath in Bankya, the synthesis of artistic and architectural elements with the functional qualities and the social significance of the building. The focus of the study is on the ceramic wall coverings, in which hand-painted tiles are applied, the floor coverings with decorative ornaments and the sculptural layouts that give the building its unique character. Comparative art analysis is used to clarify the reception of the European influences. The subject matter is particularly relevant given the restoration of the building in the period 2018-2022. The Mineral Bath in Bankya won the Grand Prize in the Bulgarian Architecture Awards 2022 competition and is a current example of a comprehensive restoration of an important site for the preservation of Bulgaria's architectural heritage. For this part, the methods of conservation research, adaptation and transformation of the spaces were used in order to preserve its functions and to bring it into line with contemporary trends for "Sanus Per Aquam" and Wellness. The topic's popularization is linked to the revival of many valuable buildings of similar purpose in Sofia, such as the Central Mineral Bath, the Bath in Gorna Banya, the Bath in Ovcha Kupel, the Bath in Knyazhevo and many others, which are about to regain their splendour through the implementation of urgent and vital restoration works.

Key words: *preservation of the architectural heritage, synthesis between architecture and the arts, spa and wellness*

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1. INTRODUCTION

At the dawn of the 20th century, the Bavarian architect prof. Karl (Carl) Hocheder (1854-1917) designed the public baths in Munich (Müller'sche Volksbad, Germany, 1901) [1], which became the model for bathing establishments after 1900, in Sibiu (Baia Populară Sibiu, Romania, 1904) [2] and Bankya (Mineral Bath in Bankya, 1907, Bulgaria) [3]. The public baths were built in the Art Nouveau style and were inspired by the ancient themed baths of the Roman Empire, the lavish Baroque buildings of Europe and oriental hammams with a unique architectural synthesis.

The design of Hocheder's first bath, the Müller'sche Volksbad, was the result of a donation by the Munich engineer Karl Müller to the city of Munich with the stipulation that a bath be built for the poor (Standl, 2001). With its architecture and interior, the Volksbad became one of the most beautiful buildings with this purpose in Europe. In terms of its architectural structure, the Baia Populară Sibiu is almost a verbatim copy of the Müller'sche Volksbad in Munich.

The method of empirical work is used - description and analysis of architecture and synthesis with fine art as the leading one. The principles of observation of synergy, architecture and art, were introduced as part of the elements of the method due to the nature of the period. Synergy refers to the analysis of the architectural plan in terms of the purpose of the building and the placement of the artistic decoration within it. The analysis and the applied method with its elements were attributed to its restoration due to its status as a cultural monument. It is a mandatory part of the principle of the general methodology in the evaluation of the building.

2. THE BATHS OF KARL HOCHEDER

The three baths were designed by Hocheder with one male and one female pool, as a result of the gender segregation that was common in early 20th century society. Unlike the baths in Munich and Sibiu, which were designed with a smaller female pool, the Bath in Bankya has two symmetrical pools that are also separated by gender but are equal in area. The pools are structurally arranged in symmetry along the central axis of the building. They include areas with wooden cabins and showers that provide direct access to the bathing area.

In times when personal hygiene is difficult to maintain in people's homes, the bathhouses designed by Karl Hocheder are public buildings equipped with modern bathing facilities. Their public role is a significant one and is rightly awarded with due architectural attention, through an imposing appearance inside and out. The construction of the Müller'sche Volksbad in Munich is a noteworthy fact in the architectural and social traditions of Western Europe, but we should pay particular attention to the appearance of similar buildings in the modern developing part of Eastern Europe and, in particular, in young countries such as Bulgaria and Romania, which for several decades have won their independence from the Ottoman Empire.

The interiors and exteriors of the three buildings contain characteristic sculptural Art Nouveau and Baroque elements, inspired by flora and fauna, combined with ceramic tiles and colourful floor mosaics that give a sacred feel to the architectural spaces. Visually, the functions of Karl Hocheder's three baths are emphasised by a common stylised sculptural element - the shell, which is associated with the water, but can also be seen as a reference to the art work of the great Florentine painter Sandro Botticelli (1445-1510), "The Birth of

Venus from the Sea Foam", a symbol of love, birth and the energy with which the healing water charges the bathers. The common feature of the three buildings is undoubtedly the richly decoration of the facades and interiors, inspired by different historical periods. The bathe rooms' interiors are characterised by wide staircases, columns, high ceilings, round arches, domes, exquisite railings and artistically designed windows.

The Bath in Bankya is the most magnificent of Hocheder's three creations. It has not been clarified how the project was commissioned in the small village near Sofia. For now, we can only assume the intervention of the Bulgarian king Ferdinand von Sachsen-Coburg-Gotha (1861-1918), who maintained active relations with Western Europe and Germany in particular.

Hocheder was not among the popular architects in Bulgaria, in contrast the builder of the Bath arch. Nikola Neshov[4] (1869-1928). It is significant that only one year after the completing the construction, the settlement became famous and its mineral waters, thanks to the Bath, became especially appreciated. According to the Illustrated Pocket Guide of 1912, the spa village of Bankya was defined as the Bulgarian "Karlsbad", after the popular spa town in West Bohemia in the 19th century. At that time, it was 15 km north-west of Sofia in the publication we read: "The Baths are particularly curative for a certain kind of illness, which is why the village - a few years ago, a pile of dirty, half-collapsed houses, is today the most beautiful resort, on the settlement of which the state has spent nearly two million leva. Instead of the half-collapsed bathhouse, today there is a magnificent monumental building, surrounded on all sides by splendid villas and hotels. In summer there are many visitors, and therefore it is impossible to make a great pleasure with little money."[4]

3. WHO WAS THE ARCHITECT KARL HOCHEDER (1854-1917)

Karl Hocheder (Fig.1) was born in Weihammer near Weiden in the Upper Pfalz. He studied architecture at the Technical University of Munich from 1874 to 1878 under Gottfried von Neureuther (1811-1887) and graduated in 1881. Together with Theodor Fischer (1862-1938), Gabriel von Seidl (1848-1913), and Hans Grassel (1860-1939), they shaped Munich's cityscape in the early 20th century. Its distinctive architectural style became known as “Munich Baroque” (also known as “Hocheder Baroque”, which united Neo-Baroque and Art Nouveau) [5].

His field is social orientation in architecture. From 1886 he worked at the Office of Spatial Planning in Munich, in 1889 he became a municipal building official and designed schools, a hospital and a church [6]. From 1898 he was a professor at the Technical University of Munich, and in 1901 he designed the Müller’s Public Baths (Müller'sche Volksbad) (Fig.2-3).

[4] Nikola Neshov is known as the head of the construction of the bathhouse in Varshets in 1930 and the design of the bathhouse in Vidin.



Figure 1. Architect Karl Hocheder [7]





Figure 2. Müller's Public Baths (Müller'sches Volksbad). Perspective. [8]
Figure 3. A watercolour drawing of the Müller'sche Volksbad. [9]

4. THE SYNTHESIS BETWEEN ARCHITECTURE AND THE ARTS

Research on the Bath in Bankya is scarce. Primarily, they are related to the natural features, the healing properties of water, medicine and health restoration [10].

In 2010, when the Bath was already in a bad state on the initiative of arch. Lyubinka Stoilova, a Jubilee exhibition was organized in the park in the front of the Bath, which introduces the history of the resort of Bankya, the personality and work of the architect and the builder. The aim of the exhibition is to promote the cultural heritage at risk. [11]

After the successful restoration in 2018-2022, the synthesis between architecture and arts can be analysed, as all details have been restored.

The architect's decision to best express the ideas of the time about European public architecture for healing and restorative purposes is significant. The Bath in Bankya is a symmetrical building in which the two wings with pools are arranged in a semi-arc around the main foyer. (Fig. 4) A similar planning scheme (with a central axial solution) has the Central Mineral Bath of Sofia, which was designed by the architects Petko Momchilov (1864-1923) and Yordan Milanov (1967-1932) in 1913. The Bath designed by them is now transformed for the Historical Museum and due to the change of use has lost the elements of the authentic author's solution of the interiors. The façade is decorated in Neo-Byzantine style, which is an expression of the national romanticism in the architecture of the first decade of the 20th century.

The Bath in Bankya has all the advantages of a fully preserved authentic decoration. In terms of European trends in architecture, and because it was designed by a foreigner, it has the imposing quality of a synthesis of Neo-Classicism with finely presented baroque details and non-intrusively hinted elements of Secession. The combination of different materials, such as marble for the floor layout, stucco for the architectural artistic decoration, wood for the framing of the wooden partitions and rich ceramic finishes, is carried out in a measured colourful unity. The arched Neo-Baroque pediment of the portico in the front of the entrance is resolved with Ionic capitals set at a 45º angle. Its stucco decoration consists of shells which enhance the impression of the also shell-like central window opening. The protruding fronts of the facades of the two wings complement the impression of Baroque architecture without dominating it.

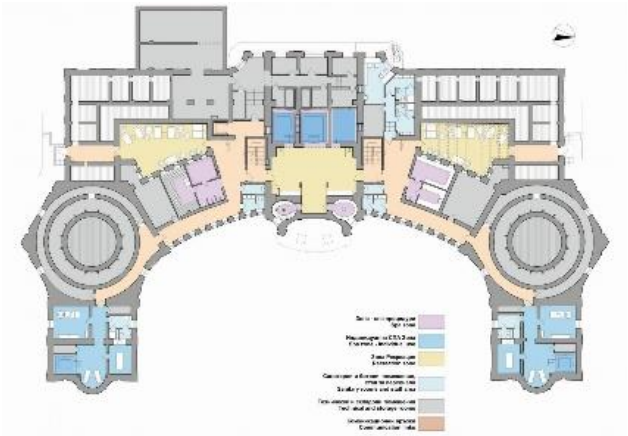


Figure 4. Plan of the Bath in Bankya. Basement. [12]

In the modest solution of the façade layout, the decoration in the interiors is developed to a considerable extent. The use of gilding to frame the stucco decoration in the foyer is impressive. The lavish ornamentation in the basins and its detailed precision is evident in the shaping of the ceilings with moulded coffers and the exquisite balustrades with intricately profiled balusters. The wooden obituaries also impress with their high artistic value. Wooden panelling, wooden partition elements made of Slavonian oak, sculpturally shaped with ornaments characteristic for the whole building are used. The materials for the interior design, including the glass bricks, were sourced specifically for the Bath from Belgium, France and Vienna. All basins and baths are lined with Italian marble and terracotta [3].

5. AESTHETIC ANALYSIS OF THE INTERIOR OF BATHROOMS

In September 2020, professors and students from the USEA “L. Karavelov” met with part of the team of the Bankya Bathhouse Restoration Project and had the opportunity to get acquainted with the site before it was put into operation. The aesthetic analysis of the interior of the bathing rooms in the Bath was made thanks to the photographic material documented during the site visit.

During the visit, architect Chavdar Georgiev shared interesting facts and details from the history of the Bath and the specifics of Karl Hocheder’s architectural solution, partially presented in his publication in the architectural magazine “Gradat” [12]. He defines the

spaces around the two round pools as a remarkable architectural solution: in plan they represent a hexagon with separate niches with showers and sinks.

Special attention here deserves to be paid to the domes above them, airy and lightened by openwork cassettes, which become smaller in proportion to the closure of the dome. On the second level, it is worth noting the gallery with a marble parapet with balustrades, as well as the round windows, which have an elegant elliptical inner opening, following the round shape of the dome. We pay special attention to the plastic design of the dome spaces, since they are in the zone of the dominant perspective of the bathers in the pool and are accordingly developed in precise architectural details. (Fig.5).

In separate areas of the first floor foyers, the richly ornamented floor coverings with predominant floral and geometric motifs have been preserved. The terracotta pattern is composed mainly of stylized flowers and leaves in pleasant combinations of ochre, orange and turquoise. The appropriately selected light shades of the tiles are characterized by a non-dominant presence and fit delicately into the interior (Fig.6). The floor coverings around the pools are consciously developed in simpler solutions of hexagonal tiles (honeycomb type), which are in unison with the hexagonal shape of the room and are coloured in the warm and saturated range of brown. In this way, the sky-earth-water zones are spatially highlighted. Overall, a colourful effect of contrast with the light and dark blue tiles lining the walls and pools has been achieved. Here, we should note the white accents of the wall plaster ornaments and the balustrades in the upper register of the room, the white faience of the sinks and the white marble, which contrast with the prevailing colours in the interior and create the much-needed air space in the bathrooms. In the decorative-plastic decoration of the halls, the symbol of the bathroom visually dominates – the shell, with which the niches of the sinks and showers are vaulted (Fig.7-8).



Figure 5. The plastic design of the dome spaces (personal photo archive).
Figure 6. The ornamented floor coverings (personal photo archive).

Each of the sections (male and female) had 10 bathtubs. Two of them were designed as individual bathtubs, which were called "royal bathtubs" and were intended for members of the family of King Ferdinand, who was one of the regular visitors to the Bath. We will pay more detailed attention to the floor and wall ceramic tiles in the royal compartments, since they are individual interior solutions and probably express the personal preferences of the royal family (Fig.9-10).



Figure 7. View from the pool room (personal photo archive).
Figure 8. The shell, symbol of the Bath (personal photo archive).



Figure 9. The queen's bathtub (personal photo archive).
Figure 10. The bathtub of the king (personal photo archive).

The queen's bathtub has a slope for leaning on the left and is covered with white faience. It is decorated in its upper part with a row of cobalt blue square tiles, and at the bottom it is lined with white relief tiles, probably for security reasons. It is accessed by two steps and is framed by brass railings. The floor in the room is decorated with white and cobalt blue terracotta, arranged in a geometric motif. The walls are lined with cream tiles. The king's bathtub is more richly decorated. It has a slope for leaning on the right and is covered with light blue (Zöllingblau) faience. Its decoration consists of a row of white-green-red square tiles at the top, which symbolize the Bulgarian flag. It is also accessed by two steps and is framed by brass railings, but there are no relief tiles at the bottom. The floor in the room is covered with light cream and light blue terracotta tiles arranged in a geometric pattern. The walls are lined with white tiles.



Figure 11. The hand-painted tile 1 (personal photo archive).
Figure 12. The hand-painted tile 2 (personal photo archive).
Figure 13. The hand-painted tile 3 (personal photo archive).

Perhaps the most interesting part of the wall decoration here are the hand-painted tiles, applied to the white background (Fig.11-13). They represent figurative compositions with marine elements. In the foreground are depicted bathing sea deities, some of which are characterized by hairstyles from ancient Greek vase painting, but with regard to the bodies, more anatomical plasticity is used. In the background is depicted the sea, with flashes of light and sea vessels sailing in the distance. The tiles are colourfully designed in several colours - light and dark blue, black, cream and white. In their plots and style, the signs of the modern Secession style for the beginning of the century are clearly visible, which was often used in the decoration of ceramic interiors and was probably preferred by King Ferdinand and his family.

6. CONSERVATION AND RESTORATION ACTIVITIES

The conservation and restoration activities of the Mineral Bath building in Bankya are an emblematic example of the preservation and adaptation of the cultural heritage in Bulgaria.

The restoration of the bath was necessitated by the advanced process of physical and aesthetic deterioration, resulting from prolonged abandonment and lack of maintenance, despite its status as a national treasure [13]. After years of disuse, the building faced serious risks as moisture infiltration, destruction of decorative and structural elements, corrosion of metal parts, partial collapse of the roof structure, and compromised domes. All this threatens not only its authenticity and artistic value, but also its integrity as a cultural monument. The emerging danger of irreversible losses called for urgent conservation and restoration measures to prevent the complete destruction of the building.

The main damages included:

- Structural deformations caused by moisture and lack of maintenance, leading to cracks in masonry and corrosion of metal elements [14].
- Degradation of the decorative elements: disintegration of ceramic tiles, wooden partitions, and dormer windows [12].
- Functional obsolescence, inconsistent with contemporary hygiene and safety standards [12].

The risks to the site included the irreversible loss of authentic details and potential collapse of load-bearing structures, necessitating immediate conservation efforts.

6.1. Changes and Adaptations

The architectural design retains the main function of the site as a spa, but introduces key interventions. During the restoration process, a complete adaptation of the building to contemporary operational requirements was carried out, while simultaneously preserving its historical identity. In various parts of the Bath, the following changes were implemented:

- Restoration of the main functional areas, maintaining the original spatial organization.
- Introduction of new technical systems (heating, ventilation, electrical installations) to meet current safety and comfort standards.
- Some rooms were repurposed for new functions, while preserving the character of the interiors.
- New interventions were implemented in a manner that ensures they are maximally reversible and distinguishable, in accordance with the contemporary principles of cultural heritage preservation.

Traditional techniques and materials, aligned with the building's original structure, were used during the restoration. Special attention was given to preserving the interior (flooring and wall decorations).

Technological adaptations included the integration of underfloor heating using the polymer additive ADIPLAST to prevent cracking, and the modernization of waterproofing systems in wet zones (pools, jacuzzis) [15].

The balance between authenticity and functionality was achieved by preserving the original façade decoration and the symmetrical floor plan composition, as well as through the use of reversible conservation techniques allowing for future interventions [12].

6.2. Modern Materials and Techniques for Conservation and Restoration

In the restoration process, modern conservation and restoration techniques were applied, including cleaning and stabilizing original surfaces with gentle agents and mechanical means, injecting special solutions to reinforce masonry and prevent further degradation, and restoring decorative elements through manual crafting based on authentic models [16].

- For the restoration of façades and decorative elements, materials as close as possible to the originals were used - natural stone, ceramics, and lime plasters.
- In areas where the original materials could not provide the necessary durability (e.g., waterproofing or foundations), modern products were selected for their compatibility with the historical fabric and their ability not to cause harmful reactions.

The compatibility of the new materials with the originals was carefully analysed through laboratory tests and consultations with restoration specialists. The introduction of vapor-permeable and water-repellent materials, such as the two-component elastic cement waterproofing AQUAMAT-ELASTIC and the grouting compound MULTIFILL SMALTO, ensured protection against moisture and long-term durability, particularly in wet areas (pools, baths, jacuzzis). The use of injection solutions for the conservation of damaged areas allowed stabilization of the original structure without replacing it with new elements.

The choice of modern materials was driven by the need for long-term durability and compatibility with the original structure, avoiding excessive intervention. In some cases, due

to the impossibility of finding identical materials or the requirements of modern operational standards (e.g., waterproofing and thermal insulation), modern materials were used that are not fully identical to historical ones but were carefully selected so as not to compromise the visual and physical integrity of the building [16].

Conservation techniques involved:

- Mechanical cleaning of façades using the agent CL–CLEAN based on formic acid for the precise restoration of details [15].
- Structural reinforcement of load-bearing walls with minimal intervention in the original masonry [12].

Table 1. Used materials

Type of Material	**Example**	**Purpose**	**Compatibility with Original**
Traditional	Wooden partitions, dormer windows	Restoration of authentic elements	Full
Modern hybrid	AQUAMAT-ELASTIC (waterproofing)	Protection against moisture	Vapor permeability similar to cement
Innovative	ALTO (grouting compound)	Zero absorption in wet areas	Visual integration into the historical context

The use of two-component cement systems was motivated by the lack of adequate historical analogues for resilience to modern loads [15].

6.3. Unforeseen Challenges

Among the main unforeseen difficulties encountered during implementation were:

- The discovery of hidden structural defects in the foundations and walls, which were not visible during preliminary investigations.
- Unexpected complications related to moisture infiltration in certain areas, requiring additional drainage and insulation measures.
- Lack of sufficient archival documentation for some decorative elements, which complicated their authentic restoration [14].
- Difficulties in reconciling the new functional solutions with the requirements for preserving the cultural value of the site.

The restoration process followed the legal framework of the Cultural Heritage Act (2009), requiring the participation of licensed restorers; a public-private partnership (approved by the Sofia Municipal Council in 2017, securing an investment of BGN 8 million); and the preparation of detailed documentation for each stage of intervention in accordance with the Spatial Planning Act [17], coordinated with the National Institute for Immovable Cultural Heritage.

The restoration adhered to the requirements of the basic ethics of scientific restoration enshrined in the Venice Charter (1964) [18], and Nara document on Authenticity (1994) [19] emphasizing a authenticity, minimal intervention, and respect for the site. In the context of the Bankya Bath restoration, requirements for thorough preliminary research and a scientific approach were met; documentation of each intervention stage was prepared; minimal interventions aimed at stabilization rather than reinterpretation of the building were carried out; and compatible materials were used. The methods and approaches in the Bankya Bath restoration align with the fundamental principles of the Venice Charter.

Supplementation of missing elements was kept to a minimum, although in some cases they are not clearly distinguishable, representing a slight deviation from the ideals of the Charter. Critical deviations involved the use of modern waterproofing systems - a principle that contradicts the exclusive use of traditional materials but was justified by the need for moisture resistance. The requirements for minimal intervention, preservation of authentic materials and structures, and clear distinction of new additions from the original were observed. Where the use of modern materials was necessary, they were chosen carefully to avoid disrupting the historical context and to remain reversible for future interventions.

The balance between preserving historical value and functional adaptation was achieved through careful planning and consultations with specialists. To ensure sustainability, annual inspections by teams from the National Institute for Immovable Cultural Heritage are planned to assess the condition of façades and waterproofing, alongside public-private mechanisms for maintenance financing embedded in contracts with investors.

7. CONCLUSION

The restoration of the Bankya Bath demonstrates a balance between strict conservation and restoration principles and pragmatic technological solutions. Despite the challenges, the design team succeeded in integrating modern functional elements without compromising the historical authenticity of the monument. The success of such initiatives depends on ongoing monitoring and the adaptability of the legislative framework to the dynamic needs of cultural heritage.

The analysis of the existing literature on the subject has shown that scientific publications on the restoration of the Mineral Bath in Bankya are too few and fail to sufficiently develop the scientific and applied focus on this very significant topic. The present study attempts to consider the restoration as a systemic process in which all components of the building – architecture and decorative arts – are present in synthetic relationships. This approach is characteristic of the aesthetic concepts of the creators of the Mineral Bath and strives for an objective and as authentic analysis as possible of the original building and its modern reconstruction and restoration.

The example thus examined is a testament to the successful and comprehensive restoration of the Mineral Bath in Bankya, with a view to preserving the unique architecture and exceptional elements of plastic art that are an essential part of the building's exterior and interior. Undoubtedly, similar methods can be used in the restoration of other buildings with the same function that abound in the Sofia area - the Central Mineral Bath, the Bath in Gorna Banya, the Bath in Ovcha Kupel, the Bath in Knyazhevo. In the future, we hope to devote a series of studies to restoration projects that aim to bring back the splendour of the forgotten mineral baths and bring these unique buildings to new life.

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Review paper

BIOMASS ASH IN ALKALI-ACTIVATED MATERIALS TECHNOLOGY - A SCOPING REVIEW

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Abstract

As the construction industry moves toward decarbonization, there is a growing focus on developing alternative binders with a lower carbon footprint to replace Portland cement. Alkali-activated materials (AAMs) have emerged as one of the promising solutions because of the lower CO_2 emissions from their production and comparable performance. The main components of AAMs are amorphous aluminosilicate-rich precursors that react with alkali activators to form a solid binding matrix. Raw materials generally used as precursors in AAMs are industrial by-products such as slag, coal combustion fly ash, or metakaolin. The most used activators to reach the desired performance of the binder are alkali hydroxides and alkali silicates. However, conventional alkali activators are chemicals characterized by a negative environmental impact and high cost, which limits the wide-scale application of AAMs in the construction sector. Replacing conventional chemical activators with alternative ones derived from waste materials is a promising solution to enhance the sustainability of AAMs while promoting their broader application. This paper presents a targeted scoping review on the use of different biomass ashes instead of chemical activators in the AAMs technology. The results showed that different biomass ashes can be used not only as a source of alkalis and silicates but also as a partial replacement for commonly used precursors.

Key words: *alkali-activated materials, biomass ash, alternative activator, decarbonization*

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1. INTRODUCTION

Alkali-activated materials (AAMs) are binders based on aluminosilicate-rich precursors and alkaline activators. Blast furnace slag (BFS), coal combustion fly-ash (FA) and metakaolin are the most widely used precursors, while alkali hydroxide, silicates, carbonates and sulphates can be used as activators. Depending on the chemical composition of the precursors the main reaction products are calcium-aluminosilicate hydrate type gel (C-A-S-H) and three-dimensional alkali-aluminosilicate hydrate type gel (N-A-S-H). AAMs with predominant N-A-S-H gel in the microstructure are usually referred to as geopolymers [1,2,3].

The most used activators are hydroxides and silicates (commercially known as “water glass”), sodium or potassium based. Due to their lower cost, sodium activators have broader application [1]. The alkalis in AAM technology provide high pH and initiate the formation of reaction products, promoting early strength development. Silicates contribute to the density of the matrix and high 28-day and long-term compressive strength of concrete. Furthermore, they enhance workability if applied in adequate amount [4,5].

Although AAMs can have lower CO_2 footprint than Portland cement binder, while keeping the satisfactory mechanical and durability performance, the energy-intense production of chemical activators significantly contribute to the carbon footprint of AAMs, along with other environmental challenges [6,7,8]. Therefore, in the past decade, research has focused on finding alternative sources of alkalis and silicon on alternative activators. Silica fume (SF) was reported as a suitable silica source in AAM technology for slag-based [6], fly ash [9] and metakaolin-slag blended AAMs [4]. Waste glass (WG) was also used as an alkali silicate activator for BFS [10] or FA and BFS-FA blends [11], metakaolin [12] and even as precursor [8].

Besides industrial by-products such as SF and WG, plant biomass ashes are reported in literature as a potential alternative activators or precursors, due to their high content of silicon, potassium and calcium, depending on the type of crop [13]. Biomass ashes are a waste material, resulting from the combustion of biomass ash as a renewable energy source. Worldwide, different crops residues are used as fuel, depending on the availability [8]. Since the biomass ashes are usually landfilled, the strategy to valorize it through AAM technology and address the environmental challenges of landfilling have become an interesting research topic.

This scoping review aims to present possibilities of using different plant biomass ashes in AAM technology. Due to the large number of variables, the data were structured according to the type of precursor and biomass ash used, accompanied by compressive strength values, without delving into detailed mix design information.

2. METHODS

The scoping review was conducted by searching the Scopus database, with the following key words: “alkali-activated materials”, “biomass ash”, “alternative activator”, “waste valorization”, “agricultural biomass ash”, “alternative silica source”, ”alternative alkali source”. Additionally, some papers were selected by screening the references of relevant papers.

The inclusion/exclusion criteria are based on the used precursor, alternative activator type and tested properties. Only papers on AAM based on BFS, FA, metakaolin and their blends were included. Papers addressing alternative alkali and silica activators and precursors

based on biomass ash were included, while papers on industrial by-products as alternative activators were excluded. Given the wide range of varying parameters reported in the literature (e.g., water-to-binder ratio, silica modulus, precursor-to-activator ratio, etc.), the present scoping review focuses on sample type (paste, mortar, or concrete), compressive strength, and curing conditions, with comments on activator preparation.

3. RESULTS

The summarized results are presented in the scheme in Figure 1. The data is structured to provide general information on the use of biomass ash. The type of precursor used with biomass ash is presented on the left (BFS, FA, metakaolin, blended systems). The data on attained compressive strength and curing regimes are given in detail in the subsections.

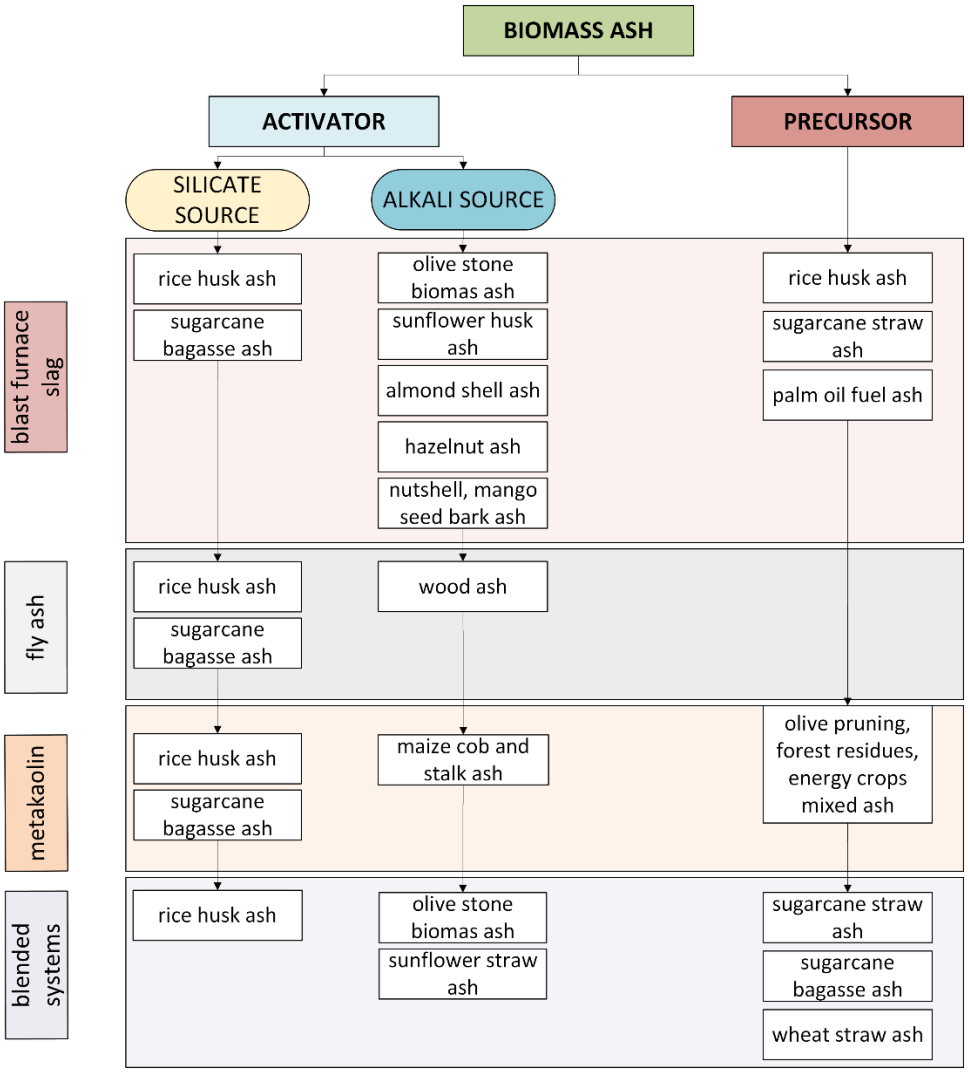


Figure 1. Schematic presentation of biomass ashes application in AAM technology

3.1 Biomass ashes as alternative activators

Biomass ashes investigated as alternative alkali silicate activators in AAM technology are rice husk ash (RHA) [4,14,15], sugarcane straw ash (SCSA) and sugarcane bagasse ash (SCBA), where the last two are also referred to as sugarcane biomass ash (SBA) [8]. These biomass ashes were used to activate BFS [14,16,17,12], FA [17,18], metakaolin [19,20,21] and blended systems: metakaolin-BFS [4], metakaolin-FA [22] and BFS-FA [17,23]. Silica sources usually must be treated to extract silica [8,9], by hydrothermal or thermochemical methods [6]. In the referenced research, RHA and SBA were mixed with NaOH solution to prepare an activator (two-part alkali-activation), usually 24h before mixing of AAMs, to ensure the dissolution of the silicon from the ashes. Some research investigated silicon extraction under elevated temperatures [18]. Paste or mortar samples were usually compared with reference mixes, activated with NaOH and commercial sodium silicate solution, or in one case, potassium silicate [19]. Although in some cases reference mixes did exhibit higher strengths, the overall performance of samples activated with alternative silica sources was comparable.

Most of the research on alternative alkali sources focused on BFS activation with: olive stone biomass ash (OBA) [24,25,26,27,28,29,30,31,32], sunflower husk ash (SHA) and sunflower straw ash (SSA) [29,30,31,33,32], almond [34] and hazelnut ashes [27,28]. Only a few papers were found on other precursors, including a combination of on BFS and RHA [15], metakaolin [35] and FA [36]. In all reviewed studies, a one-part alkali activation approach was applied (biomass ashes as activators are added as solids), while the two-part method was tested in only one case and was found to be less effective compared to the one-part alkali-activation [35].

Published research mostly investigated microstructure and compressive strength after 7 and/or 28 days of curing. Thermogravimetric analysis [4,16,37,24,15], Fourier Transform Infrared Spectroscopy [4,16,18,37,35], X-ray diffraction [22,37,24,15] were used to confirm the formation of C(N,K)-A-S-H and N-A-S-H gels in samples activated with alternative activators, depending on the chemical composition of biomass ashes and precursors. Some papers are also addressing the reactivity of component materials and workability of fresh mixes [32,38,28]. There is data on the excellent resistance against acid attack and lower capillary sorption of biomass ash activate concrete [39], however it is not the subject of this review.

3.1.1 Alternative silicate sources

Bernal et al. [14] tested RHA potential to act as silica source in activation of BFS pastes. Rise husks were burnt in the laboratory at 600˚C and ground to the desired particle size distribution. The obtained RHA had 68% of amorphous silica. RHA activated pastes showed higher 7 (>40 MPa) and 28-day compressive strength (>100MPa) than reference samples (75 MPa), activated with the commercial sodium silicate. Authors also investigated thermal stability, where RHA activated retained measurable compressive strength after exposure to 800˚C, while reference mix did not.

The use of RHA as a replacement for water glass was proven viable for BFS, FA and FA-BFS pastes [17]. BFS and blended systems were cured at 95% of relative humidity and ambient temperature, while FA pastes were cured at 80 ˚C, for 24 hours. Although the reference mix with conventional sodium silicate had compressive strength of 75 MPa after 7 days, RHA activated systems showed promising results at the same age, reaching

approximately 41 MPa for BFS-activated pastes, 49 MPa for FA and 39 MPa for blended system.

RHA and SCSA were investigated as activators for BFS mortars by Moraes et al. [16]. Two activator solutions were prepared by dissolving RHA and SCSA in NaOH. After curing at 65 °C for 3 days and at 20 °C for 28 days, the RHA-activated samples achieved compressive strengths of 49.7 MPa and 59.7 MPa, respectively, while the SCSA-activated samples reached 45.0 MPa and 54.9 MPa, respectively. However, neither of the alternative activators outperformed the reference samples, which achieved 62.9 MPa and 78.8 MPa under the same curing conditions.

Furthermore, FA was activated with RHA and SCSA to produce alkali-activated pastes in the work of Gomonsirisuk and Thavorniti [18]. After curing at ambient temperature for 7 days, samples synthesized using RHA exhibited the highest compressive strength of approximately 23 MPa, whereas the maximum strength achieved with SCBA was around 16 MPa.

Metakaolin-based alkali-activated pastes were successfully synthesized with RHA as silica source [40,37,19]. After 20 hours of curing at 72 °C and ambient curing up to 28 days, the achieved compressive strength is reported to be approximately 40MPa [19]. For the samples cured only at ambient conditions, 28-day compressive strength was reported to be 36.29 MPa [37] and 29.9 MPa which increased to 32.8 MPa after 56 days of curing [40]. Similar results were reported for activation of metakaolin with SCBA [20].

Blended metakaolin-BFS pastes activated with RHA was analyzed by Bernal et al. [4]. Authors varied BFS content and silicon-to-alumina ratio, which resulted in 7-day compressive strengths in range from 12 MPa to almost 60 MPa. Conducted curing regime was as follows: ambient conditions (25–30°C) for 24 h, then exposed to thermal curing at 60°C and >90% relative humidity for 24 hours. The samples were then stored at ambient temperature and 90% relative humidity until testing.

FA-BFS blended mortars were also activated with RHA in the work of Tong et al. [23]. RHA activated samples reached almost 60 MPa after 28 days of ambient curing, which is the same as reference mix.

3.1.2 Alternative alkali sources

The one-part alkali-activation with OBA has been reported by several research groups. De Moraes Pinheiro et al. [26] investigated OBA as alkaline activator for BFS mortars. The first set of mortar samples were made with replacement of BFS by OBA from 15 to 35 wt% BFS. The second set was made with the addition of OBA from 5% to 25% wt BFS. Samples were cured in a thermal bath at 65 ºC, for 7 days. The highest 7-day compressive strength was obtained for samples with addition of 25% of OBA (38.38 MPa).

Similar results were obtained in another study by this research group [25]. Mortar samples were cured at 65ºC and 100% relative humidity, until the day of testing. The results showed that OBA activated mix had higher 3 and 7-day compressive strength than KOH activated mix (OBA: 29.9 MPa at 7 days and 45% strength gain with respect to 3-day strength; KOH: 16.9 MPa, 33% of strength gain).

The feasibility of OBA fly ash (OBFA) and OBA bottom ash (OBBA) application as activators for BFS was also evaluated by Alonso et al. [26]. Paste samples made with 70 wt % BFS and 30 wt % of OBFA or OBBA cured at 45 °C or 85 °C, had 28-day compressive strength of 33 MPa to 18 MPa. OBFA activator induced development of higher strength than

the OBBA activator. In pastes prepared with 30 % wt. OBFA, strength values were comparable to those developed by BFS pastes activated with a commercial KOH.

To activate BFS and produce mortars made only from waste materials, Font et al. [15] used OBA as alkali and RHA as a silica source. The biomass ashes were dissolved in water 24 hours prior to mixing. Authors investigated the influence of curing regime and use of OBA as addition (15, 20 and 25%) or replacement (20%) by mass of BFS. The highest 7-day compressive strength was attained for 25% addition of OBA and curing at 65 ºC, which accelerated the early strength development, resulting in up to 58.1 MPa. for the addition of 25% of OBA. Curing at elevated temperature. Mixes with both replacement and addition of 20% of OBA 7-day compressive strength was 52.1 MPa for elevated temperature curing and 35.0 MPa for ambient temperature and 100% RH curing. These mixes, cured at ambient temperature, were also tested for 3, 28, 60 and 90 days, reaching 7.8, 46.2, 61.5, 67.4 MPa, respectively.

Almond shell biomass ash has also been studied as replacement and addition to BFS (from 15% to 35% and 5% to 25% in respect to BFS mass, respectively) [34]. Mortar samples were cured for 7 days at 65ºC, and the obtained compressive strength values were in the range 25-45 MPa. These compressive strengths were higher than the once obtained by activation with 4M and 8M KOH solution.

The same research group investigated the potential use of nutshell ashes, mango seed-bark ashes and hazelnut ashes as an alkaline activator for BFS [27]. Alkali-activated pastes exhibited 26 MPa compressive strength after 28 days. The first 7 days, samples were cure at 65 ºC, after which the samples were kept at 20 ºC until the testing.

Hazelnut was also proven to be efficient BFS activator in the research of Omur et al. [28]. The experimental testing of pastes cured at 22 ºC and 50% RH showed that the compressive strength can reach up to 26.8 MPa at 28 days, which was equivalent to reference mixtures activated with 2.0 M NaOH and 2.2 M KOH.

SSA was used as an alternative activator for BFS to form grout slurries, reaching approximately 24 MPa [29]. BFA and black RHA based grouts were successfully activated with SSA and SHA reaching 24.31 MPa, 22 MPa, respectively, after 28 days of curing at ambient temperature and 95% RH (both exceeding reference KOH activated grout) [32]. In this study, WSA was also tested as alternative alkali activator, but did not exhibit good performance (9 MPa).

The authors of this paper published research results on mortars synthesized from BFS and locally available SHA, generated by the edible oil production company in the Autonomous Province of Vojvodina, Republic of Serbia. The samples reached 29 MPa after 28 days of curing [30]. The influence of curing at elevated temperature for 5 days, followed by ambient curing, was tested on the same mixes [31], where it improved early age compressive strength. However, it was proven that 28-day compressive strength of up to 30 MPa can also be reached by curing only at ambient conditions.

Peys et al. [35] investigated the possibility of using maize cob and maize stalk ashes to activate metakaolin. The pastes were prepared by two-part and one-part activation. However, the metakaolin binder produced with ash solutions as activators exhibited instability in water and low strengths. The application of maize ashes as an activator in powder form for producing one-part pastes was successful. Tested compressive strengths at 7 days were in the interval between 27 MPa and 40 MPa, depending on the ash-to-metakaolin ratio (0.9-

1.2) and curing regime (open: 48h at 60ºC and 80ºC; wrapped: 48h at 80ºC; pre cured 24h at 20ºC and then opened for 48h at 80ºC).

FA (pulverized fuel fly ash) and wood ash with high calcium content (61% CaO) and moderate potassium content (12% K_2O) were used, in different ratios, to synthesize alkali-activated pastes [36]. The compressive strength after 7 days was 12 MPa and 16 MPa after 28 days. The significantly lower strength compared to other referenced research is due to the lower potassium content, as suggested by authors. Considering the high CaO content, wood ash would possibly be more effective as a replacement for precursor.

3.2 Biomass ashes as precursors

The possibility of using wheat straw ash (WSA), RHA, SCBA, SCSA, CCA and palm oil fuel ash (POFA) as precursor due to their higher silicon content was also tested. Mixes were activated using conventional sodium hydroxide and silicate activators. Replacement of BFS with SCBA by replacing 15% and 25% resulted in a minor increase in 7-day compressive strength compared to samples with 100% BFS and decrease in 28-day compressive strength. Replacement of BFS with maximum 25% of SCSA resulted in higher compressive strengths than reference mixes. BFS and FA replacement with up to 35% of RHA also increased compressive strength, as well as 30% BFS replacement with POFA. Mixes with higher levels of replacement resulted in strength decrease [41].

The application of biomass ashes as precursors has been investigated as partial or complete replacement of metakaolin (25-100%) for production of geopolymer pastes [42]. The ashes originated from the combustion of mixed olive pruning, forest residues and energy crops. The study showed that the 50% replacement of metakaolin increased the compressive strength of the geopolymer. It was also concluded that the biomass ash contributes to the binder as an activator due to the present of soluble alkaline salts.

Alkali-activated concrete samples with 25% metakaolin, 25% FA and 50% WSA as precursor outperformed Portland cement-based system in terms of 7-days compressive strength after ambient curing (51.3 MPa vs. 32.4 MPa) [39].

4. CONCLUSIONS

The presented scoping review showed that various types of biomass ashes can successfully substitute conventional alkaline hydroxide and silicate activators in the synthesis of AAMs. Some of them are suitable as partial substitution for the precursors. Based on the inclusion/exclusion criteria, the paper presents a structured overview based on the type of precursor, biomass ash as alternative activator, compressive strength performance, and curing conditions.

The most effective alternative alkali activators are ashes rich in potassium and amorphous silica, particularly when applied to BFS- or metakaolin-based systems. Early-stage thermal curing significantly enhances strength development, although certain formulations show potential even under ambient curing.

The reviewed papers are predominantly concerning RHA-activated BFS and OBA-activated BFS systems. Only a few papers considered ternary systems, with BFS, RHA and SSA and BFS, OBA and RHA. Silicon-rich biomass ashes are usually dissolved in alkali hydroxide solutions, i.e., two-part alkali-activation process is applied. Alternative alkali

sources were mostly added in powder form (one-part alkali-activation). Samples activated with silica derived from biomass show comparable performance to those using conventional or industrial silica sources, although lower strengths can also occur. In contrast, biomass used as an alkaline source consistently outperforms chemical hydroxides.

The highest replacement of conventional precursors was achieved for RHA replacement of BFS and WSA replacement of metakaolin-FA blend. Generally better results were attained for biomass ashes used as alternative activator than precursor.

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Research paper

STRATEGY FOR SUSTAINABLE URBAN DEVELOPMENT OF THE CULTURAL ROUTE IN SKOPJE, REPUBLIC OF NORTH MACEDONIA

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Abstract

Strategy for sustainable urban development of cultural buildings along the Cultural Route identifies urban mapping strategy for restoring circulation by activating social aspects and developing cultural activities at the cultural buildings, monuments and urban squares located along the Cultural Route in Skopje. The methodology of this scientific paper is based on the urban mapping methodology which aims to identify and analyze spatial, cultural architectural and social characteristics of the Cultural Route Case Study of the cultural buildings as nodes for sustainable strategy of development of the City Skopje. This study contributes to the creation of a comprehensive and inclusive cultural places and buildings towards contemporary and incoming features of the inhabitants and visitors of Skopje and the Republic of North Macedonia. With the strategy for urban development of the cultural buildings at the Cultural Route as an urban placemaking strategy, identified is new structural revival of intensive urban life, by providing increased circulation and movements of visitors and tourists, emerging cultural and educational activities and events. Within the proposed dynamic models of architectural and urban solutions strategy of the Cultural Route, urban network identification and uniting museums along the cultural route, provided would be inter-connections between cultural institutions and public places in the field of culture, architecture and artistic activities.

Key words: *Architectural Design, Sustainable Urban Development of Cultural Route, Urban mapping of cultural buildings*

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1. INTRODUCTION

The significance of the culture at the Cultural Route in the City Skopje demonstrates the fundamental concept of architectural-urban solution of the Cultural Route in Skopje, the urban mapping concept of connecting and integrating cultural activities, which serve as a guidance towards efforts to protect and preserve culture for future generations [1]. The transmission of messages and legacy from history, culture and the past is essential for the continuation of future generations ideas and concepts. According to Alvin Toffler: "Learning from the past, should be understood as culture of understanding the present. Cultural buildings can be seen as places 'enclaves of the past' and also 'enclaves of the future'." People must engage with culture through architecture, arts, music and aesthetics, in order to comprehend the world. This allows people to walk along the Cultural Route in Skopje that broadens perspectives towards its cultural surroundings developed in different historic periods of time [2]. The core concept of the research is founded on the idea to create a complex system that includes all cultural institutions and placemaking cultural activities at the Cultural Route in Skopje. At the same time, the Cultural Route should serve as a platform to initiate discussion and dialogue about the cultural interactions of artifacts with the city of Skopje and the Republic of North Macedonia. The architectural and urban concept of the Cultural Route recommends and encourages decision-makers and stakeholders to invest in the development of cultural, tourist and other economic sectors by engaging in different types of public national and international cultural activities. Modern changes in technique and technology demand a shift in cultural perspective in new network museum connections in a digital context [3].

2. METHODOLOGY

2.1. Case Study of the Cultural Route in Skopje

The urban mapping methodology in this research aims to identify, document, and analyze spatial, cultural architectural and social characteristics of the Cultural Route in Skopje. The mapping serves as a research and design tool, enabling the visualization of spatial dynamics, cultural values, and user experience within the urban fabric.This research adopts an interdisciplinary and mix-methods of urban mapping approach, combining qualitative, visual and participatory methods to interpret the complex layers of the Cultural Route. The hypothesis of the research defines Cultural Route in Skopje which acts as a dynamic spatial and cultural corridor that reveals how urban heritage, public space usage, and community narratives intersect to shape contemporary urban identity; by applying multi-layered urban mapping and participatory methods, hidden values, neglected nodes, and opportunities for inclusive regeneration can be identified and activated.

Research methods used in the study consist of urban mapping and spatial documentation, with GIS (QGIS, ArcGIS), Google Maps. The process includes: mapping of the spatial layout, land use, built environment, and circulation patterns, as well as identifying nodes of cultural placemaking activity, architectural heritage and cultural landmarks. The objective and aim of the study is to provide visualization of the physical structure and layering of cultural assets and spatial dynamics. The aim of the study is to identify Cultural Route's urban nodes with social integration and placemaking strategy circulation of visitors. To

achieve this, institutional and organizational coordination of existing cultural institutions is required, as well as planning of new cultural activities and contents, which are necessary for allocation of financial resources in culture. According to the current research of the urban-sociological standpoint at the Cultural Route in Skopje, most of the visitor's circulation is noticed during the working hours, and this is due to the presence of primarily commercial, catering, crafts and office buildings, with no residential or business buildings.

2.1.1 Methodology of Urban Mapping along the Cultural Route in Skopje

According to the renowned urban planner Kevin Lynch, the idea of placing focal points or nodes, will attract an extra concentration of people and public visitors [4]. Defining an axis of movement connects numerous focus points nodes, linking them together into one integrated system. Along the Cultural Route in Skopje, visitors can have artistic, cultural or educational experience that is both relevant, unambiguous and accessible to everyone. The cultural route has several connections that are integrated into process of valorization of the cultural values in relation to the rest of the city's natural and created factors. By defining urban mapping strategy it is expected that the Cultural Route will continue to increase the number of visitors, through incorporation of different types of artistic and cultural events [5].

The urban dialectic in architectural space encourages inter-relational coordination. There is consistency in the interconnection and communication of culturally significant content. These interrelations are mutually connected at a higher level, which is referred to as the urban mapping development strategy [6]. The study analysis the urban-spatial context of the Cultural Route, from Museum of the City of Skopje to the Museum of Macedonia and Museum of Contemporary Art at Skopje Kale, passing through square Macedonia and Old Skopje Bazaar complex, in order to ensure development by setting a level of valuation of cultural resources within the Cultural Route's scope. The objective is to provide conditions and develop a urban sustainable strategy for architectural-urban solutions at the Culture Route that includes museum facilities, cultural facilities and open public spaces that can be used for architectural, art and cultural activities [7]. The Cultural Route's urban mapping project defines placemaking strategy which will ultimately enable visual display of cultural contents: exhibitions, musical performances and concerts, talks, shows, events, and concept of building spiritual and cultural connections between people at the Cultural Route. This provides access and utilization of educational content by establishing venues for gatherings where people can communicate at a higher level, by establishing cultural habits through cultural workshop activities and display of data using culturally-related promotional materials. Identification of the urban mapping strategy of the Cultural route, will provide possibilities for exploring cultural heritage and historical sites in the Republic of Macedonia and the city of Skopje, providing growth of cultural tourism by engaging materials towards visitors and travelers, updating route activities with official cultural data from theaters, museums, galleries, and other cultural buildings [8].

The methodological analysis of the network of Cultural Route enables connection of cultural buildings in an urban context, which will be important in terms of: planning cultural activities, organization of cultural events, planning circulation of visitors in the urban spatial matrix defined through the Cultural Route, defining the trajectory of movement of cultural users and tourists in an urban context, defining visit to several museum complexes in the city,

planning the time interval of their visits to the cultural architectural buildings, opportunities for planning and development of exhibition spaces, architectural space planning by architects, museum professionals and users, tourists and visitors [9]. Spatial distance analysis between the cultural buildings at the Cultural Route in Skopje, defines relatively small distances of 100 - 500 m walking communication diagram [10], and pedestrian streets communication between the cultural buildings on the Cultural Route in Skopje without crossing the vehicular traffic with pedestrian circulation, the time required for movement of pedestrians from one building to another ranges from 10-15 minutes, with morphology of the terrain which has favorable accessible configuration of the terrain. For the full realization of the urban mapping strategy, it is optimal to analyze the principle of functioning of the Cultural Route in Skopje, by analyzing the placemaking nodes by incorporating the Old Skopje Bazaar into the development of the Cultural Route as an important economic and institutional urban area [11].

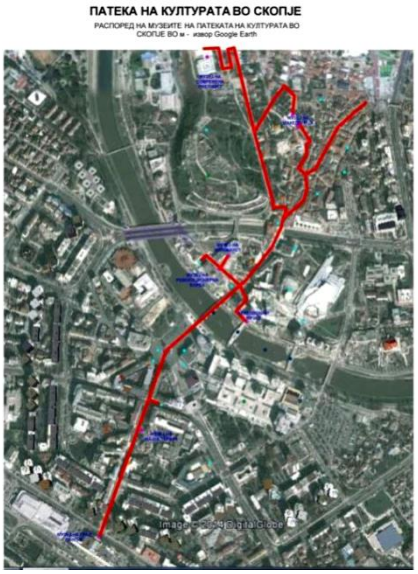


Figure 1. Cultural Route in Skopje by Mapping Cultural Institutions (Source:Author)

The strategy of urban mapping of the Cultural Route in Skopje enables: virtual mapping of cultural institutions in the city of Skopje through using the principles of modern information and communication technologies and dynamic concentration of cultural buildings in the network, increasing cultural activities in the context of revitalization of cultural buildings in long period located at the virtual network, attracting stakeholders due to growing interest of general popularization of touristic visits to cultural buildings and cultural events, involvement of project managers who will organize networked cultural activities, by increasing the interest of media, actualize presentation of the city on a regional, national and international cultural level, defining target group of national and international visitors and tourists from educational institutions, such as high schools and universities and cultural centers [12, 13]. Identification of museum buildings as cultural buildings at the Cultural Route in Skopje are defined as national and local museums, where national museums are: NI Museum of Macedonia Skopje, NI Museum of Contemporary Art Skopje, NI Museum of the Macedonian Struggle for Statehood and Independence Skopje, NI Museum of the Holocaust Skopje, NI Art Gallery

Skopje, NI Memorial House of Mother Teresa Skopje, NI Archaeological Museum of Macedonia - Skopje, and local museums are: Museum of the City of Skopje. Strategy for urban development of the cultural buildings should include the following aspects that need to be addressed: complete protection and revitalization of the existing, newly built and historical buildings of the Old Skopje Bazaar, construction of trade facilities and other business and commercial facilities next to the museums and their connection with the core of the Old Skopje Bazaar, visual presentations, panoramas and virtual reality for all cultural institutions on the Cultural Route, organization of simultaneous creative workshops in all cultural buildings for making jewelry, crafts organization of simultaneous cultural events, manifestations and performances, architectural workshop for traditional construction, creating information and communication technology network by entering all the information about the old and new cultural buildings, posting mapping of cultural buildings and route around Old Skopje Bazaar.

3. RESULTS

3.1 Defining Focal Points of Cultural Contents along the Cultural Route

Strategies for sustainable urban development of the cultural buildings at the Cultural Route in Skopje define strategic placemaking cultural activities that will promote culture [14]. Defining focal points at the Cultural Route in Skopje represents: cultural buildings, museums, historical sites along the Cultural Route in Skopje. Skopje City Museum is the beginning point of the Cultural Route in Skopje, located in the historic Old Railway Station, which was largely wrecked after the 1963 earthquake. Its location in the central city center provides convenient access to different types of visitors of cultural services. It should envision different cultural activities: info-center for the Cultural Route by obtaining information, catalogs and maps for movement along the route, information on pedestrian and car access, descriptions of significant objects on the route and cultural-historical monuments, accompanying activities at each point, video information, and the purchase of discount cards for museums and monuments. The Memorial Center of Mother Teresa represents a historical exhibition of the life and humanitarian work of the worldwide famous historical person born in Skopje Mother Theresa. The ARM Cultural Hall which can host different types of cultural and artistic events and musical concerts, along the Cultural Route in Skopje. Theatre for Children and Youth can host different types of outdoor performances on the Cultural Route in Skopje. Macedonia Square and the city fountain is a central city urban space located on the Cultural Route, a location which can provide organization of many political, cultural, social events, space for socialization in Skopje. Stone Bridge represents the historic structure of the bridge and its surrounding area on both banks of the river Vardar, which offers excellent venues for a variety of cultural events, religious performances and tourism attractions. The new pedestrian Art Bridge in front of the Macedonian Opera and Ballet, represents pedestrian circulation between the two existing cultural buildings. The Old Theater, Museum of the Revolutionary Independence, Museum of the Holocaust, Church of St. Dimitria, Ibni Pajko and other buildings on Karpošovo Uprising Square define another urban cultural complex which can host many cultural activities. This urban mapping identifies complex which has a large

concentration of cultural buildings, that can provide cultural placemaking activities to tourists and visitors. National Gallery of Macedonia Daut Pasha Hamam, Macedonian Opera and Ballet and Philharmonia, located on the left bank of river Vardar, is highly appealing cultural location to artists and art enthusiasts, where many art exhibitions and other cultural activities can take place (outdoor artist painting, art sale exhibition, concerts and theater performances). Macedonian Opera and Ballet activities can take place on the plateau in front of the building.



Figure 2. Cultural Heritage Buildings at the Cultural Route in Skopje, Skopje Old Bazaar, Museum of N. Macedonia in Skopje, Kurshimli Han in Skopje, National Art Gallery Daut Pashin Hamam (Source: Macedonia Timeless)

The entrance to the Old Skopje Bazaar can be defined by the elevated plateau of the Department Store Most, as an attraction point for visitors and tourists to visit the Old Skopje Bazaar. Kapan Han as cultural node can include new tourism and visitor materials with cultural and restaurant activities. Skopje Kale has two functional units: archaeological and recreational. The archaeological section will be node interesting for researchers, while the recreational section can be designed for the relaxation of Skopje's inhabitants and visitors. Skopje Kale site should be connected not only physically to the Cultural Route, but also as an integrated component of the Cultural route. Church Saint Spas is frequently visited due to visits to the church, iconostasis, and Goce Delcev's cemetery. The historic Skopje Old Bazaar represents significant Skopje's shared cultural heritage and history, which dates back almost a millennium. On the Cultural Route, its architectural entity offers an opportunity for urban cultural revival. This area of the city is rich in layers of cultural life, history and art. It also serves as an example of coexistence and shared cultural past throughout many centuries. The concerts, exhibitions, seminars and art displays can be planned in order to bring this area of the city back to its former historical glory. Skopje's Old Bazaar should have a clear visual display of placement of mapping and information boards directing visitors to museums and cultural-historical landmarks as necessary information along the Cultural Route through the Old Skopje Bazaar [15]. The development of the pedestrian route and the vehicle access in the southern portion of Skopje Kale will improve access to the Museum of Contemporary Art. This location offers stunning views of the City Skopje. Outdoor performance stages and

amphitheaters are proposed to be built in the sculpture park, with the option of hosting cultural events. The Old Post Office, Mustafa Pasha Mosque provide great opportunities for cultural events of different types and character. They would be used for educational, commercial religious and other cultural events. Suli Han, Bezisten and National Gallery Cifte Hamam are historical buildings that provide excellent venues for a variety of cultural events. Suli Han and Bezisten can be transformed for art, architecture, and other traditional conservation activities. Suli Han is the location of the Faculty of Fine Arts and it is acceptable to link the organization of these workshops. It also includes the Museum of Old Skopje Bazaar, where visitors can learn more about the Bazaar's history, trades, and merchandise. Cifte Hamam is the National Art Gallery in Macedonia, with amazing remains from the architecture of the historic building in Skopje. Kurshumli Han at the Skopje Old Bazaar is the historic structure which offers an amazing venue for hosting cultural events of various types and styles. The Lapidarium, which features a vast collection of stone monuments from many locations and eras, is situated inside Kurshumli Han. The Museum of Macedonia as cultural building represents Macedonian culture. The Museum of Macedonia's structure is a modern architectural interpolation into the historic core of the city. Instead of presenting the items in the traditional manner, the museum focuses on showcasing the identity of the Macedonian people. The museum is more than just a collection of objects, relics, and works; it also represents museum and cultural place of people, tourists and visitors [15]. The museum should provide gathering place for cultural heritage and the advantages of presenting cultural activities with digital multimedia technology. It should be representing location for meeting point of visitors, as networking place for friends of museum and culture. Museum of Contemporary Art and the plateau in front of the Museum of Contemporary Art in Skopje represent the possibility for organization of several cultural activities with viewpoints towards Skopje and the river Vardar. The concept of the project is to encourage communication between cultural activities, exhibitions, performances, learning, socializing and collaboration, adaptable to allow cultural dialogue and discourse between tourists and visitors [16].

4. DISCUSSION

4.1 Cultural Placemaking Strategy at the Cultural Route in Skopje

For the full realization of the urban mapping strategy and optimal functioning of the new idea of the Cultural Route in Skopje as European City of Culture 2028, it is important to plan placemaking strategy by incorporating of Old Skopje Bazaar as economic and institutional urban area for the development of the Cultural Route; building retail, residential, business, and commercial facilities near museums in Old Skopje Bazaar according to the urban regulations for revitalization. The proposed content will help the economic growth of the regions of the city around the Cultural Route and construction of a strong economic base for future operations, by creating sociologically integrative environment for all visitors. Complete preservation and restoration of historic structures in accordance with the planned protection system, as long as they remain inside the existing boundaries of the Old Skopje Bazaar. The goal is to establish protection and preservation guidelines according to the regime of valorization of cultural buildings. It is especially crucial to present cultural items and

monuments, in order for them to actively display content at the Cultural Route [17]. Museum activities that are already present in the Cultural Route, should continue to plan and organize cultural activities within the network of the cultural institutions at the Cultural Route in Skopje, therefore providing a platform for the development of cultural tourism in the City and in the Republic of North Macedonia. Through the development of the Cultural Route and connecting all cultural institutions in one system and network, a new type of tourism with a cultural component will emerge, taking up a significant portion of the entire tourist offering in the city of Skopje. The type of tourists visiting the Cultural Route will also influence the types of spaces that should be additionally created at the Cultural Route. As a result, there would be responsibility for infusing culture into tourism. Several measures can be defined in order to improve the invertarization, valorization and protection of the cultural activities at the Cultural Route: reconstruction of historic buildings, creating a web page with cultural object information for improved information for visitors, in addition to implementation of the onsite visual displays, panoramas, and virtual reality created for all objects on the Cultural Route [16]. The following placemaking interventions should be planned at the Cultural Route: performance venues for mass meetings at the open space on the location Skopje Kale, representation of old traditional crafts and workshops, souvenir shops, educational program activities, jewelry and traditional weaving workshops, placement of explanatory mapping signposts along the Cultural Route and entrances to all cultural facilities should be renewed and emphasized. Engaging a multidisciplinary team of professionals and experts should provide a full comprehension of all evaluated aspects of the cultural facilities, restaurants, hotels, shops, cultural buildings and facilities, cafeterias, and services, enabling various solutions to the new contents of the Cultural Route in Skopje.



Figure 3. Museums of Macedonian Independence and National Theater in Skopje, Cultural Route at the Stone Bridge in Skopje (Source: Macedonia Timeless)

As a result of the research, it is expected to explore and define the application of modeling in the planning of the current and future development of the cultural buildings and museums, in the virtual development of the city, by defining the existing and future programming factors that influence the development of the cultural buildings, defining factors in the process of modeling of the spatial organization, location and relational connection of the cultural buildings in the network and defining the degree of influence of the development cultural buildings on the virtually created development of the city of Skopje.

5. CONCLUSION

The case study of the Cultural Route in Skopje demonstrates the value of a multidisciplinary approach that integrates spatial analysis, sensory perception, and community participation to better understand and interpret complex urban heritage systems. Through urban mapping methods—including GIS documentation, sensory and ambiance mapping, participatory workshops, and archival research—this study revealed that the Cultural Route is not a static heritage corridor, but rather a dynamic and evolving urban spine that reflects both historical memory and contemporary urban challenges.The implementation of this urban strategy at the Cultural Route will significantly revive cultural activities and urban life while also increasing visitors and tourists through cultural and educational events. This paper provides conditions and the strategy for an architectural-urban solution of the Cultural Route that will include proposed actions towards cultural and museum facilities, as well as open public spaces that can be used for art and cultural purposes. Actualization of cultural activities by visitors and tourists will result in the enhancement and development of their content and capacities. In conclusion, the study confirms that the Cultural Route in Skopje holds great potential as an active framework for inclusive urban regeneration, educational programming, and cultural activation. Future strategies should build upon the insights gained through this research to implement targeted interventions that preserve cultural heritage while enhancing public accessibility, experience, and participation. This methodological approach bridges the gap between technical planning and cultural storytelling, offering a dynamic basis for sustainable urban regeneration and policy innovation.The strategic urban concept embodies cornerstone concept of the project, which encourages communication between cultural activities, exhibitions, performances, learning, socializing and collaboration. The Cultural Route concept should be adaptable enough to allow for cultural dialogue discourse between tourists and visitors.

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Research paper

SENSITIVITY ANALYSIS OF REFERENCE EVAPOTRANSPIRATION TO KEY CLIMATE VARIABLES IN AN URBAN AREA

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Abstract

Evapotranspiration is a key parameter of the agrohydrological systems and is critical factor for water resources planning. The objective of the study is to analyze the sensitivity of the monthly reference evapotranspiration (ET_0) to climate variables. Data were used for Nis urban conditions, for the period from July 2022 to December 2024. Sensitivity analysis was based on the calculation of sensitivity coefficients for four meteorological parameters: minimum and maximum air temperature (T_{min} and T_{max}), wind speed (U_2) and solar radiation (R_s). The ET_0 values were defined using the FAO 56 Penman-Monteith method. The results of the sensitivity coefficients showed that the two variables – R_s and T_{max} have the greatest influence on ET_0, with the values of coefficients of 0.423 and 0.374, respectively. The analysis showed that T_{min} has the lowest influence on ET_0, in defined conditions.

Key words: *Reference Evapotranspiration, Sensitivity Analysis, Urban Area*

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1. INTRODUCTION

Evapotranspiration is one of the most important components of the balance between water and energy in urban conditions. Its importance is especially recognized at green infrastructure solutions, where it represents part of an effective strategy for negative urbanization consequence mitigation. Reference evapotranspiration (ET_0) depends on meteorological parameters and location, i.e. only meteorological variables have a direct impact on ET_0 [1].

According to [1], the Food and Agriculture Organization at the United Nations strongly recommends the FAO 56 Penman-Monteith equation (P-M) for defining ET_0. This equation belongs to a combined group of methods, i.e. a group of physically based methods that combines energy and mass transfer. The method is reliable for defining ET_0 in different climatic conditions, and this fact is confirmed by using the P-M method for the calibration of other methods, especially those with a limited number of input data [2-4].

The spatial variability of the land cover causes different microclimatic conditions, especially in an urban area. These conditions usually include a change in the surface heat flux and complex wind patterns. Urban vegetation heterogeneity and different structures, together with the variability of meteorological parameters, affect accurate urban ET_0 estimation [5]. For these reasons, it is necessary to define the degree of meteorological parameter influence on ET_0, i.e. it is necessary to conduct a sensitivity analysis.

The sensitivity analysis is used for the identification of the most important variables in the model and for the establishment of the error effect of the input data on the model outputs. There are different types of methods for defining the sensitivity analysis, i.e. there is no general procedure for the estimation of sensitivity, so the interpretation and comparison of the results from literature can be a challenge [6-9].

Sensitivity analyses for the ASCE Penman-Monteith equation were done for several meteorological factors (wind speed, air temperatures, vapour pressure deficit and solar radiation) in the different regions of the United States [10]. The daily basis was the level for the calculation of sensitivity coefficients. Authors concluded that ET_0 was mostly sensitive to changes of the vapour pressure deficit, while it was not sensitive to minimum temperature changes, at all locations. Also, the analyses of other variables showed significant variations of sensitivity between locations.

The analysis of reference evapotranspiration to the changes of climatic parameters, based on the daily data, was conducted in China (Jiangsu province) [11]. The analyzed area was covered with 60 stations, and the data covered a period from 1961 to 2015. Overall, authors indicated that actual vapour pressure was the most important parameter for ET_0. Wind speed was separated as the parameter to which ET_0 is not sensitive. The analysis of the seasonal influence of the parameters on ET_0 revealed that it was the most sensitive to changes of air temperature and sunshine hours during the summer period.

The monthly analysis of the sensitivity of climatic factors to ET_0 trends was performed in Iran by using a qualitative detrend method [12]. The territory of Iran was observed by five synoptic stations for the period between 1963 and 2007. The main factor which affected the significant positive trend of ET_0 was relative humidity, i.e. relative humidity and sunshine hours at Tabriz station, and minimum temperature, relative humidity and wind speed at Mashhad.

The paper covers the sensitivity analysis of reference evapotranspiration to the key meteorological variables (air temperature, wind speed and solar radiation) using the sensitivity coefficients and sensitivity curve method.

2. METHODOLOGY

2.1. Study Area and Data

The study area in the paper is one urban area in Nis, South-eastern Serbia. The climate in Nis is humid subtropical with continental influences. The main characteristics of this climate are average high temperatures during the summer period and moderately cold winters. The sunniest month during the year is August, while February is the driest month. Moderate precipitation is characteristic of Nis, with an average annual amount of 607 mm. There are approximately 134 days with rain and 40 days with snow cover during the year.

The automatic weather station, installed in the urban area of Nis with coordinates 43°19' N and 21°56' N and an elevation of 197.2 m a.s.l. was used for data collection. The station is equipped with sensors for the measurement of air temperature and relative humidity (HC2S3-L Temperature and Relative Humidity Probe, Campbell Scientific), wind speed and direction (05103-5 Wind Monitor RM Young, Campbell Scientific) and solar radiation (CS300-L Pyranometer, Campbell Scientific). Datalogger (CR1000 Measurement and Control Datalogger, Campbell Scientific) is used for the management and operation of the station. The analyzed period is based on the average daily data on a monthly basis, from July 2022 to December 2024.

2.2. The FAO 56 Penman-Monteith Method

The FAO 56 Penman-Monteith method was used for the calculation of reference evapotranspiration [1]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where:

ET_0 – reference evapotranspiration [mm day^{-1}]
R_n – net radiation at the crop surface [MJ m^{-2} day^{-1}]
G – soil heat flux density [MJ m^{-2} day^{-1}]
T – air temperature at 2 m height [°C]
U_2 – wind speed at 2 m height [m s^{-1}]
e_s – saturation vapour pressure [kPa]
e_a – actual vapour pressure [kPa]
e_s-e_a – saturation vapour pressure deficit [kPa]
Δ – slope vapour pressure curve [kPa °C^{-1}]
γ – psychometric constant [kPa °C^{-1}]

2.3. Sensitivity Analysis

Sensitivity analysis represents the technique that defines the influence of variables on ET_0. For this study, the sensitivity analysis is based on the dimensionless relative sensitivity coefficient [13]:

$$SC = \frac{\Delta ET_0}{\Delta CV} \frac{CV}{ET_0} \quad (2)$$

where:

ΔET_0 – relative change of ET_0 with respect to variable changes

CV – climate variable, the base value before change

ΔCV – relative change of CV

ET_0 – reference evapotranspiration, the base value before change

The variables analyzed through the sensitivity process are minimum and maximum air temperature (T_{min} and T_{max}), wind speed at 2 m height (U_2) and solar radiation (R_s). The calculation procedure was done by changing one variable in the ET_0 calculation, while the others were fixed. The relative changes of variables cover the range of $\pm$ 20%, with an interval of $\pm$ 5% (-5%, -10%, -15%, -20%, 5%, 10%, 15%, 20%). All the calculations were done on a monthly basis.

The SC value, positive or negative, implies that the ET_0 value will increase or decrease as the CV increases. The relative effect of the analyzed CV will be larger on ET_0, with the larger SC value. In order to have the most precise assessment of sensitivity, the classes of SC values were proposed by [14] according to the degree of sensitivity, table 1.

Table 1. Sensitivity classes

Sensitivity coefficient	Degree of sensitivity
$0.00 \leq \|SC\| < 0.05$	small to negligible
$0.05 \leq \|SC\| < 0.20$	medium
$0.20 \leq \|SC\| < 1.00$	high
$\|SC\| \geq 1.00$	very high

3. RESULTS AND DISCUSSION

The values of monthly sensitivity coefficients for all the analyzed variables are shown in Figure 1. The figure clearly indicates that there are large fluctuations in all variables. Temperature sensitivity coefficients show a similar pattern. The SC values for T_{max} are higher than those for T_{min}, i.e. ET_0 is more sensitive to T_{max} than to T_{min}, which is reasonable because T_{max} values are always higher than T_{min} and have a greater influence on the ET_0 equation. Based on Figure 1, it is obvious that SC(T_{min}) has the lowest values of all the other variables (ET_0 is not sensitive to the changes of T_{min}). This conclusion is supported by the numerical value of the unique SC of 0.087 for the entire analyzed period. The analysis of the average monthly SC values recognizes September as the month with the highest SC(T_{min}) values of 0.142, while February has the lowest values of SC(T_{min}) (0.008). According to the values of average yearly SC for T_{min} and T_{max}, 2022 stands out as the year with the greatest P-M equation sensitivity to temperature changes, i.e. 0.112 and 0.396, respectively. According to the unique SC(T_{max}) value of 0.374, it can be concluded that the ET_0(P-M) equation is highly

sensitive to T_{max}. This sensitivity is especially expressed during the autumn months of October and November, with SC(T_{max}) values of 0.465 and 0.458, respectively.

The sensitivity coefficients for U_2 exhibit an opposite correlation than those for temperature. This statement is supported by the numerical values of SC(U_2) on an average yearly and monthly basis. Yearly SC(U_2) determines 2024 as the year with the highest sensitivity to U_2 (0.168). A monthly analysis of the SC reveals that the winter session is the most sensitive to U_2, especially in February (0.289). The results of SC(U_2), with an average value of 0.157, define U_2 as the parameter with a medium influence on the ET_0 equation.

The behavior of SC(R_s), on a monthly basis, deviates from the other analyzed parameters. According to Figure 1, there are especially noticeable peaks at SC(R_s) during the summer periods, which is reasonable considering the intensity of R_s during this period. The average monthly SC(R_s) exhibits the highest values in June and July, with 0.771 and 0.753, respectively. November is the month with the lowest sensitivity of ET_0(P-M) to the R_s variable (0.060). The results of the average yearly SC(R_s) show that, in 2023, R_s had the highest influence on ET_0 (0.429) of all the other years. It can be concluded that the ET_0 equation has a high sensitivity to R_s, based on the average SC(Rs) of 0.423. The final comparison of the average SC values for the entire analyzed period determines the prominence of R_s as the variable to which ET_0 is the most sensitive, followed by variables T_{max}, U_2 and T_{min}, respectively.

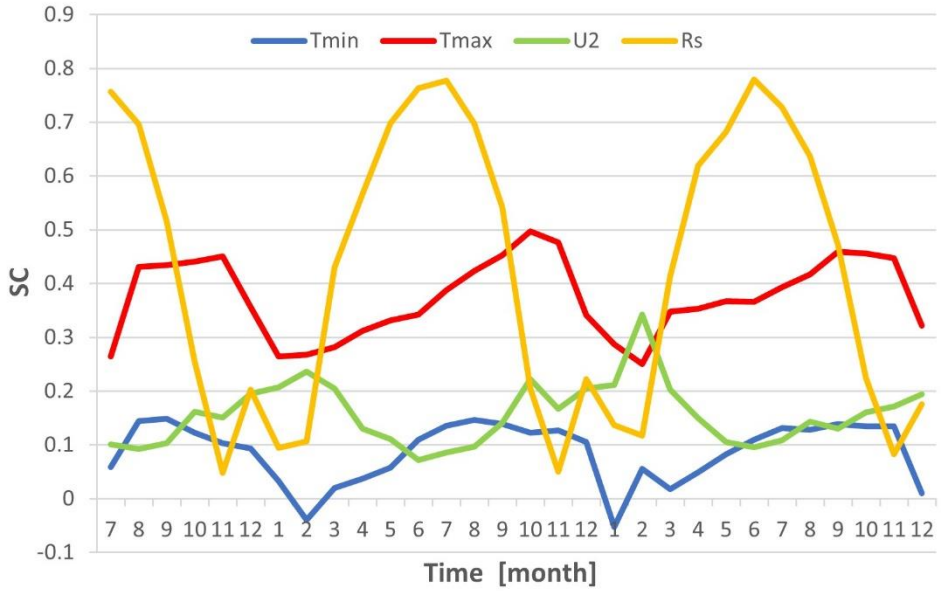


Figure 1. Sensitivity coefficients on a monthly basis

Table 1 represents the percentage change of ET_0 due to the relative change of meteorological variables. The relative change of variables includes T_{min}, T_{max}, U_2 and R_s, used for the calculation of ET_0. The visual relationship between the change of ET_0 and the variables is presented in Figure 2 in the form of the sensitivity curve. According to Figure 2, there is a linear sensitivity relationship, with a positive trend, between the relative changes of ET_0 and the variables. What is more, based on Table 1 and Figure 2, it can be concluded that the changes of T_{max} and R_s have a greater influence on the ET_0 changes than other variables do. The negative relative changes of T_{max} and R_s are almost the same, while there is a small

difference between the positive changes. The influence of U_2 change on ET_0 is relatively low, i.e. lower than that of T_{max} and R_s. This result is expected, considering the urban conditions and their impact on U2 (trees, houses and other urban obstacles).

Table 1. Change of ET_0 (%) considering the change of meteorological variables

	-20%	-15%	-10%	-5%	5%	10%	15%	20%
T_{min}	-1.696	-1.283	-0.863	-0.435	0.443	0.895	1.355	1.825
T_{max}	-7.179	-5.436	-3.660	-1.849	1.888	3.816	5.788	7.806
U_2	-3.161	-2.365	-1.573	-0.785	0.781	1.559	2.334	3.104
R_s	-7.111	-5.333	-3.556	-1.778	1.778	3.556	5.333	7.111

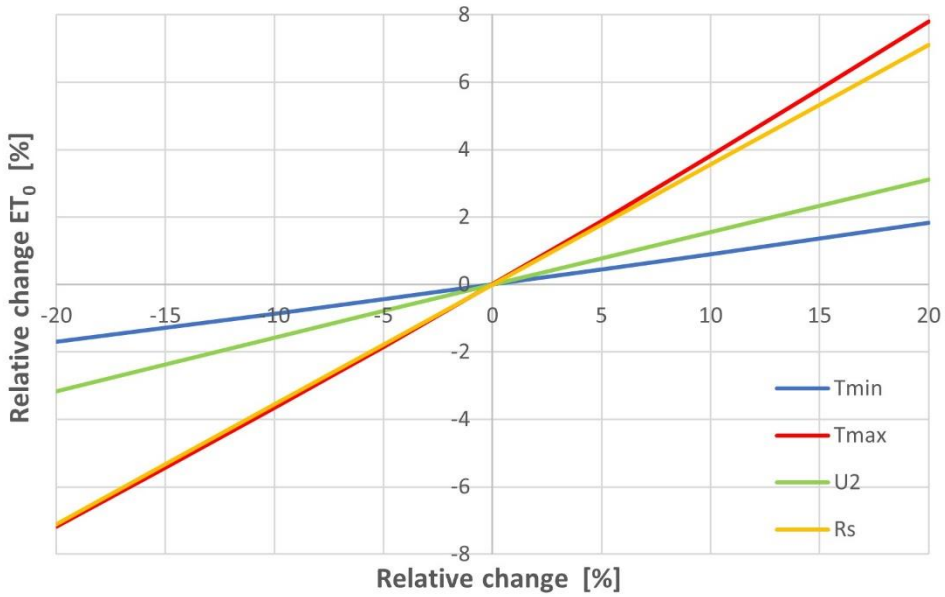


Figure 2. Sensitivity curve for four meteorological variables

4. CONCLUSION

The sensitivity of reference evapotranspiration on key meteorological variables was conducted in one urban area of Nis. Reference evapotranspiration was observed using the FAO 56 Penman-Monteith equation and the mentioned key variables included in the equation calculation, which are T_{min}, T_{max}, U_2 and R_s. The sensitivity analysis was based on the sensitivity coefficients and sensitivity curve method, where the influence of variables was separately analyzed. All the relative changes of variables have demonstrated the linear connection with the relative change of ET_0. The results revealed that the P-M equation is highly sensitive to the changes of T_{max} and R_s, while T_{min} caused the lowest changes, i.e. sensitivity of the equation. The monthly values of SC showed that there is a high variation in the changes of variables, especially in terms of the variations of R_s.

Further study will be oriented towards the connection of the sensitivity analysis with the dependence and uncertainty analysis. Moreover, the urban areas of Nis will be analyzed using the data from more positions.

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Research paper

THE PRINCIPLE OF RECESSING RESIDENTIAL SPACES INTO THE DEPTH OF THE APARTMENT AND ITS APPLICATION IN APARTMENT ORGANIZATION IN SERBIA

Đorđe Alfirević[1], Sanja Simonović Alfirević[2], Sanja Nikolić[3]

Abstract

Natural lighting is a key factor in the organisation of residential space, influencing visual comfort, psychological well-being, and energy efficiency. This paper analyses spatial configurations of apartments in Serbia, focusing on the retreat of residential rooms, particularly kitchens, into interior zones lacking direct access to natural light. During the period of directed housing development, this principle was part of experimental architectural strategies aimed at spatial optimisation and flexibility. Today, however, it predominantly stems from investor-driven models prioritising economic profitability over housing quality. The research methodology involves a comparative analysis of floor plans from different periods, with special attention to lighting strategies for interior rooms. Findings highlight the dominance of layouts where kitchens are recessed behind dining and living spaces, often leading to reduced lighting and ventilation quality. The paper identifies architectural strategies, such as skylights, internal windows, and flexible partitions, to improve daylighting in compact residential units. The results contribute to understanding contemporary trends and propose guidelines for enhancing living quality in apartments where natural light is limited.

Key words: *apartment layout, design principles, Belgrade School of Housing, contemporary apartment, transitional apartment*

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1. INTRODUCTION

Natural lighting is a fundamental factor affecting the functionality, visual comfort, and energy efficiency of residential space, while also positively influencing psychological well-being, mood, and circadian rhythm regulation [1]. Contemporary architecture increasingly highlights natural light not only for energy efficiency but also for improving living quality. Different residential activities require varying daylight levels: living areas (living room, dining room, kitchen) demand abundant light, bedrooms and workspaces require controlled lighting, while auxiliary spaces (hallways, bathrooms) can function with reduced illumination, although natural light enhances spatial openness [2].

Contemporary housing construction in Serbia increasingly compromises lighting quality for economic viability. Investor-driven models, prioritising space maximisation and more units per floor, often withdraw kitchens, dining rooms, and even living rooms into interior zones without direct daylight, raising concerns about living quality [3].

The aim of this research is to investigate how the inward relocation of residential rooms affects natural lighting quality and living comfort. Furthermore, the study explores potential strategies for improving the illumination of these spaces through architectural solutions such as skylights, internal windows, reflective surfaces, and flexible partitions.

The research is based on the hypothesis that the principle of relocating residential rooms towards the inner zones of the apartment has been present in Serbia since the period of directed housing construction, where it was employed as an experimental design approach aimed at enhancing living quality. In contemporary housing, however, this principle predominantly appears as a consequence of an investor-oriented model, which prioritises economic efficiency at the expense of natural lighting and the quality of the living environment.

1.1. Review of existing research

Previous studies provide the theoretical framework for analysing the relationship between natural lighting and the spatial organisation of apartments, as well as trends in contemporary Serbian housing. Key directions include studies on the principles of lighting in architecture, the Belgrade School of Housing, spatial flexibility and optimisation, and the retreat of rooms into deeper zones.

Several authors highlight the fundamental role of natural lighting in shaping residential spaces: Guoqing et al. discuss the "light and darkness" conceptual system [4]; Kaheneko examines how spatial and façade design influence lighting optimisation [5]; Gill underlines the role of window placement in defining spatial atmosphere [6]; Kristl and Krainer focus on skylights with reflective surfaces [7]; Madsen introduces the concept of light zones [8]; Morales-Bravo and Navarrete-Fernandez connect improved lighting with emotional well-being during the pandemic [9]; Saadat et al. emphasise the traditional link between lighting, spatial layout, and culture [10]; while Wirz-Justice, Skene & Münch highlight its effect on circadian rhythms and quality of life [11].

Research on apartment organisation in Serbia documents historical evolution: from the early modern Belgrade salon-type apartment [12], to the "extended communication" concept in the late modern Belgrade apartment [13]. Marušić identifies ten key design principles from this era, including day-night zone separation and circular connection [14], while Čanak emphasises the regulatory contribution of Bajlon and IMS [15]. Milenija

Marušić stresses the importance of daylight in defining quality housing [16]. In the post-socialist period, Serbia's housing architecture was reshaped by neoliberalisation, leading to reduced quality, privatisation, and illegal construction [17]. Stoiljković analyses investor-driven housing for diminished spatial quality [18], while Petrović et al. highlight the marginal presence of high-quality housing [16] and later define a new organisational type featuring room retreat into interior zones [19].

Flexibility and optimisation are addressed by Alfirević & Simonović Alfirević through multi-layered spatial strategies [2], by Stoiljković et al. through circular economy principles [20], and by Biondić through rational layouts and multifunctional spaces [21]. Krstić et al. propose regulatory changes to improve flexibility in Niš apartments [22].

Regarding room retreat, Petrović et al. note that linear organisation in investor-driven housing leads to reduced daylight and ventilation [19]; Knežević warns that excessive building depth reduces housing quality [23]; Kondrat'eva & Volkov propose glass partitions and stained-glass solutions to compensate for interior depth [24]. Ovenden & McKelvie observe the dominance of open-plan layouts facilitating daylight but reducing flexibility, with secondary uses often relegated to bedrooms [25]. Đukić, Lojanica, and Antonić report severe shortcomings in natural lighting in new Belgrade residential projects [26].

Overall, a review of existing studies highlights a clear gap: while the importance of natural light and spatial organisation has been widely acknowledged, research explicitly linking the retreat of rooms into deeper zones with lighting issues in the Serbian housing context remains limited.

2. RESEARCH METHODOLOGY

The research methodology is based on the analysis of apartment floor plans collected from online sources, professional publications, and previous studies. The aim is to systematically examine characteristic spatial configurations in Serbia to investigate the retreat of residential rooms into interior zones and its impact on natural lighting.

In the first phase, floor plans illustrating various models of room positioning relative to façade openings and daylight access were selected, based on criteria including: a) the position of rooms relative to the façade, focusing on inward-set spaces; b) the placement and size of windows; c) applied lighting strategies for deeper zones; d) apartment typology.

Subsequently, a comparative analysis identified dominant patterns of spatial organisation and assessed their consequences for visual comfort. Possibilities for improving daylighting are addressed in the discussion and conclusion.

In the final phase, a systematic categorisation of spatial models and their daylighting characteristics was carried out, aiming to provide insights into existing design patterns and strategies for enhancing daylight comfort in contemporary residential architecture.

2.1 Theoretical framework: Lighting requirements of residential functions and their spatial positioning within the apartment

Optimal natural lighting in residential rooms depends on their orientation and façade openings, directly affecting daylight access and spatial comfort [27]. Stojiljković notes that room layout should align with sun exposure: south-facing façades receive most sunlight,

north-facing façades provide diffuse light, while eastern and western sides vary throughout the day [28].

During summer, sunlight strikes the southern façade at a steep angle, resulting in shallow interior penetration, while in winter, lower solar angles allow deeper light entry. The east façade is suitable for bedrooms and dining areas due to moderate morning light, while the west façade, prone to overheating, is recommended for secondary rooms. North-facing spaces benefit from stable diffuse light, ideal for work areas. In multi-family buildings with limited orientation, optimising light distribution becomes crucial [28].

Natural lighting influences the layout of rooms relative to building orientation and tract depth. Traditional apartments with rooms along the façade offer good lighting but require wider plots. Deeper residential tracts often push kitchens and secondary spaces inward, reducing daylight access [29]. Compact apartments (7–10 m depth) with single orientation allow only partial daylight access, necessitating compromises where living rooms and bedrooms are placed near façades, while kitchens, dining rooms, and bathrooms are pushed into less illuminated areas. The layout of rooms within an apartment largely depends on their specific requirements for natural lighting, which are determined based on the function of the space, frequency of use, and user needs. (Fig. 1)

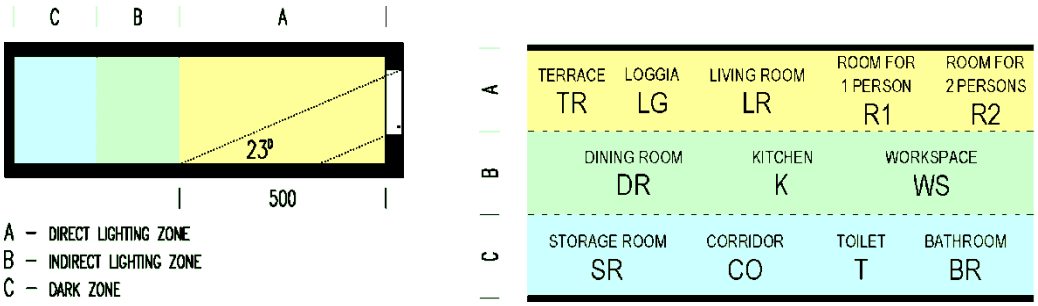


Figure 1. Positioning of rooms according to their need for natural light (Source: author's archive)

Rooms are grouped into three zones based on lighting needs (Table 1):

A) Direct lighting zone – includes living rooms, terraces (loggias), and bedrooms, requiring abundant daylight, ideally from south, east, or west. While terraces may benefit from shade, bedrooms benefit from morning light but require darkness for sleep.

B) Indirect lighting zone – covers dining rooms, kitchens, and workspaces, where indirect or stable northern light suffices for informal activities and computer work. Kitchens, however, need strong lighting for precision tasks.

C) Dark zone – consists of bathrooms, toilets, hallways, and storage rooms, typically located internally, relying on artificial lighting.

Table 1. Residential rooms categorised by their need for natural light (Source: author's archive)

Room Type	Most Common Activities in the Room	Lighting Requirements by Room Type		
		Need for Direct Natural Light	Acceptable with Indirect Natural Light	Acceptable without Natural Light
Terrace / Loggia	gymnastics, animal keeping, leisure, socializing, conversation, rest	✓ (desirable)	✓ (depending on orientation)	✗
Living Room	leisure, socializing, conversation, reading, watching media	✓	✓	✗
Bedroom	sleeping, rest, dressing, isolation, socializing, sexual activity, taking care of family members, gymnastics, storing clothes	✓ (for waking, dressing)	✓ (for resting)	✗
Study Room	reading, writing, socializing, computer work	✓	✓	✗
Dining Room	food serving, eating, socializing, conversation	✓	✓	✗
Kitchen	food preparation, food serving, dishwashing by hand or dishwasher, food storage, kitchen utensils storage, waste disposal	✓	✓(if well ventilated)	✗
Pantry	food storage, storage of objects, kitchen utensils storage, waste disposal, maintenance	✗	✓	✓
Bathroom	shaving and cosmetic care, washing, showering, hygiene, laundry by hand or machine	✗	✓	✓
Toilet	shaving and cosmetic care, hygiene, toilet use, washing, laundry by hand or machine	✗	✓	✓
Laundry room	laundry, ironing, storage of laundry and household items	✗	✓	✓
Hallway	movement, storage of various items: books, household appliances, dressing, undressing, maintenance	✗	✓	✓

This table outlines minimum daylighting requirements based on room function, frequency of use, and the nature of activities performed. Rooms listed as "acceptable without natural light" are not recommended to be windowless, but rather can function with appropriate artificial lighting. Natural light remains beneficial in all rooms for comfort, hygiene, and energy efficiency.

Natural lighting provides health, psychological, and energy-efficiency benefits superior to artificial sources [1]. Therefore, despite minimum illumination standards, natural daylight remains preferable wherever possible [30].

2.2 Analysis of characteristic examples of room withdrawal into the depth of the apartment in Serbia

The principle of withdrawing residential rooms deeper into the apartment has been present in Serbian architecture for several decades. Its early traces appear in the spatial concept of salon-style apartments, where a centrally positioned multifunctional room served as an antechamber and formal dining space. This spatial pattern, developed between the two World Wars in Belgrade and later adopted in other cities, became known as the "Belgrade apartment" through the works of architects such as B. Kojić, A. Medvedev, G. Samojlov, A. Sekulić, and M. Borisavljević [31, 13, 32].

After the Second World War, professors from the Faculty of Architecture in Belgrade (M. Bajlon, B. Milenković, and B. Aleksić) introduced the concept of an “extended circulation area” as a reinterpretation of the salon model, centrally positioned to accommodate a family dining table [13]. In spatially constrained apartments, this area served as an informal gathering space [33]. During the 1970s and 1980s, the influence of Alvar Aalto’s kitchen concept, introduced in the "Hansaviertel" residential complex (Berlin, 1957), became evident in Serbia [34]. Prior to this, dining rooms were usually directly lit and placed next to kitchens or living rooms [35]. Aalto’s design enabled the kitchen to be relocated behind the dining room, deeper into the apartment, using indirect lighting and thereby reducing building depth, aligning with the trend of compact apartment layouts during the era of directed residential construction [36]. (Fig. 2)

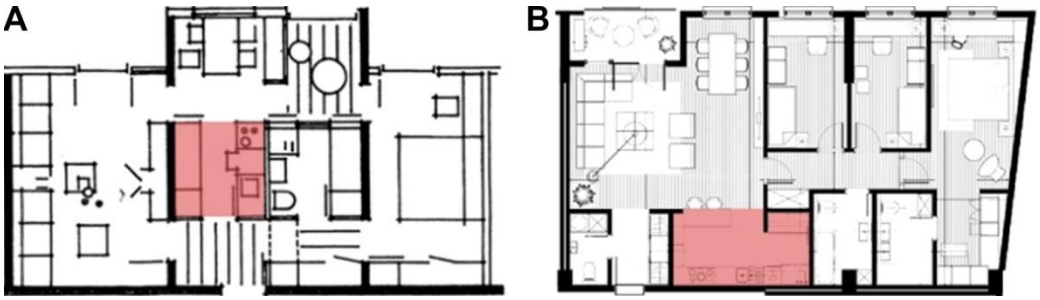


Figure 2. Characteristic examples of room recession in Serbia: a) the period of directed housing construction; b) contemporary example. (Source: author’s archive)

2.2.1 Examples from the period of directed housing construction (1960–1990)[3]

Numerous examples of multi-family housing in Serbia during the period of directed housing construction were based on the concept of linear arrangement of residential rooms along the façade, with the auxiliary rooms set back in a second row behind the residential ones. This layout enabled optimal daylight access and visual comfort within the apartment.[4]

A major breakthrough occurred with the residential building in Kralja Petra Street, Belgrade (Macura, 1957), where a dual-tract layout set the kitchen towards an internal light well. This model encouraged experimentation with spatial recession among Serbian architects [40]. The implementation of the Aalto kitchen significantly influenced this trend, particularly during directed housing construction. The Aalto concept enabled efficient layouts, improved lighting, and enhanced dining room flexibility, relying on direct illumination of dining spaces and indirect or artificial lighting for kitchens. This rationalised space use

[3] The period of "directed housing construction", during which the primary objective was to define the existential minimum in collective housing, while ensuring maximum spatial rationalisation and optimal functionality of flats, represents the most significant phase in the development of residential architecture in Yugoslavia [37, 38].

[4] Notable examples include: Block 2 (Petričić, 1963), Šumice estate (Mendelson, Carević, 1968), Blocks 45 and 70 (Šekerinski, 1970), Konjarnik (Ćirković, Jerotijević, Vrbić, 1976), Kijevo-Kneževac (Đokić, Čanak, 1976), Nova Galenika (Bakić, Bakić, 1978) in Belgrade, “Kablovi” and “Pivara” estates in Jagodina (Brašovan, Petrović, 1967), “Rasadnik” towers in Kruševac (Pejčinović, 1975), “Rudar” estate in Majdanpek (Stanković, Novaković, 1987), and Bulevar Oslobođenja building in Novi Sad (Jankov, 1967) [39].

and facilitated daily activities, especially in small and medium-sized apartments. Numerous examples in Serbia adopted this model, withdrawing kitchens behind dining areas.[5]

Beyond the Aalto kitchen concept, other innovative layouts emerged, such as placing the kitchen in front of the dining area, or more frequently, positioning the dining room behind the living room. This arrangement optimised kitchen lighting and ventilation, crucial due to its intensive daytime use. Direct natural light and air access enhanced work conditions, reduced moisture, and improved odour elimination. Conversely, recessing the dining area improved living room daylighting and visual openness, enabling a clearer functional division and greater flexibility.[6] (Table 2)

Table 2. Characteristic examples from the period of directed housing construction and the application of the principle of recessing rooms deeper into the apartment; Source: author's archive

Name of the Building or Complex	Recessing rooms deeper into the apartment				
	kitchen behind dining	dining behind kitchen	dining behind living	living behind dining	kitchen by skylight
Blocks 1 and 2, Belgrade (Petričić, 1963)			●		●
Block 21, Belgrade (Čanak, Lenarčić, Mitić, Petrović, 1965)	●				
Šumice estate, Belgrade (Mendelson, Carević, 1968)	●				
Banjica estate, Belgrade (Drinjaković, Karadžić, Stjepanović, 1971)	●				●
Julino Brdo estate, Belgrade (Lojanica, Cagić, Jovanović, 1971)	●				
Building O2, Kraljevo (Todorović, 1971)	●				
Vojvode Stepe Boulevard towers, Belgrade (Aleksić, Aleksić, 1973)			●		
Liman 3 towers, Novi Sad (Vučković, Komadina, Đerasimović, 1973)	●				
Blocks 61 and 62 (southern section), Belgrade (Marušić, Marušić, Miodragović, 1978)			●		●
Block 22, Belgrade (Janković, Karadžić, Stjepanović, 1974)	●				
Block 23, Belgrade (Janković, Karadžić, Stjepanović, 1974)	●				
Block 28, Belgrade (Arnautović, 1974)	●				
Block 30, Belgrade (Martinović, 1977)	●				
K1 and K3 buildings, Kraljevo (Gajčanin, 1977)	●				
C3 and C4 buildings, Kraljevo (Maričić, Dimitrijević, Simeunović, 1978)	●				
Blocks 61 and 62 (southern section), Belgrade (Marušić, Marušić, Miodragović, 1978)	●				
Novo naselje, Novi Sad (Milidragović, 1982)				●	
Block 19a, Belgrade (Lojanica, Cagić, Jovanović, Marić, 1982)			●		●
Cerak Vinogradi, Belgrade (Marušić, Marušić, Borovnica, 1985)		●			
Toplička mixed-use building, Užice (Mitrović, 1985)		●	●		
"United Nations" estate, Kruševac (Đorđević, Kovačević, 1986)	●				

[5] Notable examples include: Block 21 (Čanak, Lenarčić, Mitić, Petrović, 1965), Block 22 and 23 (Janković, Karadžić, Stjepanović, 1974), Block 28 (Arnautović, 1974), Block 30 (Martinović, 1977), Šumice estate (Mendelson, Carević, 1968), Banjica estate (Drinjaković, Karadžić, Stjepanović, 1971), Julino Brdo estate (Lojanica, Cagić, Jovanović, 1971), Blocks 61 and 62 (southern section) (Marušić, Marušić, Miodragović, 1978) in Belgrade, Building O2 (Todorović, 1971), K1 and K3 buildings (Gajčanin, 1977), C3 and C4 buildings (Maričić, Dimitrijević, Simeunović, 1978) in Kraljevo, Liman 3 towers (Vučković, Komadina, Đerasimović, 1973) in Novi Sad, and "United Nations" estate in Kruševac (Đorđević, Kovačević, 1986) [39].

[6] Notable examples include: Cerak Vinogradi (Marušić, Marušić, Borovnica, 1985), Blocks 1 and 2 (Petričić, 1963), Vojvode Stepe Boulevard towers (Aleksić, Aleksić, 1973), Blocks 61 and 62 (northern section) (Marušić, Marušić, 1974), Block 19a (Lojanica, Cagić, Jovanović, Marić, 1982) in Belgrade, and Toplička mixed-use building (Mitrović, 1985) in Užice. [39].

2.2.2 Examples from the post-2000 period

The early 21st century in Serbia marked the end of a prolonged political, economic, and social crisis, culminating in the 1990s. The transition from socialism to capitalism unfolded amid rising economic inequality and social polarisation. Private investors, often linked to political structures, assumed a dominant role in architectural production. Privatisation accelerated the degradation of the construction industry, with state-owned firms closing or being mismanaged. Although the state promoted housing development through privatisation and legalisation of informal construction, initial projections proved misguided [41, 42]. This period saw the emergence of the “transitional” apartment, an intermediate typology between socialist and contemporary housing, distinguished by the separation of day and night zones, grouping of bedrooms and bathrooms around a hallway (degažman), and the formation of an entrance corridor with a toilet. A pivotal change was the notable introduction of the open-plan concept, integrating the living room, dining area, and kitchen [43].

Over the past two decades, residential construction expanded significantly, particularly in Belgrade, Novi Sad, and Niš. This growth was dominated by “developer-led” construction, with investors exerting substantial influence over design, construction, and planning. This approach often prioritised private interests over societal needs and the public good [44]. Consequently, a new type of contemporary apartment emerged, tailored to market demands, maximising the number of rooms within minimal floor area, prioritising spatial efficiency over living quality. A study by V. Petrović, B. Stoiljković, N. Petković, and H. Krstić identified the following characteristics [3] (Fig. 3):

- Linear spatial development, often lacking a clear focus;
- Entrance position having little effect on the layout;
- Open-plan integration of living, dining, and kitchen areas;
- Kitchens typically recessed, without direct natural lighting or ventilation;
- Bedrooms arranged along corridors, reducing privacy;
- Excessively long circulation spaces due to poor organisation;
- Absence of auxiliary rooms and storage, even in larger apartments;
- Predominantly single-sided orientation of units.

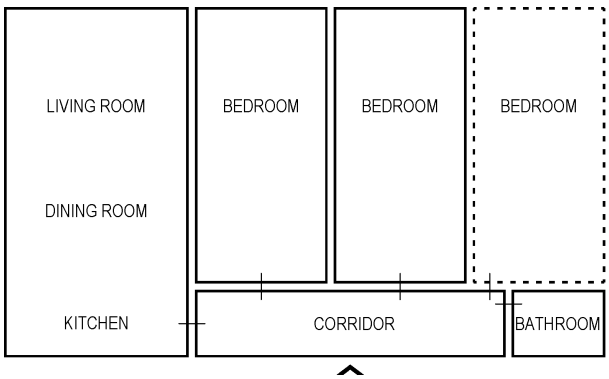


Figure 3. Diagram of the spatial and functional organisation of the contemporary apartment in Serbia (Source: [3])

The recessing of kitchens behind living and dining areas results in several adverse effects: increased dependence on artificial systems, odour retention, heat accumulation,

reduced external connection, and extended circulation spaces, diminishing functionality and flexibility. Additionally, kitchen noise disrupts activities within the open-plan area, while poor ventilation fosters moisture and hygiene issues. Loss of spatial hierarchy and intimacy further compromises living quality.

Table 3. Characteristic examples from the post-2000 period and the implementation of the principle of recessing rooms into the depth of the apartment (Source: authors' archive)

Name of the Building or Complex	Recessing rooms deeper into the apartment				
	kitchen behind dining	dining behind kitchen	dining behind living	living behind dining	kitchen by skylight
Residential building Suncity, Belgrade (Merin Group, 2017)	●		●		
Residential complex Cara Dušana, Belgrade (Bureau Cube Partners, 2018)	●		●		
Central Garden residential complex, Belgrade (Mašinoprojekt Kopring, 2018)	●		●		
Palace One residential complex, Belgrade (Koling, 2022)	●		●		
Keneddy Residence residential complex, Belgrade (Zabriskie, 2022)	●		●		
Kosa Quart residential complex, Belgrade (Energoprojekt, 2023)	●		●		
Savada residential complex, Belgrade (NeimarV, 2022)	●		●		
K District residential complex, Belgrade (3LHD, 2023)	●		●		
Novi Dorćol residential complex, Belgrade (Synthesis Inženjering PPI, 2023)	●		●		
Sakura residential complex, Belgrade (2023)	●		●		
Elixir Garden residential complex, Belgrade (2023)	●		●		
Skyline residential complex, Belgrade (Ami Moore, 2023)	●		●		
The One residential complex, Belgrade (Lotus architecti, 2024)	●		●		
Smartblock residential building, Pančevo (2023)	●		●		
Laguna Residence residential building, Novi Sad (2013)	●		●		
Sokolis residential complex, Kragujevac (2025)	●		●		●

Table 3 confirms the dominant trend of recessing kitchens and dining areas into deeper apartment zones, most commonly positioning kitchens behind living and dining spaces. This principle was consistently applied in all analysed buildings, demonstrating its widespread use. Instances of the dining area behind the kitchen are rare, and living rooms located internally are even rarer. These findings corroborate earlier observations of market-driven spatial optimisation and highlight the resulting negative impacts on natural lighting, ventilation, and functionality.

3. RESULTS AND ANALYSIS

The analysis of contemporary residential construction in Serbia has revealed a clear tendency to recess certain residential functions into the inner parts of the apartment, most commonly affecting the kitchen and dining zones. The most frequently applied configurations include positioning the kitchen behind the dining area, the kitchen behind both the dining area and living room, and, in less frequent cases, the living room placed behind the kitchen. These patterns were identified in the floor plans of the analysed apartments and confirm a trend toward surface rationalisation through linear spatial organisation. A kitchen positioned within the interior of the apartment often lacks direct

natural lighting and ventilation, while recessing the living room behind the kitchen adversely affects spatial perception and the quality of the living experience. The predominant pattern involves placing the kitchen in a shaded zone, whereas the loss of direct natural lighting in the dining area is less commonly observed in contemporary practice. These spatial configurations reflect current trends in residential construction, where surface optimisation is prioritised, frequently at the expense of adequate lighting and ventilation quality [3].

A comparison between apartments from the period of directed housing construction and contemporary examples reveals significant changes in spatial organisation. Apartments from the era of directed housing development were characterised by separate and clearly hierarchised residential rooms, typically with direct natural lighting, a central circulation core enabling functional distribution of spaces, and sufficient surface area allocated to auxiliary rooms [39]. In contrast, contemporary housing models increasingly involve rationalised layouts with reduced circulation areas and the integration of multiple functions into shared spaces, resulting in diminished privacy and compromises in lighting and overall functionality. A notable contribution to mitigating these effects is the implementation of the open-plan concept, which allows diffuse natural light to penetrate deeper into the apartment, thereby partially compensating for the loss of direct illumination in recessed spaces [2]. (Fig. 4)

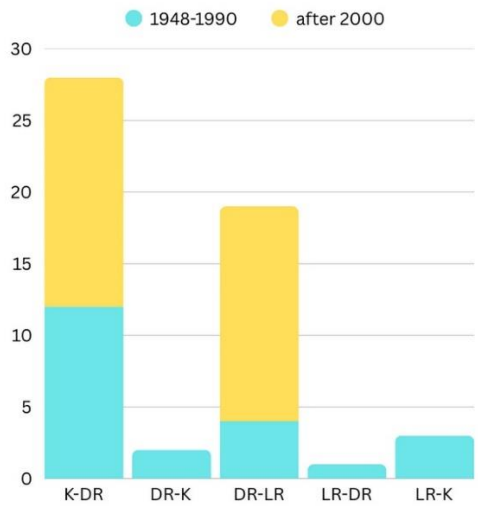


Figure 4. Prevalence of the Principle of Recessing Residential Rooms into the Interior of the Apartment in Serbia (K-kitchen, DR – dining room, LR – living room) (Source: Authors' archive)

The main problems and challenges concerning the lighting conditions in these apartments relate to the lack of natural light in recessed rooms, the reliance on artificial lighting which increases energy consumption, the absence of natural ventilation in interior-positioned kitchens, as well as potential negative psychological effects associated with reduced daylight exposure. The identified patterns suggest that spatial transformations are most often driven by investor-oriented logic, while alternative design strategies for lighting are marginalised or entirely omitted. These findings point to the need for innovative design approaches that can ensure improved lighting and ventilation in residential units, without compromising market demands and economic considerations in contemporary housing development.

4. DISCUSSION

The results of the analysis of spatial configurations in Serbian apartments indicate that the principle of recessing residential functions into the interior of the dwelling is not a contemporary construct, but rather has theoretical foundations in the experimental practices of the Belgrade School of Housing from the second half of the 20th century. During that period, this approach formed part of broader research into the flexibility of housing units and the optimisation of space within the context of mass housing construction. However, in current practice, the recession of rooms increasingly appears as a consequence of investor-driven rationalisation, in which economic profitability is prioritised over the quality of everyday life for users.

Previous research has emphasised the significance of natural daylight for the visual and psychological comfort of residents [1], while contemporary authors warn that the lack of daylight can lead to sleep disturbances, fatigue, reduced productivity, and impaired mental health. In this context, the study confirms that positioning rooms in the interior zones of the apartment has direct consequences for daylight comfort, energy needs, and the subjective perception of spatial quality. The main issues associated with recessed rooms manifest in reduced natural lighting and ventilation, resulting in increased reliance on artificial lighting, higher energy consumption, and a decline in residential quality.

Psychological aspects also play an important role, as spending time in spaces with limited daylight can induce feelings of confinement, isolation, and diminished comfort, especially for users who spend most of their time indoors. This highlights the necessity of integrating design solutions that enable the influx of natural light into deeper parts of the dwelling.

To mitigate the negative consequences of such spatial arrangements, the following strategies can be implemented in practice:

- **Use of light wells (skylights)** - enabling the entry of natural light into central areas of the apartment, thereby improving illumination in interior rooms. This solution is particularly effective in multi-storey buildings where vertical lighting is feasible;
- **Use of internal windows (transom lights)** - allowing daylight from one room (which has access to the façade) to penetrate into another room without direct natural lighting, thus improving the illumination of interior zones. This solution was frequently employed in earlier periods of housing construction and may be reintroduced in the contemporary context;
- **Light reflection** - the use of light-coloured materials, mirrors, and reflective surfaces can enhance the distribution of light in internal rooms. This approach is especially effective when combined with semi-transparent partitions or open-plan layouts;
- **Flexible partitions** - transparent and semi-transparent partitions (e.g., glass, polycarbonate) allow for the transmission of light while preserving visual and spatial openness without compromising functionality;
- **Spatial reorganisation** - designing apartment layouts in such a way that spaces with the highest daylight requirements (e.g., living room, study) are placed along the façade, while those with lower lighting demands (e.g., bathrooms, storage rooms) are located in the central areas of the dwelling.

By combining these strategies, it is possible to improve daylight comfort even in apartments where the spatial organisation of rooms is constrained by plot limitations, building typologies, or market requirements. In this way, design approaches that take into account the lighting needs of different spaces can contribute to an enhanced quality of living, while maintaining economic rationality.

5. CONCLUSION

The research clearly indicates a dominant trend in contemporary housing construction in Serbia: the recession of kitchens, dining areas, and occasionally living rooms into the interior zones of apartments. Although this practice may be justified by the need for spatial rationalisation, it most often results in a deterioration of essential housing qualities - primarily in terms of natural lighting, ventilation, and the psychological perception of space.

The study's hypothesis, that the principle of recessing residential rooms into the interior was previously employed as an experimental design strategy to enhance housing quality, whereas today it is primarily applied for economic reasons, has been confirmed through the analysis of spatial configurations. The results show that this principle now appears predominantly in its extreme form, as a consequence of an investor-driven approach, where maximum space efficiency is prioritised, often at the expense of natural light and the overall quality of the living environment.

Further research could focus on the quantitative analysis of the effects of various lighting strategies in interior rooms, as well as comparative studies between apartments with different organisational models. It would be particularly beneficial to explore the long-term impacts of such solutions on energy efficiency, housing-related health aspects, and users' perceptions of spatial quality.

Within the field of architectural practice, it is recommended to consider innovative approaches to lighting interior rooms, with increased integration of transparent and reflective elements. Apartment design should aim to balance spatial rationalisation with residential quality, whereby architects and investors are encouraged to seek sustainable models that do not compromise fundamental spatial standards. Additionally, the implementation of adaptable and flexible partition systems should be considered, as these allow for greater responsiveness to lighting conditions and enhance the functional versatility of interiors.

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Research paper

TOWARDS A SMART CITY: A SMART DAM INITIATIVE IN NIŠ

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Abstract

A smart city represents an urban environment in which the application of digital technologies enables the improvement of the efficiency of city services such as energy, water management, waste disposal, and public safety. Its primary goals are to promote economic growth and innovation, improve the quality of life for residents, and create a more liveable, sustainable, and inclusive urban space. By establishing a connected and data-driven environment, cities can attract businesses and generate new opportunities. This paper presents a strategic initiative formed during the hackathon activity under the WATERLINE project and aimed at transforming the city of Niš into a smart city, focusing on revitalizing the Nišava River as a central element of urban development. The river training works from 1988 were constructed in both the minor and major riverbed of the Nišava River in the city zone, satisfying the architectural and urban planning requirements at that time. However, the minor riverbed has suffered from a lack of regular maintenance, resulting in significant challenges. In particular, the section of the river between the "Stone" Bridge and the "Mladost" Bridge is challenging due to non-functional thresholds, specifically three inflatable dams that have deteriorated due to insufficient maintenance and the effects of climate change. This decline has undermined the essential cityscape and urban planning objectives, making the Nišava riverbank less attractive for residential, recreational, sporting, tourism, cultural, and entertainment activities. The paper advocates for adopting new sustainable development concepts and intelligent digital solutions, proposing an integrated approach to enhance the community's overall well-being through incremental improvements. A key component of this initiative is establishing a smart dam project, which could be implemented through a public-private partnership (PPP) model. Additionally, this paper conducted a detailed SWOT analysis to assess the feasibility of the smart dam project.

Key words: *smart city, digital solution, river engineering, sustainable development, public-private partnership, SWOT analysis*

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1. INTRODUCTION

In the final decades of the 20th century, two significant trends emerged that dramatically reshaped urban landscapes: rapid urbanization and the widespread adoption of intelligent digital solutions. Technological developments pushed cities worldwide to seek efficient ways to manage new urban challenges.

Smart cities all share the characteristic of acting on their services and activities to make them more efficient. The ways they achieve this are very diverse, but they often have in common the use of digital technology resources (or ICTs, information and communication technologies) [1].

Figure 1 illustrates the technologies for creating smart cities. Data is a fundamental resource for any smart city, powering intelligent solutions. A smart city is considered 'data-driven,' meaning its operations and decisions revolve around data [2]. Rather than relying on gut instinct or outdated practices, smart cities leverage real-time data analytics to support evidence-based decision-making, ensuring urban interventions are precise, efficient, and responsive to citizens' needs.

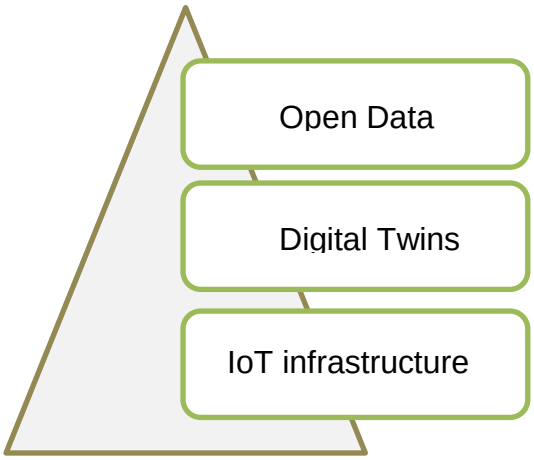


Figure 1. Technologies for creating smart cities

Smart cities initiatives generate transformative scientific value by merging IoT-enabled urban sensing, cyber-physical digital twins, AI-driven governance, distributed edge-cloud systems, and blockchain-secured collaboration into an integrated urban intelligence framework [3].

This paper presents a draft initiative to restore one of the three inflatable dams on the Nišava River in Niš and highlights how ICT solutions can improve the city's overall image and quality of life. Implementing it through Public-Private Partnerships (PPPs) can enhance urban resilience, optimize costs, and improve efficiency.

The study evaluates internal capabilities (Strengths and Weaknesses) and external factors (Opportunities and Threats) to determine the initiative’s strategic positioning and implementation challenges through SWOT analysis.

2. STUDY AREA

2.1 The City of Niš

Niš serves as a compelling case study in urban development, offering valuable insights into the dynamics of post-industrial transition, the integration of smart city initiatives, and regional economic resilience within Southeast Europe.

Scientifically analyzing its transformation reveals several key patterns: the city has successfully cultivated a knowledge-based economy through strategic clustering in the ICT sector [4], demonstrating an annual growth rate of approximately 15% [5], while simultaneously navigating the challenges of shifting from traditional manufacturing to high-value electronics production. According to [6], demographic trends present both challenges and opportunities, with negative net migration (-0.8% annually) among skilled youth contrasting with the IT sector's growing capacity for talent retention.

Over the past two decades, Niš has increasingly positioned itself as a regional innovation hub in Southeastern Europe, leveraging its university ecosystem, availability of skilled labor, and improving digital infrastructure. The presence of the Science and Technology Park, alongside initiatives supporting startup incubation, has further embedded innovation into the urban fabric. Nevertheless, the city continues to wrestle with infrastructural legacies from its industrial past, especially regarding environmental sustainability, energy efficiency, and water resource management. These issues have brought attention to the need for integrated, smart infrastructure solutions that combine digital technology with green urban planning principles. The "Smart Dam" initiative thus emerges as a natural extension of Niš's broader smart city agenda. By incorporating real-time monitoring systems, predictive analytics for flood prevention, and citizen-centric data platforms, the project serves as a pilot for integrating resilient water management into urban development strategies. Such efforts are aligned with EU smart specialization policies and reinforce the city’s ambition to become a model of sustainable urban transformation in the Western Balkans.

The city's ongoing transformation generates valuable data for researchers examining the complex relationship between legacy infrastructure, digital modernization, and spatial equity in developing urban contexts. In this sense, Niš stands not only as a case of economic transition but as a testing ground for adaptive governance, digital experimentation, and the democratization of urban innovation.

2.2 The Nišava River

The completed works in the minor and major riverbeds of the Nišava River within the urban zone meet architectural and urban planning requirements. The riverbed platforms include promenades and amphitheatres for sports and cultural-recreational activities. According to the Institute Jaroslav Černi [7], along the Nišava River from the railway bridge near the old "Vulkan" to the "Fortress" bridge, the left bank quay wall was constructed in the period 1957-1958. The bilateral river engineering structures of the Nišava River through the City (begun in 1987) cover the reach from the "Stone Bridge"to the bridge in "Proleterska" Street.

The minor riverbed is generally well-maintained and regularly cleaned. However, a problem persists on the section between the "Stone Bridge" and the "Mladost" Bridge, where three defunct inflatable dams (due to poor maintenance) have compromised the original

architectural and urban planning objective: creating a wider water surface in the minor riverbed to enhance aesthetic and microclimatic effects, making the Nišava riverbanks more attractive for leisure, sports, tourism, and cultural activities (Figure 2).



Figure 2. Urban zone of the Nišava River between the Fortress Bridge and the "Mladost" Bridge



Figure 3. The Nišava River Cross Profile at the Section between the Fortress Bridge and the “Mladost” Bridge near the kayak club “Gusar”

During low-water periods, when the riverside promenade is most appealing, the shallow water level and low flow velocity, combined with poor water quality, promote algae growth, often covering the entire minor riverbed (Figure 3).

The condition and maintenance of the river engineering structures along the Nišava in the city area are satisfactory. While the structures are generally well-maintained, the non-functional inflatable dams and the proliferation of algae during low-flow periods diminish the intended urban aesthetic and recreational benefits. Revitalizing these elements could enhance Nišava's role as a central public space in Niš. For instance, Figure 4 presents an illustrative example of an inflatable dam installation in Svrljig, in Serbia. It is evident that such a structure improves not only the aesthetic appeal of the river and its banks but also serves as a starting point for urban development. By improving the visual and functional quality of the waterway, the installation exemplifies how infrastructure can act as a foundational component for further urban revitalization efforts.



Figure 4. Before and after inflatable dam installation in the City of Svrljig

3. THE SMART SYSTEM

Over the past two decades, advancements in applying ICT in the water sector have increasingly transformed water resource management. These innovations will enhance real-time monitoring, predictive analytics, and adaptive governance of river systems, addressing critical challenges in efficiency, equity, and sustainability [8].

Industry 4.0 comes with high demands for system interconnectivity and high system autonomy. In order to provide high system autonomy, dependence on human factors should be minimized. Nowadays, with the fast development of artificial intelligence (AI) techniques, especially Machine Learning (ML) and Deep Learning (DL), it is possible to design intelligent control systems with viable applications in water level management [9-11]. The greatest advantage ML and DL models provide is noticing and learning patterns invisible to the human eye that exist in the data. Here, we propose a Smart IoT solution to solve the problem of water level management in the Nišava River. Figure 5 represents the position of the sensors for real-time monitoring according to the position of the inflatable dam.

The Smart IoT water level management system scheme is proposed in Figure 6. A Rubber Dam Controller unit (3) would control the rubber dam (2), which would receive information from several sensors (1) such as water level, water flow, and water quality sensors. The controller would also get information from a DL model, previously trained on the data from the Republic Hydrometeorological Service of Serbia. The DL model would be used to predict potential hazardous events such as droughts or floods based on the precipitation data and signals from the previously mentioned sensors. That way, the controller could react in advance and inflate or deflate the rubber dam. If such an event is predicted, the DL model could send a signal to the data center to alert the citizens of a potential problem.

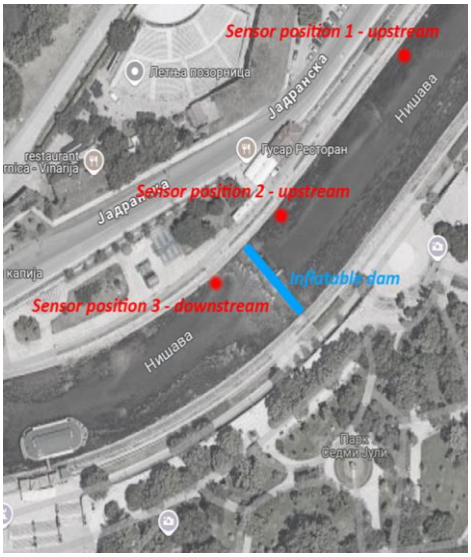


Figure 5. The Nišava River sector with sensor network deployment relative to the inflatable rubber dam

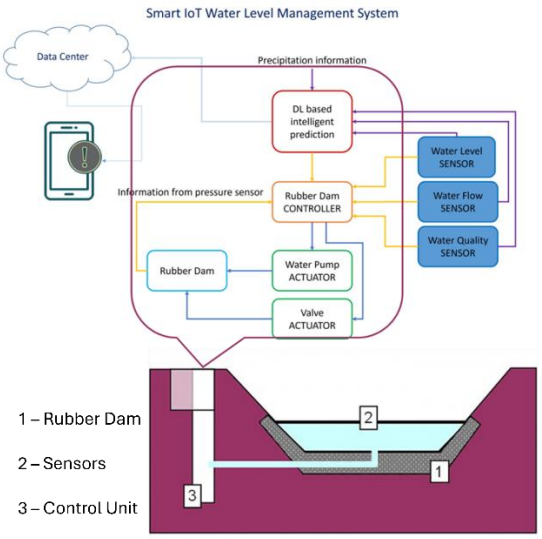


Figure 6.(on the right) Smart IoT Water Level Management System

4. INFLATABLE DAM

An inflatable dam is a modern hydraulic structure made of flexible, rubberized material, typically consisting of multi-layer fabric like nylon that is rubberized on one or both sides. Designed as an elliptical, inflatable, and deflatable structure, it is anchored to a concrete base and can be filled with water, air, or both using pumps, blowers, or valves. The inflatable dams are very similar in their structure. In this case, the water-filled inflatable dam is selected.

These dams are highly adaptable, allowing for adjustable heights to manage varying water levels, making them ideal for flood control, irrigation, water supply, and small-scale hydropower generation. Their installation is simple, requiring minimal labor and foundation work, and they perform well in low-resistance soils. Additionally, inflatable dams are cost-effective, with lower construction and maintenance costs, and their flexibility makes them resistant to earthquakes. However, they are vulnerable to damage from debris, extreme cold, and intentional harm, requiring careful design considerations such as deflectors to manage overflow. Despite these challenges, their ability to be deflated when not in use and their minimal environmental disruption make them a practical solution for modern water management needs [12].

The installation's cross profile of the Nišava River section is presented in Figure 7.

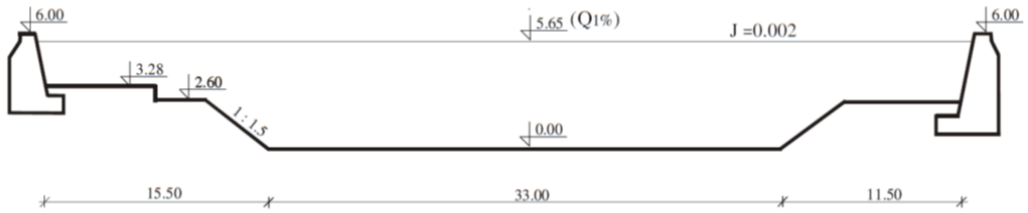


Figure 7. Cross Profile at the Nišava River section [13]

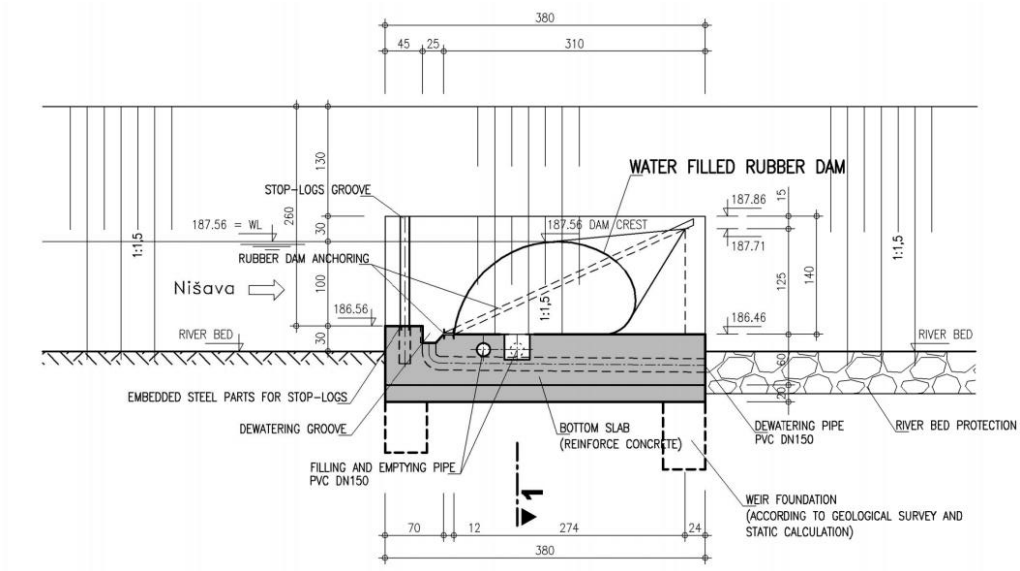


Figure 8. Inflatable Dam Construction Cross Profile

Figure 8 illustrates a proprietary solution of water-filled rubber dam co-developed with Korekt Company in Serbia, a technical partner of Trelleborg Slovenija. In recent years, this company has significantly enhanced its offering by introducing comprehensive turnkey solutions for rubber dam projects. This integrated approach is a fully operational system comprising of: rubber dam anchoring system, piping and control infrastructure, and electronic monitoring and control systems.

Considering the technological and functional benefits of the inflatable dam, its implementation in the urban core of Niš brings to light not only engineering challenges but also governance, financing, and community engagement issues. In such an urban and socially sensitive environment, traditional infrastructure delivery models may fall short in addressing the broader goals of sustainability, inclusivity, and public trust. Therefore, exploring public-private partnerships (PPPs), particularly the emerging “people-first PPP” (4P) approach, offers a promising avenue for balancing financial viability with social value. The next section evaluates the feasibility of applying a PPP model to this project in Niš, focusing on aligning local needs, private sector capabilities, and institutional readiness. A SWOT analysis is also presented to assess the strategic implications and potential risks associated with adopting such a model in the Serbian context.

5. PUBLIC-PRIVATE PARTNERSHIP AND SWOT ANALYSIS

The successful implementation of public-private partnership (PPP) projects is closely linked to improvements in infrastructure service quality, timely delivery, and broader economic growth. By mobilizing private sector investment and fostering efficiency, PPPs can generate significant macroeconomic benefits, including increased public sector capacity to invest in social services. However, achieving these outcomes requires strong institutional frameworks, transparent governance, and sound regulatory policies. When properly implemented, PPPs not only enhance local and regional development but also contribute to long-term national economic advancement by attracting long-term capital to strategic infrastructure sectors [14]. In this specific project, alongside the ordinary PPP project, which would include a public and a private partner, a 4P could be implemented and also include the "people" component, as the 4P accounts for public-private people partnership. This can be done through incorporating local non-governmental organisations, groups of citizens, or, for example, a local kayaking club that also has an interest in a smart working dam and improved conditions in the Nišava river in the center of the city. The public partner would be the City Council of Niš, and a private partner could be the producer of smart dams or some other entity that could find their interest in realising this project.

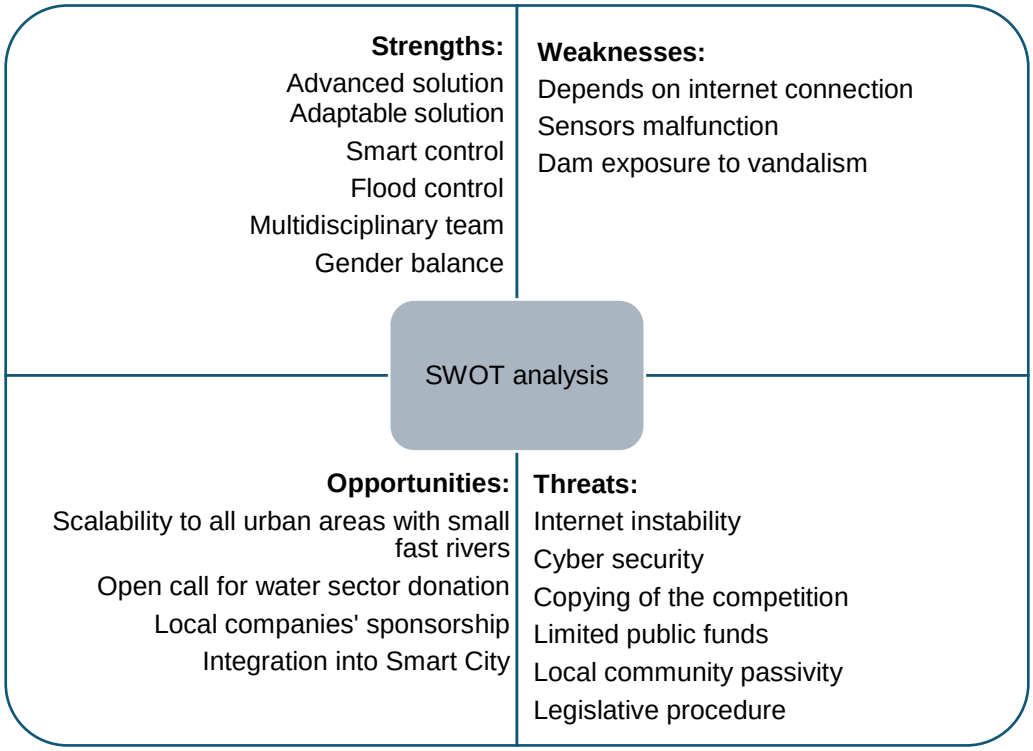


Figure 9. SWOT diagram of the Smart Dam initiative

This paper undertakes a detailed SWOT analysis to systematically assess the feasibility, strategic positioning, and potential challenges of the smart dam project. The SWOT framework examines strengths, weaknesses, opportunities, and threats and offers a structured methodology for evaluating internal and external factors that could influence project outcomes (Figure 9). Specific attention is given to local environmental conditions,

urban planning needs, technological infrastructure, and socio-economic benefits for the Niš community. Furthermore, the analysis considers the smart dam's capacity to foster community engagement, promote digital innovation in water resource management, and contribute to Niš's long-term sustainable urban development objectives [15]. Some strengths also refer to the team (authors of this manuscript) proposing the solution, as this paper was made after the authors took part in an entrepreneurship initiative during the hackathon activity under the WATERLINE project. The solution presented by the team aimed at transforming the city of Niš into a smart city, focusing on revitalizing the Nišava River as a central element of urban development and proposing ways to finance it. This should explain the multidisciplinarity of the team (architect, water engineer, automation engineer, computer engineer, and economist) as one of the strengths listed above. Another item that may need clarification is gender balance, as the team consists of three women and two men. The main trait of a multidisciplinary team is that it is able to analyse the problem from various angles and propose innovative and out-of-the-box solutions, while the gender balance, among other benefits, may serve well when applying for some grants or funds, both locally and internationally. In Table 1, some additional aspects from SWOT analysis are described.

Table 1. SWOT analysis categories and items of the Smart Dam Initiative

Categories	Items
Strengths	Enhanced flood control and water management capabilities; Promotion of digital innovation through real-time monitoring and smart infrastructure; Potential for public-private partnership (PPP) financing; Reducing public fiscal burden; Improved urban resilience and climate adaptation capacity; Opportunity for integration with urban revitalization projects (e.g., recreational spaces along the riverbanks)
Weaknesses	High initial capital investment costs; Potential technological maintenance complexity and long-term system sustainability issues; Dependence on effective governance and regulatory frameworks for PPP success; Limited existing experience with large-scale smart water infrastructure in Serbia; Possible resistance from stakeholders unfamiliar with smart technologies
Opportunities	Strengthening regional leadership in smart environmental infrastructure; Attracting EU funding and support through alignment with Green Deal and digitalization priorities; Fostering community engagement through educational and participatory initiatives; Development of new eco-tourism and recreational activities along revitalized riverfront areas; Potential replication model for other mid-sized cities in the Western Balkans
Threats	Economic fluctuations and fiscal pressures affecting investment capacity; Delays in administrative approvals and regulatory bottlenecks; Cybersecurity risks associated with smart infrastructure technologies; Environmental concerns if the project disrupts natural river ecosystems without careful planning; Public distrust if community involvement and transparency are not adequately ensured

The proposed inflatable smart dam in Niš exemplifies a strategically significant infrastructure initiative that aligns with local needs and broader sustainable development goals. As demonstrated in the SWOT analysis, the project presents a range of strengths, from enhanced flood resilience and digital water management to potential integration with recreational urban revitalization. Moreover, it offers a valuable opportunity to mobilize blended financing through public-private partnerships, thereby reducing fiscal pressure on local governments while ensuring timely and efficient project delivery. Critically, including a "people-first" public-private-people partnership (4P) model adds a unique social dimension to the project. By engaging local community stakeholders such as NGOs, sports clubs, and environmental groups, the initiative can foster public trust, increase community ownership, and ensure that the infrastructure serves not only technical but also social and environmental functions. Such participatory governance mechanisms have been increasingly recognized as essential for the long-term sustainability and public legitimacy of infrastructure projects [16]. Nonetheless, the project's viability depends on several preconditions: securing institutional support at the city level, ensuring technical competence and maintenance capacity, and mitigating risks related to digital infrastructure and environmental integrity. In addition, as this would be one of the first large-scale smart water infrastructure projects in Serbia, careful planning, transparent communication, and capacity building among public officials and citizens will be vital.

If these challenges are addressed through a robust implementation framework and community-centred planning, the inflatable dam in Niš could serve as a benchmark for similar mid-sized cities across the Western Balkans. It would not only demonstrate how to leverage smart technology for environmental resilience but also how to effectively operationalize inclusive PPP frameworks for holistic urban development. Such projects, when well-executed, have the potential to transform micro-level innovation into macro-level impact, thus stimulating economic activity, enhancing public services, and promoting regional competitiveness in line with EU integration and green transition objectives.

6. CONCLUSION

The development of smart cities represents a comprehensive strategy to address modern urbanization challenges through the strategic integration of cutting-edge technologies and collaborative governance models. By leveraging AI, IoT networks, and big data analytics, these initiatives enable evidence-based urban management that enhances infrastructure efficiency and improves the quality of life for residents. Within this framework, the presented Smart Dam initiative emerges as an innovative solution to critical water management challenges, combining technological sophistication with practical adaptability. This approach demonstrates how smart technologies can be effectively applied to solve pressing urban issues while maintaining cost-effectiveness and environmental sustainability.

The Smart Dam initiative embodies the principles of smart urban development through its intelligent water level management system, which offers real-time monitoring and adaptive control capabilities. This system provides cities with a powerful tool to address two major contemporary challenges: climate-induced flooding and water scarcity. The project's success stems from its versatile implementation team, whose multidisciplinary expertise ensures seamless integration with existing urban infrastructure while maintaining operational reliability. What makes this solution particularly valuable is its combination of technical

performance and economic viability, featuring significantly lower implementation costs compared to traditional alternatives and minimal environmental disruption during both deployment and operation.

The proposed inflatable smart dam project in the City of Niš represents an innovative and sustainable infrastructure initiative with strong potential to address local environmental and urban challenges. The project aligns economic efficiency with social inclusion and environmental responsibility by integrating the principles of public-private partnerships (PPP) and expanding toward people-first public-private partnerships (4P). The SWOT analysis underscores that the strengths and opportunities significantly outweigh the weaknesses and threats, especially when backed by strategic planning, transparent governance, and community engagement. The involvement of local citizens and organizations enhances the project's legitimacy and long-term success, transforming a traditional infrastructure investment into a collaborative model for urban resilience and digital innovation. As such, the smart dam project in Niš can serve as a scalable example for other cities in Serbia and the Western Balkans seeking to modernize water infrastructure through inclusive and sustainable partnership models.

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Research paper

ACCURACY IN BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

Ani Stefanova[1]

Abstract

This article examines the cantilever method for constructing bridge superstructures and highlights the lack of specific accuracy requirements in Bulgarian regulations for this technique. The study defines the necessary accuracy for building bridge superstructures using the cantilever concreting and assembly methods and calculates the precision required for determining the spatial coordinates of observed points on the bridge cantilevers. Through mathematical analysis, permissible deviations in height and plan position are established. The findings emphasize the importance of precise geodetic measurements and high-accuracy instruments to ensure structural integrity and minimize construction errors, ultimately contributing to improved quality control in cantilever bridge construction projects.

Key words: *Bridge superstructure constructions, Cantilever method, Regulations, Accuracy, Spatial coordinates*

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1. INTRODUCTION

Bridges are critical civil engineering structures designed to facilitate the safe passage of vehicles and pedestrians over physical obstacles such as rivers, valleys, roads, or industrial zones. A typical bridge consists of three main components: the substructure (piers and abutments), the superstructure, and the deck (roadway and associated elements). Each of these components requires precise planning, execution, and monitoring to ensure structural stability and long-term functionality.

The superstructure—the focus of this paper—is the primary load-bearing system of the bridge and can be constructed using different methods depending on factors such as terrain constraints, material availability, and construction technology. Two of the most widely adopted methods for constructing bridge superstructures are the cantilever method (using in-situ concreting or segmental assembly) and the segmental construction technique (typically involving precast elements). Both methods present specific challenges with respect to construction accuracy, particularly in terms of segment alignment, geometric control, and deflection management during erection.

The accuracy with which these methods are executed has a direct impact on the bridge's structural performance. Misalignments or positioning errors can accumulate and lead to significant deviations from the design geometry. This is especially critical in long-span or continuous bridges, where even minor angular errors can cause large displacements at the free ends. As such, geodetic surveying plays a vital role at every stage of construction—from the initial layout of foundations to the final positioning of segments.

This paper evaluates and compares the achievable accuracy of bridge superstructures constructed using cantilever concreting and cantilever assembly methods. It investigates the key technical factors that influence construction precision, including support system geometry, bearing alignment, segment fabrication, and real-time monitoring. By analyzing case studies and geodetic data, the study aims to identify best practices that help minimize geometric errors and improve construction accuracy in modern bridge engineering.

2. BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

One of the most common, effective and fine technologies for bridge construction is that of cantilever construction. It ensures the bridge construction in difficult-to-access terrains and/or deep valleys and water obstacles. The "cantilever construction" technology was created more than 60 years ago by the Norwegian company "Jacobsen" and is applied in two versions: monolithic (cantilever concreting - with 70 ÷ 330 m spans) and assembly (cantilever with 45 ÷ 135 m spans) [1], [2], [3], [4], [5], [6]. The largest bridge span built using the "cantilever concreting" method is 330 m (cantilever length - 165 m) - Figure 1.



Figure 1. Road bridge "Shibanpo", China [7]

There are two bridges in Bulgaria built via the "cantilever concreting" technology - the bridge at "Makaza" pass (Figure 2), near the town of Momchilgrad and the viaduct at the 48th kilometer of "Hemus" highway.



Figure 2. Cantilever construction of "Makaza" viaduct [8]

The principle of cantilever construction is shown in Figure 3 [1]. The building of the superstructure construction begins after the construction of the abutments and pillars which are implemented monolithically. The superstructure block "O" (Figure 3) in cantilever concreting is constructed monolithically and in cantilever assembly – either monolithically or as an assembly block on the corresponding pillar.

The supporting structure between each two adjacent piers is built with cantilevers symmetrically from each pier until they meet the opposite cantilevers built from the adjacent piers. When the two adjacent cantilevers meet, a "rigid connection" is formed, known under the term "key segment" - "A" (Figure 3 d) which makes it possible to level out the small spatial discrepancies of the two cantilevers.

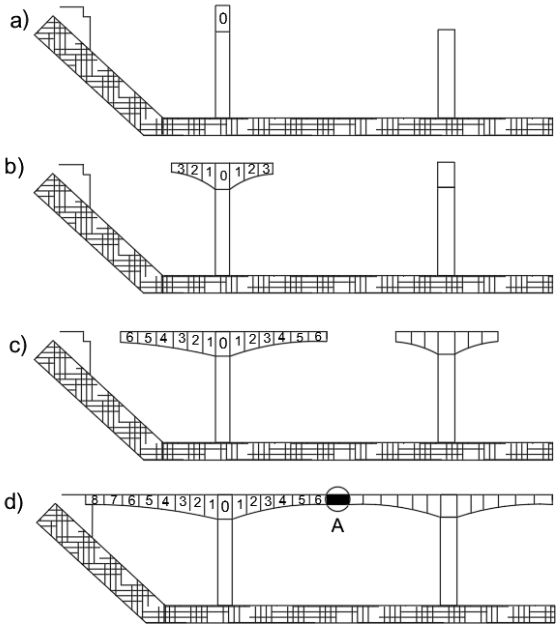


Figure 3. Cantilever construction principle [1]

Throughout the whole construction period, precise geodetic measurements are carried out to determine the spatial position of the frontal cross-section of each constructed segment and its deviations from the design. Based on these results, the necessary corrections are calculated in the position of the next segment and in the deformation, calculation models in order to reconcile the deformation characteristics with the results obtained from the measurement. The described sequence is repeated until the final completion of the bridge.

The scarce literature [6], [9], [10] mentions that measurements are performed with a total station, and for each stage of the implementation of the cantilevers, depending on the project geometry, relevant preparatory calculations are carried out - mainly coordinate transformations and setting out data.

Considering the extreme importance of geodetic measurements in the cantilever bridge construction, reliable control of the computational work and geodetic setting out works for the spatial orientation (so-called navigation) of the cantilevers must be carried out at each stage of the implementation. According to the author, this implies the development of a geodetic control system, including at least a high-precision geodetic device for determining spatial coordinates, a portable field computer with specialized software for calculation setting out data, and means of communication between them.

This idea is the basis of a research project developed at the University of Architecture, Civil Engineering and Geodesy, by means of which a working model of a geodetic control system for cantilever bridge superstructures construction was created. The geodetic control system is described in detail in the author's dissertation [11].

3. ACCURACY IN BUILDING BRIDGE SUPERSTRUCTURE CONSTRUCTIONS VIA CANTILEVER CONCRETING OR ASSEMBLY METHOD

The current regulations in Bulgaria for the implementation and realization of construction and installation works lack specific requirements for accuracy in the bridge superstructure construction using the cantilever concreting method.

In the "Technical Specification" of the Road Infrastructure Agency under the Ministry of Regional Development and Public Works since 2014, part 10200, table 10212.1, only permissible deviations of geometric parameters in the construction of abutments and pillars are given. In parts 10300 "Monolithic superstructure constructions for road bridges" and 10400 "Assembly superstructure constructions for road bridges" similar requirements are also not specified. In [9] there are permissible deviations δH given for the achieved elevation when constructing the supporting structure by cantilever concreting, namely: for the upper slab δH = +/-15 mm, for the lower slab δH = +/- 30 mm. These are accuracy requirements set by the manufacturer of the cantilever installation – "Jacobsen" used in the construction of the viaduct at 48^{+000} km of the "Hemus" highway.

Due to the lack of other information, the smaller of the two tolerances will be used in the following calculations, i.e. this is the one used in the manufacture of the upper slab.

It is known that from a geodetic point of view, the permissible deviation in the geometric parameters (dimensions, elevations, slopes, etc.) of constructed building elements is considered as an allowable error of the corresponding parameter. In this case, the permissible deviation δH is treated as an allowable error m_H in the height of a point on the upper contour of a completely finished cantilever segment. According to Gauss Law of Error Propagation, m_H (1) can be represented as a function of several consisting errors:

$$(m_H)^2 = (m_H)^2_{GN} + (m_H)^2_{meas} + (m_H)^2_{CIW} \quad (1)$$

where:

- $(m_H)_{GN}$ – allowable error in the height of the initial point from the geodetic network (observation station);
- $(m_H)_{meas}$ – allowable error when defining the height of the observed point from the cantilever due to errors in geodetic measurements;
- $(m_H)_{CIW}$ – allowable error in the height of the point from the cantilever as a result of the implementation of construction and installation works.

The required height accuracy $(m_H)_{meas}$ that must be ensured in geodetic measurements for setting out and control of the implementation of the cantilevers can be established from formula (1) with an assumed influence ratio of the consisting errors on m_H. If the principle of equal influence is accepted, at m_H =15 mm, we get:

$$(m_H)_{meas} = (m_H)_{GN} = (m_H)_{CIW} = \frac{m_H}{\sqrt{3}} = 8.7mm \quad (2)$$

The corresponding mean square error for the measured height at the confidence interval (-2m, +2m) will be m_H = 4.35 mm. Since there are no requirements for permissible deviations in the plan, we will assume the same for them as for the height, i.e. δP=+/-15 mm. By analogy with the above analysis, the mean square error in the plan position of a measured point with confidence interval (-2m, +2m) is m_p = 4.35 mm.

3.1. Accuracy in determining the spatial coordinates of the observed points from the bridge cantilevers

The plan coordinates and heights of the observed points from the bridge cantilevers can be defined using linear-angular measurements, carried out with a total station providing the necessary accuracy.

The heights H_p are determined by the well-known formula:

$$H_P = H_i + S_{ip}\, cos\, Z_{ip} + J - T + \frac{1-k}{2R} S_{ip}^2, \quad (3)$$

where:

- H_i is the height of the observation station;
- S_{ip} – the inclined distance;
- Z_{ip} – measured zenith angle;
- J, T – instrument and signal heights;
- k – refractive index;
- R – average Earth radius; R= 6371 km.

The accuracy of the measured heights depends mainly on the accuracy of the measured zenith angles, the influence of the Earth curvature and the vertical refraction. The height H_i of the observation station in most cases can be defined with an error of about 1 mm by geometric levelling and the J and T values can be measured without any problem with such accuracy. Therefore, when assessing the accuracy of the measured heights based on formula (3), their respective errors can be neglected.

In such case, after applying Gauss Law of Error Propagation to formula (3) for the arguments S_{ip} , Z_{ip} и $c = \frac{1-k}{2R} S_{ip}^2$ we get:

$$m^2{}_H = \cos^2 Z \ . m^2{}_S + \frac{S^2 m^2{}_Z \sin^2 z}{\rho^2} + m_c^2 = (m_H^{z,s})^2 + (m_H^c)^2 \ , \quad (4)$$

where:

- $m_H^{z,s}$ is the error in the measured height, due to errors in the measured zenith angles and distances;
- m_H^c – the error in measured height, caused by the Earth curvature and the vertical refraction;

In case we can ignore the influence of the Earth curvature and the vertical refraction, it is necessary that $m_H^c \le m_H /3$ (m_H=4.35 mm), i.e. $m_H^c \le 1.45$ mm

Based on this value m_H^c and the values for *R = 6371 km* and *k=0.106*, the largest value of the distance S_{max} (i.e., the system range) can be calculated where the error $m_H^c \le 1.45\ mm$, namely $S_{max} = 144\ m$.

Similarly, in case we can ignore the influence of the error in the measured distance, the value of the corresponding term in formula (4) should be $cosZ\ .m_S \le m_H/3 \le 1.45mm$. Based on this assumption, at a minimum zenith angle $Z=60^g$ (assumed maximum inclination of the sights) and $S_{max}=144\ m$, it follows that the distances must be measured with a mean square error $m_S \le 2.5\ mm$.

The required accuracy of measuring the zenith angles m_Z is obtained from the equation:

$$m^2{}_H = \frac{S^2 m^2{}_Z \sin^2 z}{\rho^2}. \quad (5)$$

Given that m_H = 4.35 mm, *Z=60 g* and S_{max}*=144 m* it follows that m_Z *= 24 cc*.

The scope of the system can be increased if the errors involved in formula (4) are defined using the principle of equal influences, namely:

- the error caused by the Earth curvature and the vertical refraction is $m_H^c = 2.5\ mm$.

With the so defined value of m_H^c, at *R=6371 km* and *k=0.106*, the system range comes to be S_{max} *= 188 m.*

- the required accuracy of the measured distances is defined by the equation $cosZ.m_S = \frac{m_H}{\sqrt{3}} = 2.5\ mm$. Hence, at a minimum zenith angle *Z=60g* and a maximum length of the sights S_{max}*=188 m*, it follows that the distances must be measured with a mean square error m_S*=4.2 mm.*
- the required accuracy of measuring zenith angles is derived from:

$$m_Z = \frac{m_H.\rho}{S.sin\ Z.\sqrt{3}}. \quad (6)$$

where m_H = 4.35 mm, Z=60g and S_{max}=188 m we get m_Z =10.5 **cc**.

As it can be seen from the results, the system range increases by about 40 m, at the expense of double increase of required accuracy of measuring zenith angles.

The preliminary accuracy assessment is based on the assumption that the setting out will be carried out from stations located on the terrain below or above the supporting structure. When constructing bridges over steep or deep gorges as well as over water obstacles, it is better to place the observation stations on the superstructure block ("O" – Figure 3) of the already constructed piers. In this case, the slope of the sight's changes in a relatively small range. For example, with a maximum sight length of 188 m, a maximum slope of the grade line of 5% and a cantilever height of 5 m, the sights will have zenith angles in the intervals of 97-99 g, respectively 103-105 g.

When changing the sight inclination in the above mentioned intervals, the system range S_{max}*=144 m* and the assumption that the error in the measured heights caused by the Earth curvature and the vertical refraction and the error in the measured distances are assumed to be insignificantly small (i.e. $m_H^c \leq 1.45\ mm$ *и cosZ .*m_S *≤ 1.45 mm*), it comes that the mean square error in measuring distances for different values of the zenith angles in the specified intervals varies from 18.5 to 92 mm. The zenith angles must be measured with accuracy m_Z *=19.3 cc*.

With a system range of S_{max}*=188 m*, an error caused by the Earth curvature and the vertical refraction $m_H^c = 2.5mm$ and a sight inclination in the intervals 97-99 g, respectively 103-105 g, it comes that the average error of the measured distances varies from 32 to 159 mm and the required accuracy of measuring the zenith angles is m_Z *=8.5 cc*.

4. CONCLUSION

A preliminary accuracy assessment in building bridge superstructure constructions via the cantilever concreting or assembly method has been carried out. The permissible deviations in plan and height have been established. The calculated values should be used as a minimum criterion for accuracy when selecting geodetic tools and measurement methods suitable for the construction using the cantilever concreting method.

The accuracy in determining the spatial coordinates of the observed points from the bridge cantilevers has been calculated. The already made calculations confirm once again that the required accuracy in defining the heights of the observed points depends primarily on the accuracy of the measured zenith angles. Therefore, in the bridge construction along with other similar expensive facilities, it is reasonable to purchase precise and high-quality tools with an angular accuracy of 1 " or 2 ". They can ensure the required accuracy of angular measurements when working in two positions of the sighting telescope with appropriate signaling of the observed points - for example, with reflective symbols.

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Review paper

USE OF DEEP GEOTHERMAL ENERGY AS A LOCAL RENEWABLE ENERGY SOURCE

Aleksandar Jovanovic[1]

Abstract

Abstract text (Style Abstract text) When temperatures of geothermal resource are high enough, i.e. exceeding 150 degrees Celsius, one can engage into electricity production from geothermal. In some cases, lower fluid temperatures are used in so called Organic Rankine Cycle (ORC) or Kalina cycle to generate electricity. This complex mechanical process makes use of turbines which utilize pressurized vapor to produce electrical power. ORCs can also be used in combined heat and power systems to provide city parts with district heating from geothermal energy. The importance of strategical steps for further improvement of such systems aims at lowering the cost of drilling and utilizing primarily natural resources, thus enhancing their level of utilization and more efficient use of energy. As many countries worldwide are not as lucky as geothermally potent countries (Iceland, New Zealand, Italy, The Philippines for once), they would have to utilize lower temperature fluids. If a country has an unstable economy, the upfront costs for GE projects, especially with lower temperature fluids, can be much larger than the same projects in developed countries. More upfront effort for creating suitable incentives is necessary for securing such projects´ successful outcomes, which can be beneficial for the country in stake in terms of local renewable energy source utilization in the long run, as it creates policies and ultimately affects the law and consolidates efficient procedures on planning.

Key words: *cascade system of GE, district heating system, electricity production*

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1. INTRODUCTION

In this paper, a geothermal utilization in terms of highly potent resources is given. The focus is on the geothermal resource as an opportunity for city development in terms of electricity production, district heating and combined systems of these two, within a cascade use of geothermal energy (GE).

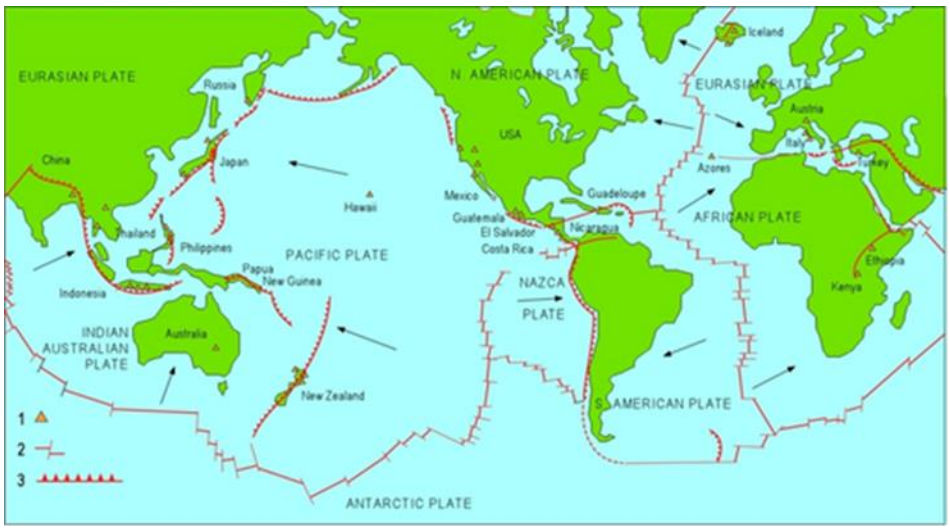


Figure 1. Tectonic plates of the Earth´s crust, the lines represent the plates 'boundaries, for example, Iceland is between Eurasian and North American plate, a volcanically active region, source: http://www.unionegeotermica.it/images/What_is_geothermal_en_html_2f5bdb15.jpg, accessed 04.03.2018

Geothermal energy is derived from the thermal energy naturally stored within the Earth's crust. It is classified as a renewable energy source due to its vast potential—capable of meeting humanity's energy needs for centuries—while posing minimal environmental risks compared to fossil fuel exploitation. As a clean energy source, geothermal energy offers significant environmental advantages, particularly when integrated alongside solar, wind, hydro, and biomass energy within urban contexts.

GE is generally categorized into two main types: shallow and deep geothermal. Shallow geothermal, typically utilizing low-enthalpy resources, involves extracting thermal energy from depths ranging from the surface down to approximately 400 meters. This form of GE is primarily used for heating and cooling applications. In contrast, deep geothermal systems access higher-temperature resources at greater depths, making them suitable for more intensive energy production [1].

2. CITY VS. GEOTHERMAL USE

The suitability of a city for utilizing shallow or deep geothermal energy—or both—largely depends on local geological conditions and environmental factors. These include soil characteristics, surface solar irradiation, recent volcanic activity, and the natural geothermal heat flow in the region. Very shallow geothermal systems, typically installed at depths up to

200 meters, often rely on heat pump technologies to enhance the relatively low temperatures encountered at those levels.

At greater depths, hydrothermal resources—such as naturally heated water or steam within permeable rock formations—can be directly extracted for use in district heating systems. In areas where subsurface rock temperatures are sufficiently high but natural water is absent, Enhanced Geothermal Systems (EGS) may be implemented. These systems enable the use of high-enthalpy geothermal energy by artificially creating permeability in the rock, often through a process known as hydraulic stimulation or “fracking.”

While EGS can significantly expand geothermal potential, especially in urban settings, it is not without controversy. The process of fracking—used to create fractures in deep rock formations for fluid circulation—has raised environmental concerns, particularly regarding its potential to induce seismic activity. In the U.S., this method has been particularly scrutinized for its environmental implications in urban areas [1].

Deep geothermal systems are usually “open loop” systems, which imply extraction from one place and injection of cooled fluid in another pipe, coming as used from district heating or cascade heating, to the other. This is also called “doublet”, as there are two separate drillings one for extraction, the other for re-injection of the fluid (see Figure 3).

Current capacity of Geothermal District Heating System (GDHS[2]) in Europe (direct use) is estimated at 4400 MWTh with the annual production of 13 000 GWh on European level. There were 250 GDHS installed in Europe up to 2016, with some 200 currently being developed, mostly in central and Eastern Europe [2].

Nevertheless, there are still constraints which limit the use of geothermal energy (GE) for heating, such as low level of incentives for GE and unfair position of it to other fuels, upon which whole cities and communities are largely dependent on. Deep geothermal projects require access to financial incentives, that help reduce the upfront costs and risks related to unsuccessful drilling and they help build necessary infrastructure. EU’s net-zero industry act (adopted in 2024) is one of the acts that supports further GE use, not only its manufacturing but supply chain as well. This indirectly intensifies GE`s relation to the built environment, both in terms of securing heating and resilient electricity networks in the future [3, 4].

3. ELECTRICITY FROM GE

Although the United States is among the leading producers of electricity from geothermal energy, investments in geothermal district heating systems (GDHS) have been limited, largely due to the continued availability of inexpensive fossil fuels. As a result, the current installed capacity for GDHS remains relatively small compared to the country's overall geothermal potential. Nevertheless, certain regions in the U.S. present significant opportunities for future GDHS development [5].

[2] GDHS Geothermal District Heating Systems

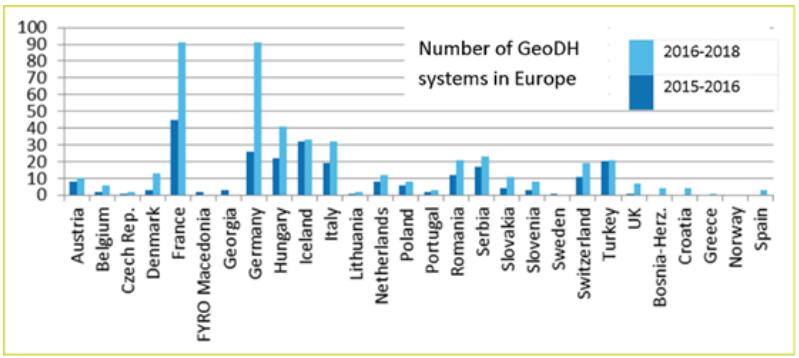


Figure 2. Number of installed GDHS in Europe, source: http://geodh.eu/wp-content/uploads/2012/07/District-Heating-Project-in-Europe-2014-2018-EGEC-market-Report.png, accessed 05.03.2018

In the U.S. or western European countries, such as Germany, the risks and upfront costs are even less for large district heating geothermal projects, compared to non-Eu countries, such as Serbia for example. Here, the investors are faced not only with large geothermal upfront costs, but are faced with hardship regarding bank loans and state incentives, as Serbian economy is considered unstable and too risky for financial institutions to allow for geothermal projects. Another obstacle is that larger geothermal projects are not realized in major cities in Serbia and geothermal energy is mostly considered as balneological resource here. On the contrary, the EU policy and conclusions from December 2024, mainly determine GE` s role as net-zero energy source of the future on the European territory. In this aspect, the conclusions indicate necessity to continuously educate for securing skilled force for GE utilization, and this aspect is even more vital for European countries in the South-East of Europe, as the upfront costs and at the same time risks are larger there and current fossil fuels infrastructures need to be strategically converted into geothermal energy systems over time. However, the EU or countries such as Serbia, have to develop a special incentive strategy which is even more profound and viable in terms of luring investors and securing energy stability through focused mindset change among the population, in terms of combined efforts both of the state and industry in Serbia and the EU [6].

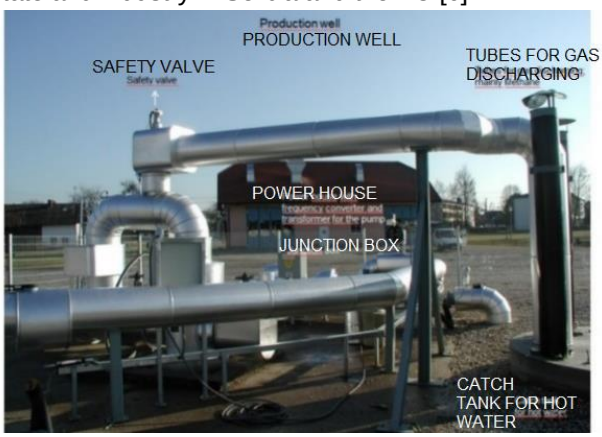


Figure 3. Geothermal system (doublet) in the Austrian town of Altheim, showing its main components, other than district heating piping, source: G. Pernecker, presentation of the project at the GeoCalgary conference [7]



Figure 4. Installment of the Geothermal District heating piping in Iceland, source: www.verkis.is presentation by T. Johanesson, Cornell 2016, used by courtesy of the presenter



Figure 5. Usual size of the piping within the geothermal system based on hot water, Iceland, www.verkis.is, presentation by T. Johanesson at Cornell, 2016

4. FUTURE RESEARCH

A comparative analysis of the literature demonstrates that cascade use of geothermal energy is among the most effective approaches. In addition to electricity generation, geothermal energy can be utilized for district heating, agricultural applications, spa and wellness facilities, aquaculture, and aquaponics. Evidence shows that such multi-use systems are already successfully implemented in Iceland, various parts of Europe, and other geothermally active regions worldwide. These findings highlight the potential of cascade systems as a promising model for countries that have yet to fully develop their geothermal resources, among which Serbia is [8].

5. CONCLUSIONS

There are several constraints to large geothermal projects, that include large upfront cost of GDHS or combined heat and power systems. They require access to financial schemes and more elaborated incentives. Not only do they supply the financial part, they also help to lower the risks related to drilling and exploration, and, help build the necessary GDH infrastructure, which is largely undermined but determining factor for a successful GE project implementation.

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Review paper

TTHE ROLE OF GEOTHERMAL ENERGY PLANNING IN CREATING URBAN MORPHOLOGY OF CITIES AND TOWNS

Aleksandar Jovanović[1]

Abstract

Different manuscripts on the importance of energy planning at a community level explain why energy planning should go hand-in -hand with urban planning. They put emphasis on self-sufficient heat and electric power supply of communities, with locally available renewable energy such as geothermal energy (GTE). It also emphasized that this transition toward energy efficient communities does not have to be costly and that it could be done by means of system´s thinking. This article, however, puts more focus on general renewable energy integrative approach with refurbishments by analyzing literature. The presented case studies´ methods and conclusions are beneficial as they add to the knowledge on different geothermal energy utilization potentials within communities. The outcomes can help determine tools for similar approaches in future cities. Additionally, the presented research questions are beneficial as the results of the presented paper as they have been derived from different cities' experiences through the method of expert interviews. The paper gives foundation for a more comprehensive analysis' methodology in the field of geothermal energy use in architecture in the future.

Key words: *renewable energy, energy planning, case studies, review, geothermal energy*

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1. INTRODUCTION

The integration of Renewable Energy Sources (RES) into the energy infrastructure is a significant task, as future energy demands must align with low carbon emissions alongside sustainable and reliable energy sources. The highest demand for heating and cooling energy lies in the building sector, and it is expected to increase as urbanized areas grow over the coming years. Geothermal energy is recognized as a renewable resource that can provide stability in heating and cooling energy supply, utilizing known technology with cost benefits. Due to these facts, this paper addresses common practices in urban morphology and important topics that can enhance geothermal energy integration in urban planning.

In this paper, a short but detailed overview of the current state of research on geothermal utilization within cities is given. The elaborated studies focus on the geothermal resource as an opportunity for city development. In the context of urban refurbishments required across many cities in Europe and the U.S., particularly alongside the integration of geothermal energy, several innovative studies have expanded the knowledge base. The studies presented examine various types of geothermal energy, including low and high enthalpy systems, heat production and power production, individual and collective (district) systems, as well as Enhanced Geothermal Systems (EGS), and Ground Source Heat Pumps (GSHP). This diversity although challenging, is necessary in order to assess all possible aspects of GTE use in architecture and lead towards outcomes on the current state of research on their utilization in the conclusions. Currently, there are 395 geothermal district heating systems in operation in Europe (out of which 267 in EU27) and more than 500 systems at various stages of development [1], along with 6.46 million installed geothermal heat pump (GHP) units installed in the world, with China, United States, Sweden, Germany and Finland accounting for 77,4 % of the total number [2]. The paper presents an overview of selected studies that went ahead from the usual procedure of GTE integration in urban planning.

2. ON THE IMPORTANCE OF COMMUNITY-LEVEL ENERGY PLANNING

Notably, a 2014 study by Mastrucci et al. [3] developed a tool for calculating energy demand and supply in Rotterdam, covering 300,000 dwellings. A key achievement of this study was the creation of an energy analysis tool adaptable to other urban contexts. Additionally, the study's findings provided valuable insights for urban planning, particularly in shaping policies related to district heating networks and the decentralized use of renewable energy. As a result, local renewable sources gained stronger support at the policy level in efforts to reduce energy dependency. The study also proposed improved energy scenario modeling for future applications, offering a potential framework for refurbishment strategies in cities worldwide.

A study on the significance of community-level energy planning [4] underscores the necessity of aligning energy strategies with urban planning. It advocates for self-sufficient communities powered by locally available renewable resources, emphasizing that this transition need not be costly if approached through systems thinking. While the study takes a broad view of renewable energy integration in urban refurbishments, it provides limited focus on the potential of geothermal energy (GTE) as a catalyst for urban development. In contrast, detailed case studies contribute more concretely to understanding the diverse

energy potentials across different communities. They help identify practical tools and strategies tailored to specific urban contexts. Although there is a strong push among researchers to develop universal "magical tools" for urban redevelopment, this approach often overlooks the unique characteristics of individual cities. This book therefore argues that in-depth case studies, rooted in local realities and expert insight, are more effective than one-size-fits-all solutions. The prevailing global emphasis on sustainability often imposes rigid frameworks, neglecting local energy data, the historical evolution of cities, and the nuanced roles of buildings and community voices in shaping energy policy [5][6].

Addressing cultural influences on GTE adoption, Shortall and Kharrazi [7] explored geothermal utilization in Japan and Iceland, revealing that cultural factors significantly shape the application and acceptance of geothermal technologies. Although overlapping elements exist, cultural specificity remains a key driver. The study emphasizes the importance of incorporating cultural analysis prior to techno-economic assessments and calls for greater public engagement. A lack of awareness among local stakeholders—such as Onsen owners in Japan—hinders broader adoption of GTE. A positive example of cultural influences and public engagement that go hand-in-hand with techno-economic is shown in the example of Altheim, shown on Figure 1.

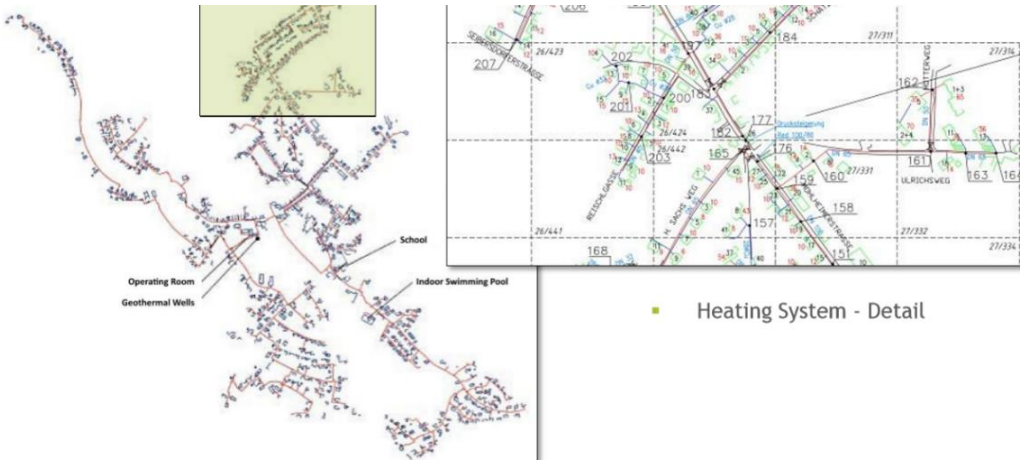


Figure 1, GDHS of Altheim, Upper Austria, with a detail (upper right), built around the beginning of the 1990s. As GTE came only after most of the urban tissue had been created, it was developed around the existing urban matrix of Altheim, the town can expand in many directions, possibly access to GTE stations and proximity of it, may have an influence on the position or length of the streets and neighborhoods.

Even though the first Historical utilization in the modern history of GDHS occurred at the end of the 19th century in the U.S, although 140 years later, no inference of this plan to other U.S cities schemes, is commonly made (see Figure 2 for details).

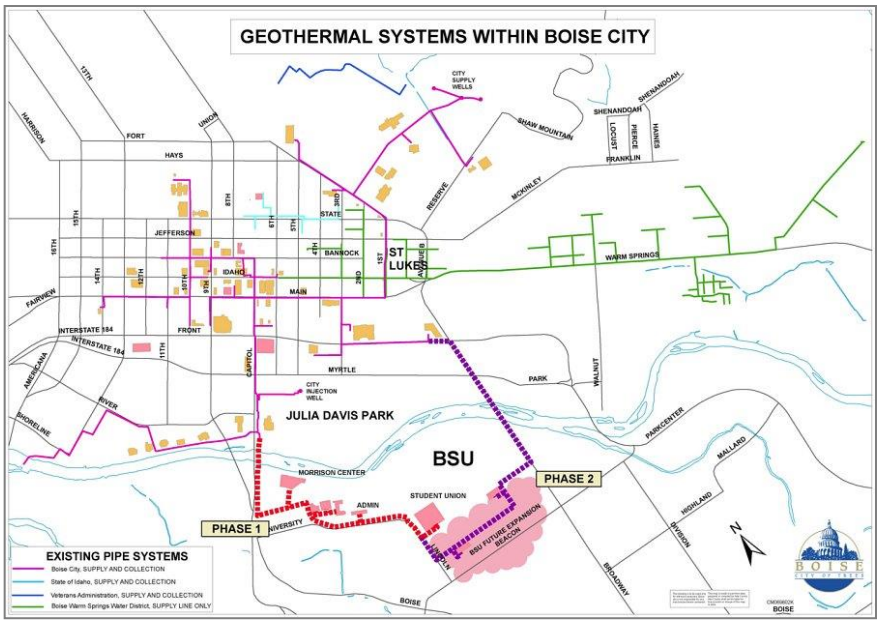


Figure 2, Boise, Idaho, USA, first contemporary geothermal district heating system in the world, operational since 1890. The urban morphology analysis implies the urban matrix of American cities and towns from the end of the 19th century, with GTE not reflected on the level of urban planning.

In another significant study, Carrera and Mack [8] employed the Delphi expert interview method across four European countries, using social indicators to evaluate renewable energy issues. Their methodology yielded insights that could complement public opinion surveys on renewable energy projects, while also introducing innovative methods like phone interviews to the field of social energy research. Inspired by this, the research presented in the book [9] also applies similar approaches to both European and American case studies. In particular, a study on Reykjavik, Iceland by Thorleikkur Johanesson on urban morphology of Reykjavik, shows the marginal status of GTE in terms of urban planning of the sprawled areas around the urban core (see Figure 3).

Ali et al. [10] examined the use of GTE in desalination, comparing it to other renewables like wind and solar. GTE's continuous thermal energy output was identified as a major advantage, though its potential application in urban contexts remains underexplored. However, progress has been made in studying shallow geothermal systems. Miglani et al. [11] investigated heat pump applications in urban neighborhoods, highlighting the gradual decline in geothermal potential due to prolonged heat extraction using borehole heat exchangers (BHE). They propose maintaining ground thermal balance—particularly during summer—through supplementary technologies like solar thermal energy. This study is among the few that explicitly address spatial constraints in applying geothermal systems to urban environments and emphasizes the need for integrated planning of energy systems and building typologies.

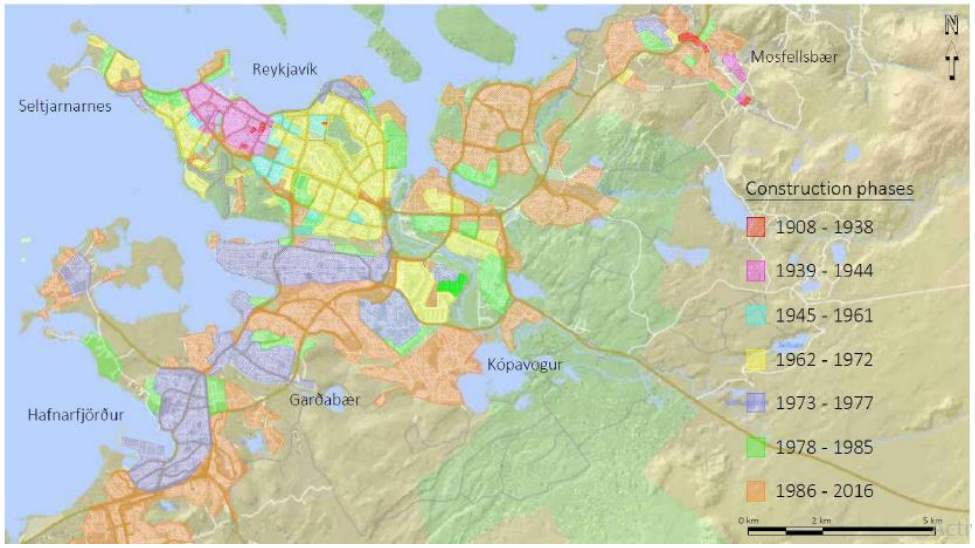


Figure 3, Reykjavik GDHS, evolution phases between 1908-2016, GTE and its vast technological use in Iceland, in particular in Reykjavik, made no reference to urban planning, as the city sprawled nonetheless due to its development, led by sole construction and infrastructure aspects [9]

On the other hand, deep geothermal systems—particularly Enhanced Geothermal Systems (EGS)—are the focus of several studies. Reber et al. [12] conducted a cost analysis of EGS in New York State, demonstrating its feasibility even in regions with low geothermal gradients. Although drilling and reservoir completion remain cost-intensive, the existence of district heating infrastructure makes transitioning to geothermal district heating systems (GDHS) economically viable. The study stresses the importance of clean energy in aging U.S. communities, particularly in the Northeast, and positions GDHS as a potentially transformative solution, despite its current underutilization.

However, although EGS primarily serve as a source of power, these systems are not commonly developed in towns and cities. To establish an EGS, it is necessary to "create" a geothermal reservoir, typically at depths of over 3-4 kilometers. This process entails drilling multiple deep wells and employing hydraulic fracturing and other reservoir stimulation techniques, which can be challenging to develop in populated areas.

In the U.K., McMahon et al. [13] explored the application of ground source heat pump (GSHP) systems in older Victorian buildings. Their study found that conventional thermal modeling tools, like the Standard Assessment Procedure (SAP), often underestimated the capabilities of GSHP systems. Despite SAP limitations, GSHP installations showed a payback period of five to seven years. Key success factors included installer expertise, user behavior, and long-term system monitoring. The findings challenge the prevailing focus on new, well-insulated buildings and suggest that older structures—especially those off the gas grid—stand to benefit significantly from GSHP adoption. This is especially relevant for Europe and the U.S., where many architecturally and historically significant buildings require energy-efficient retrofits. GSHP systems may play a critical role in revitalizing cities facing economic decline, urban shrinkage, or social fragmentation.

Fourth-generation district heating systems (4GDH) also present promising opportunities. Lund et al. [14] and Girardin et al. [15] propose integrating 4GDH with smart thermal, gas, and electricity grids, supported by low-energy buildings on the demand side. A GIS-based

model developed by Girardinet al. provides valuable guidance for optimizing urban energy efficiency, identifying appropriate conversion technologies, and improving the integration of renewable energy sources.

A recent study by Schiel et al. [16] focused specifically on the integration of shallow GTE in the urban context of Ludwigsburg, Germany. The study calculated heating demand and geothermal extraction potential at the parcel level and introduced the Smart City Energy Platform, which visualizes GE borehole placements and spatial constraints. The research concluded that shallow geothermal is best suited for low-density urban areas—such as single-family homes and low-rise buildings—where it can efficiently provide space heating and hot water. The study highlighted the importance of stakeholder collaboration and comprehensive data analysis as prerequisites for successful project implementation.

3. METHODOLOGY

These diverse studies collectively underscore the value of context-specific research and stakeholder engagement in advancing the role of geothermal energy in urban development. This paper uses these insights as a foundation for further inquiry and for shaping a more tailored, evidence-based approach to energy planning in cities.

Table 1. Research Question as methodological approach of the paper

R1: To what extent have architectural and urban planning practices acknowledged geothermal energy (GE)?
Methodology: Expert interviews focused on selected case studies.
R2: Has geothermal energy been integrated into urban morphology—the physical form and structure of cities?
Methodology: Historical analysis combined with expert interviews based on case studies.
R3: How has the integration of geothermal energy unfolded historically, and in what ways has it influenced urban development?
Methodology: Examination of historical documents and expert interviews centered on case studies.
R4: Is geothermal energy currently being incorporated into contemporary architectural and planning practices?
Methodology: Expert interviews focusing on recent and ongoing case studies.

There were four expert interviews, all done within Austria. Two interviews were done in Altheim Gemeinde, Upper Austria, the second was done in Kirchdorf an der Krems, Upper Austria, followed by an expert interview in Graz, Styria, and, these were then triangulated

with expert interview done at Cornell University in Ithaka, NY and one in Reykjavik, Iceland. Please refer to [9] for more detailed explanation of the interview sample.

4. IN CONCLUSION

There is a potential for using GTE as a source for supplying cities and towns with heat and power. Probably the EGS will play a greater role in these processes as the need for energy independence of cities and countries is a necessity due to different political implications. The analysis of the use of GTE for district heating in towns and cities in Europe and in the U.S., indicated that towns used geothermal energy as an external element of technology that does not affect how cities are developed or planned. Enhanced Geothermal Systems (EGS) primarily contribute to cities and towns as sources of power, but these systems are not commonly developed in them, as due to the employed fracking and reservoir stimulation methods, it remains a challenge to develop these in populated areas. Therefore, GTE's future in cities and towns lies in the heating and cooling sector, utilizing organized systems such as district heating and cooling (DHC) or single-use systems.

The analyzed papers show that the number of installed units of GSHP as well as DHS that utilize GTE as well as EGS, will rise in the years to come. The technological aspects of GTE have been advancing significantly in the years before now. What fails to follow is the re-thinking of how GTE finds a place in urban morphology creation, and, how urban planning that addresses heat transfer rules, combined RES utilizations and passive design may affect the future towns and cities and their current urban morphology stereotypes.

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Abbreviations:

(RES) Renewable Energy Sources
(GTE) Geothermal Energy
(EGS) Enhanced Geothermal Systems, (GSHP) Ground Source Heat Pumps
(GDHS) Geothermal District Heating System

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Research paper

INVESTIGATION OF MARBLE POWDER AND WASTE AS PARTIAL REPLACEMENT FOR CEMENT AND SAND ON MORTAR PROPERTIES

Azra Mahinić Vrce[1], Marko Ćećez[2], Merima Salčin[3], Merima Šahinagić-Isović[4]

Abstract

In this paper an investigation of marble powder (MP) as partial replacement for cement and marble waste (MW) as partial replacement for sand is presented. MP replaced the cement at the rate of 5%, 10% and 15% of cement by mass. MW was used as a replacement for sand at constant 50% replacement level. Control mixture was prepared without MP and MW. Water to cement (w/c) ratio varied since MP was considered as binder, thus w/b ratio was constant. Fresh properties were determined by air content, workability and density, while hardened properties were evaluated with compressive and flexural strength, absorption and quality. The results indicate a small decrease in workability, but no significant change in compressive strength for samples with 5% and 10% MP addition and 50% MW addition. However, increasing the MP replacement level beyond 10% leads to decrease in compressive strength.

Key words: *marble powder, waste, cement, binder*

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1. INTRODUCTION

Marble waste has emerged in recent years as a suitable material for research as addition in mortars and concrete [1 – 5]. Large number of studies suggest the application of marble powder (MP) as supplementary cementitious material, and marble waste (MW) as substitution for sand or coarse aggregate. The research is in line with Sustainable development goals related to waste reduction, recycling and reuse, i.e. specifically goal 12 [6]. Since concrete industry is one of the largest contributors to waste generation and environmental pollution, the logical conclusion is to reduce consumption of cement and aggregate using waste materials form other industries [7]. In ordinary concrete mix, the aggregate participates with about 70% and cement with about 15%. Considering that concrete production is roughly 0.6 m^3 per capita in EU countries [8], the amount of natural materials needed is enormous.

Marble is one of the most used stones in the construction industry. The use is diverse, from load-bearing elements to decorative material. World production of marble reached 318 Mt in 2021 [9]. In Bosnia and Herzegovina marble production is around 285 Tt in 2023 [10], which is approximately the production level of recent years. During marble processing waste is generated as powder and granulates [5]. Marble powder (MP) is rich in calcium, silicon and aluminum oxides, resembling cement chemical properties. Marble waste (MW) as granulates can be used as replacement for sand, due to particle properties [2].

In work [11], it was found that MP can improve concrete compressive strength up to a 10% replacement, but beyond that, it can cause a decrease in strength. The use of marble powder can also enhance workability characteristics. According to [12], replacing 15% of sand with marble powder led to a 4.5% increase in compressive strength. Additionally, substituting 10% of cement with silica fume or metakaolin in marble powder concrete resulted in a remarkable strength improvement of 60% and 64.3%, respectively. The introduction of marble powder also increased the split tensile strength of the concrete mixtures. Moreover, the concrete mixtures with a replacement of 15% sand with marble powder exhibited improved carbonation depth after 56 days of exposure. Furthermore, the marble powder concrete with silica fume or metakaolin showed superior carbonation resistance and enhanced durability properties in the concrete mixtures. The study by [13] investigated the use of marble dust particles (MDP) as a partial replacement for cement in the concrete mix. The results showed that the optimal percentage range for replacing cement with MDP was between 5% and 10%, leading to significant improvements in the compressive and flexural strength of the concrete mix. The concrete mix with 5% and 10% replacement of cement by MDP exhibited higher values compared to 0%, 15%, and 20% replacements at different curing times (7, 14, and 28 days) for compressive strength. Yifru and Mitikie [14] used marble waste and scoria as partial replacement for sand. Results indicate an increase in compressive strength up to 30% with marble waste replacement level of 22.5%. Also, concrete waste decreased by about 5% without compromising the compressive strength. In the work of Vardhan et al. [15], the sand was replaced with MW in concrete mix. It was found that the presence of 40% MW in the mix led to an increase in compressive strength and reduction in drying shrinkage. MW in the mix leads to denser mixture with better filler effect and binding.

In this paper we used marble powder (MP) as partial replacement for cement and marble waste (MW) as partial replacement for sand in mortar mixtures. MP replaced the cement at

the rate of 5%, 10% and 15% of cement by mass, while MW replaced the sand for 50% for all mixtures except reference mix, which had no replacement for cement and sand.

2. MATERIALS AND METHODS

All mixtures were prepared as cement mortar with cement-to-sand ratio of 1:3. As cement, CEM II/A-M (S-V) 42.5N was used. This cement has a density of 3.05 g/cm^3 and specific surface area of 2900 cm^2/g. Ground limestone from local production was used as sand (0/4 mm). This sand has a specific gravity of 2.70 g/cm^3 and meets all the requirements for application in mortar and concrete. MP and MW were taken from a local stone production company located near Mostar, B&H. Due to small particles MP is stored in basins with water, thus liquified samples were taken. Before the mixing process, MP was dried at 105°C until constant mass and sieved through 0.09 mm sieve to eliminate the residuals. MW was taken directly after the stone cutting process. Since it had significant residuals, it was first dried at 105°C and then sieved through 4 mm sieve.

The chemical analysis of MP is presented in table 1. As it can be seen, MP is mostly composed of silicon oxides, with relatively low calcium, iron and aluminum oxides content. However, the sum of pozzolanic oxides (silicon, iron and aluminum oxides) is 71.56%, which meets the requirements of EN 450-1 (requirements for fly ash) as addition for concrete production. Another requirement listed in EN 450-1 is limited Na_2Oeq content (under 5%) which is calculated as $Na_2O+0{,}658K_2O$ and is 3.63%.

In figure 1, particle size distribution of MP, MW, cement and sand is presented. MP particles are mostly smaller than 10 μm and similar to cement. MW has about 57% of particles smaller than 0.5 mm, opposite to sand which has 36%. Specific gravity of MP was measured 2.833 g/cm^3, while for MW is 2.77 g/cm^3 with compacted bulk density of 1.776 g/cm^3.

Table 1. Chemical analysis of MP

Element	Oxides (%)	Element	Oxides (%)
SiO_2	50.43	Na_2O	2.83
Fe_2O_3	6.86	K_2O	1.22
Al_2O_3	13.96	TiO_2	0.42
CaO	12.73	SO_3	0.05
MgO	5.87	LOI	4.78

For testing procedures four mixtures were prepared with MP addition at the rate of 5% (CM10), 10% (CM11) and 15% (CM12) of cement by mass, while MW replaced the sand for 50% for all mixtures except reference mix. Reference mix (CM1) had no replacement for cement and sand. Detail mix properties are given in table 2. Since cement+MP sinergy was considered as binder, water-to-binder ratio (w/b) was kept constant, thus w/c ratio varied.

All mixtures were prepared in automatic mortar mixer in accordance with EN 197-1. After the tests on fresh mortar, the mixtures were pured in 4x4x16 cm molds with 3 samples. The samples were kept in the molds for minimum of 24h, demolded and placed in water curing tanks unitl testing.

Table 2. Mix proportions

Mix	Cement (g)	MP (%)	MW (%)	Sand (g)	w/b	w/c
CM1	450.0	0	0	1350.0	0.52	0.52
CM10	425.5	5	50	675.0	0.52	0.55
CM11	405.0	10	50	675.0	0.52	0.58
CM12	382.5	15	50	675.0	0.52	0.61

On fresh mortar, workability, bulk density and air content were tested. Workability was tested in accordance to BAS EN 1015-3, on flow table determining average spread in two perpendicular directions. After the test, mixture is pured in 1 liter container, leveled and weighed, thus determing the bulk density. The container is then sealed with with an air content test attachment. Air content was tested according to BAS EN 1015-7 by pressure method.

After the curing process, flexural tensile strength and compressive strength were tested for 7, 14 and 28 days of curing, accoriding to EN 1015-11. Prior to this testing procedures, the UPV and absorption was tested. The samples were dried at 105°C untill constant mass, then by ultrasonic testing aparatures the pulse velocity was measuder and calculated as v=d/T, where d is 16 cm, and T is the time needed for pulse to reach the reciver from transmitter in seconds. After the UPV test, the samples were submerged gradually in water in order to test the absorption. The absorption was calculated as m_w/m_o in percentage, where m_w is mass of absorbed water and m_o is the mass of dried sample.

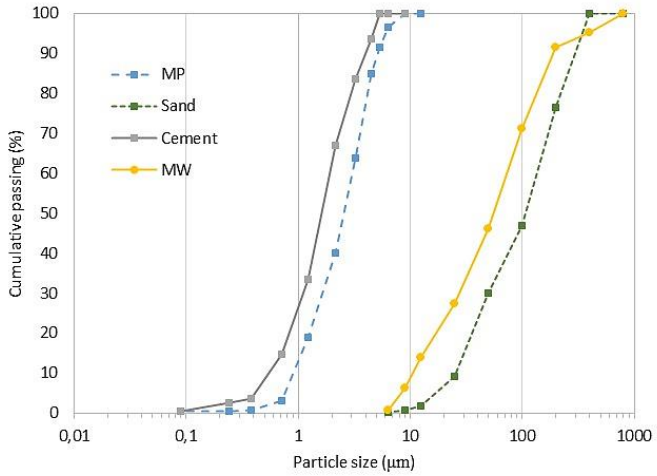


Figure 1. Particle size distribution

3. RESULTS AND DISCUSSION

Workability is one of the most important properties of fresh mortar. The workability can indicate the quality of the installed mortar. By higher bulk density, usually lower air content is expected if no additives were used. The results of workability, bulk density and air content are presented in table 3.

The workability decreases with the increase of MP. The average measured spread is 170 mm in the case of reference mix and gradually decreases to 153 mm for the mixture with

15% of MP and 50% of MW indicating high impact of MP on the workability of the mortar. Similar results can be seen in [16] where the workability is reduced due to small MP particles. As workability decreases, the change in other properties is visible. The bulk density is decreasing, for a small increment but the decrease is observed. Following the decrease in bulk density, the air content is increasing from 2.70% to 3.30% for the CM12 mix. These results are expected due to the presence of MP, but MW had no significant effect on the properties, which can be concluded from the fact that bulk density did not decrease significantly.

Table 3. Workability, air content and density test results

Mix	Spread (mm)	Air content (%)	Bulk density (kg/m^3)
CM1	170	2.70	2306.9
CM10	163	3.20	2229.2
CM11	165	3.20	2228.8
CM12	153	3.30	2220.7

On the following figures (2, 3, 4, 5 and 6) properties of hardened mortar are presented for 7, 14 and 28 days of curing. Compressive strength is generally decreased with the presence of MP and MW. For the 7 days of curing significant reduction in compressive strength is visible, up to 29% for CM12 mix. Similar is registered for 14 days of curing, with 28% of strength reduction for CM12 compared to reference mix. However, after 28 days of curing, mixture with 5% of MP showed similar result as reference mix, with only 0.9% of reduction. Also, mix CM11 has about 6% lower compressive strength, which is negligible. But when adding 15% of MP with 50% of MW reduction is significant of 20% compared to reference mix.

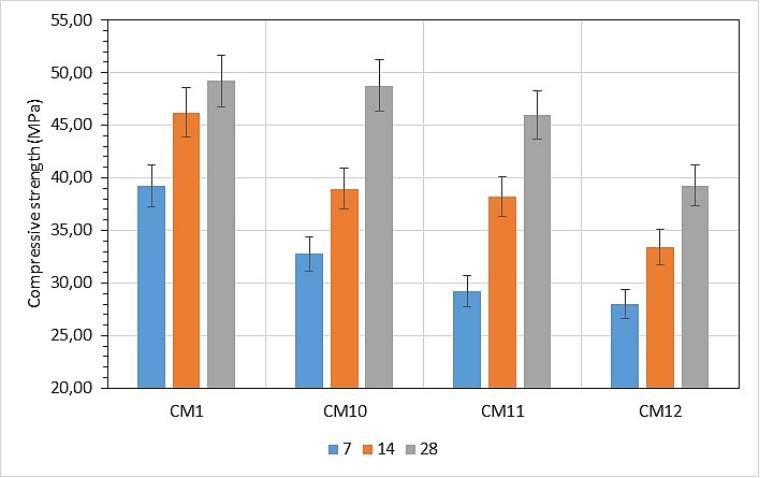


Figure 2. Compressive strength test results

Similar results can be seen for the flexural tensile strength test results for 7 days as for compressive strength for the same period. Reduction in strength is visible for all mixtures with additives, up to 22% for CM12 mix. However, an increase in flexural tensile strength is observed for CM10 and CM11 for the 14 days of the curing period. CM12 has similar results

to reference mix. For 28 days of curing an increase of 10% in flexural strength for CM10 mix is registered. CM11 and CM12 have small reduction in strength of 6% and 3% respectively, compared to reference mix.

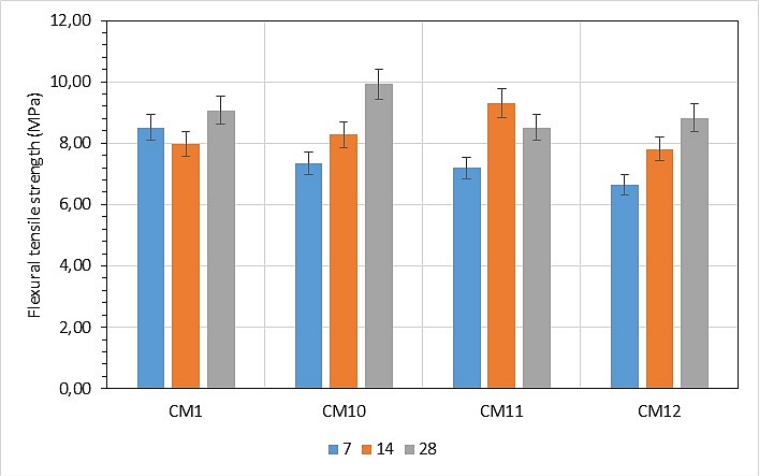


Figure 3. Flexural tensile strength test results

The UPV test results show an increase in the quality of the mixtures when MP and MW are present. Only CM12 mix showed reduction in measured UPV of about 4% compared to reference mix. The results indicate better packaging of the MP particles in the mortar mix, thus increasing the quality of the mixture for all curing periods. Similar results can be seen in [16].

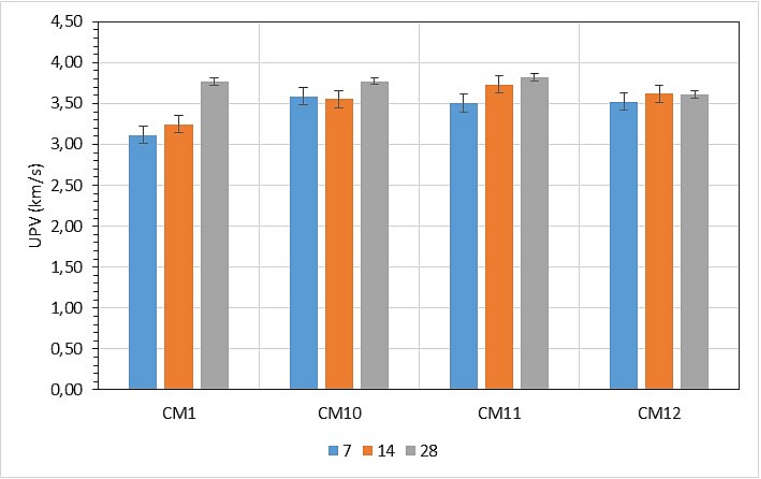


Figure 5. UPV test results

Water absorption test results indicate a reduction in absorption in the presence of MP and MW for small amount of MP. For increased MP content (CM12 mix) an increase in absorption is visible for 7 and 14 days of curing. However, for 28 days of curing constant reduction in absorption is visible, for 7%, 18% and 23% respectively. CM10 and CM11 mixtures exhibit lower absorption for every curing period, for 7% for CM10 and 18% for CM11 at 28 days of curing.

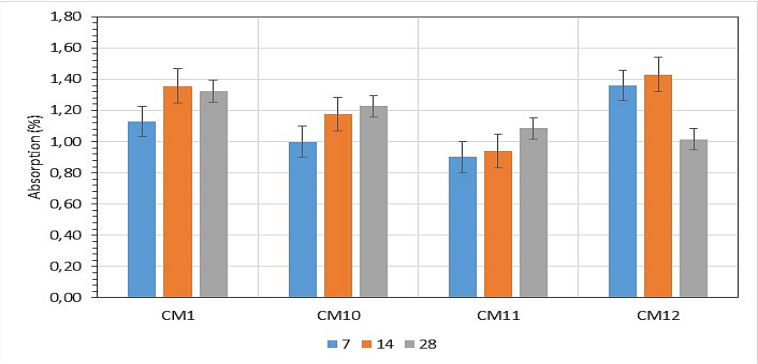


Figure 6. Absorption test results

The results indicate that after the hardening process, the MP particles have filling effect, providing a higher quality mix, as also can be seen in [2]. This is visible from the UPV and absorption test, where the samples have shown higher quality and lower absorption for small amount of MP. Also, filling effect of the smaller particles can help to "glue" the mixture, providing higher flexural tensile strength results. However, for the enhancement of compressive strength MP should participate in hydration process, which is not seen in this case. But the registered reduction in compressive strength is not significant, meaning that the presence of MP did not affect the hydration process itself, and that MW presence had practically no effect on compressive strength. This means that MW is suitable as replacement for sand. This is also confirmed by similar particle size, specific gravity and bulk density of MW and sand. Similar results can be seen in [15].

4. CONCLUSIONS

The paper presents the research results of mortar properties with partial replacement of cement with marble powder (MP) and partial replacement of sand with marble waste (MW). As the results indicate, there is no significant impact on mortar properties when a small amount of MP is added. Since the addition of MW was constant, it can be concluded that even the high content of MW did not impair the tested mortar properties. 28-days compressive strength for mixture with 5% of MP is only 0.9% lower than reference mix. Flexural tensile strength for the same curing period is increased by about 10% for the mixture with 5% of MP. The UPV test indicates higher quality mixtures when MP and MW were added for all curing periods. In addition, water absorption was reduced for mixtures with MP. However, the replacement level of cement with MP should be up to 10% for application, which is also recommended by available literature.

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Research paper

BUILT HERITAGE AND COLLECTIVE MEMORY: THE RELATIONSHIP BETWEEN THE ENVIRONMENT AND THE MONUMENT ON THE EXAMPLE OF THE TJENTIŠTE MEMORIAL COMPLEX

Stefan Slavić[1]

Abstract

The research objective is to determine the context of the natural environment and the built environment in it, through the prism of the author of the memorial complex as the sender of the message to the visitor who is its recipient. The paper will be focused on the memorial complex Tjentište in Republic of Srpska, Bosnia and Hercegovina and architectural values of the monument "Battle on Sutjeska" by the sculptor Miodrag Živković. The main goal is to detect the spatial and ambient values of the projected trajectory that the visitor crosses and to recognize the relationship that the monument establishes with its environment. The significance of the research is based on the attitude about the importance of preserving the built heritage, recognizing its values and passing it on to future generations. The applied scientific methods are a theoretical review, analysis of archival materials, case study and spatial analysis. The research is predominantly based on the gathering of archival materials in the form of drawings, plans, photographs, written documents, and the relevant materials are collected in archives, libraries and museums. The results refer to the presentation of the role of space in the process of creating collective memory in the context of social, economic, political, and cultural circumstances with a special focus on the importance of built heritage in the complex process of establishing a relationship with the past. The significance of the work is reflected in highlighting the role of architectural design and the values of monument as element that inherit testimonies of the past.

Key words: *Built heritage, Collective memory, Tjentište memorial complex, Spatial analysis*

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1 INTRODUCTION

The perception of the role of the monument and its understanding as a synonym for artistic, sculptural and architectural works dedicated to the People's Liberation Struggle during the Second World War and their creation from a close connection with current politics resulted most often in abstract works of art of high aesthetic value. The diversity of marking the place of suffering was reflected in a wide range from modest memorial plaques to monumental sculptural solutions and urban-architectural complexes of great artistic value. The division of activity according to Aristotle into praxis - an activity that is significant in itself and poesis - an activity whose goal is a product that enables another activity, is important for understanding artistic activity. Accordingly, it is important to understand artistic action as poesis - it has a purpose in another, more precisely in human being. [1] The Second World War marked the territory of the former Yugoslavia with great suffering, with the aim of emphasizing the importance of the lives lost in the People's Liberation Struggle, after the end of the war the state leadership was actively engaged in marking the places of suffering. Architecture and sculpture become a medium for conveying a political message. Social interaction made the monument a place for constructing the ethical norms of the community [2]. By building memorial complexes, the past of high anti-fascist ideals is represented. This recognized the possibility and power of architecture to preserve the past with the possibility of experiencing and understanding the continuity of culture and tradition, where it is important to understand existence not only in spatial and material reality, but also in cultural, mental and temporal reality. Understanding this relates to the constitution of official memory of past events within the framework of contemporary society. Official memory is fed primarily by what is visible at one particular moment - in the form of a performed ritual, a published text, a built monument [3]. The reference and creation of official remembrance of the events and suffering from the Second World War has its spatial manifestation through the creation of memorial complexes in which monuments are assigned a significant role in the transmission of memory. The motive of passing on memories becomes extremely important in terms of communication between different generations, those who were witnesses and participants in war conflicts and future generations who were not direct participants, but through visits to memorial complexes adopted testimonies about the events of the past. The role of the monument thus becomes the possession of a narrative about the event to which it bears witness with the power of transmitting memories and transposing them to future generations.

2 PLACE OF REMEMBRANCE

The monument on Tjentište was built with the aim of marking and memorializing the battle on Sutjeska. In historical chronicles, the battle is recorded as the fifth offensive and lasted from May 15 to June 15, 1943, known as the German war operation "Schwarz" [4]. During the battle, 7,356 people from the NOVJ (*People's Liberation Army of Yugoslavia*) died, of which 6,753 were men and 603 were women. The significance and role of the Battle of Sutjeska has been characterized by historians as one of the most significant battles of the NOVJ fought during the Second World War. Establishing an analogy with the entire context of war conflicts during the Second World War, the importance and role of the Battle of Sutjeska, by many historians, has been compared to the Battle of Stalingrad. By

establishing this parallel, the Battle of Sutjeska or the fifth offensive acquired the status of an important historical event, the marking and memorialization of which became part of the socio-cultural aspect and an integral part of collective memory. The memorialization of this event in the spatial-architectural sense was manifested by the construction of a monument as a central symbol of the battle at the place from where the breakthrough of the enemy's encirclement began. The memorial complex of the Battle of Sutjeska, colloquially known as the "Valley of Heroes", is located within the Sutjeska National Park. Within the Sutjeska National Park there are 8 landmarks related to the period of the Second World War. The most dominant monument of the battle on Sutjeska is the work of the sculptor Miodrag Živković, and next to it, 7 other places characteristic of the battle itself are marked. The following places are marked: the grave of Sava Kovačević - the place of death of the commander of the Third Division, the grave of Nurija Pozdrerac, then the place of death of the National Hero Šerif Loj, the place of wounding of Tito, as well as Ljuba's grave and monuments erected to the II Dalmatian and IV Montenegrin Brigades. It was also planned to mark another 79 significant localities according to the events of the fifth offensive in the area of the national park, but their marking was never realized [5]. The central part of the "Valley of Heroes" is a monument to the battle on Sutjeska with an ossuary, as well as a memorial house with panoramic views of the battle. The memorial house built in 1975 is located in the immediate vicinity of the monument and was designed by architect Ranko Radović, with a characteristic design inspired by the steep roofs of mountain houses. The interior of the memorial house is painted with frescoes by Krsto Hegedušić, which represent panoramic views of the battle on Sutjeska. As part of the memorial house, there is a list of 7,376 names and surnames of the soldiers who died on Sutjeska called "Roll call on Tjentištu". Also within the memorial house are 13 frescoes by Krsto Hegedušić on an area of 124 m², made in fresco secco and fresco buono technique, and on them are presented the themes and scenes of the battle itself. The importance and role of the Battle of Sutjeska in the post-war period and its status in the social context is evidenced by the speech held at the celebration of the 35th anniversary of the battle, in which the battle of Sutjeska was characterized as the most famous epic of the national liberation struggle, an epic that lives and will live forever with unquenchable brilliance [5]. An important segment in the composition "Valley of Heroes" is a memorial - an ossuary built in 1958 according to the project of Sakib Hadzihalilović. The remains of 3,301 participants of the Battle of Sutjeska were transferred to the memorial ossuary. According to the original project, an access staircase led to the ossuary itself, overcoming a height difference of 33 meters. The staircase led to the access rectangular plateau of 209.18 m², paved with stone slabs. The ossuary itself is buried in the ground and has a volume of 200 m³. Above the surface of the earth is a stone cube measuring 5 x 5 meters built from 6 stone blocks measuring 80x166.5x250 cm, which is separated from the ground by 30 cm by a recessed plinth. Until the construction of the Sutjeska Battle Monument in 1971, the memorial ossuary was the central element of the "Valley of Heroes" and the main commemorative place. The fact that the ossuary was given the epithet of the central element in the composition "Valley of Heroes" is also indicated by the condition of the competition for the monument to the Battle of Sutjeska, according to which the monument must not obscure the view of the ossuary [3]. The competition was announced in 1962 and was of an open nature, however, on April 10, 1962, Miodrag Živković received a request from SUBNOR to participate in the competition. The original project envisaged the construction of a stone bridge 255 meters

long and three meters wide, and it was supposed to represent a monumental architectural symbol. The construction of the project was not realized for financial reasons, but also because of the explanation that the bridge did not establish adequate spatial relations with the ossuary. The authors of the project were Bogdan Bogdanović and Ranko Radović, but Bogdanović withdrew from the project due to the short deadline and he was then replaced by Miodrag Živković. The project that was accepted was Miodrag Živković's proposal to build a monumental stone monument that represents a clear and at the same time abstract representation and memory of the battle. In order to emphasize the visibility of the ossuary, the author believes that a sculptural solution should be placed near it, as a new accent and dominant space. The sculptural mass is in a close, functional relationship with the ossuary, with which it forms a whole. The stone masses of the sculpture are dynamically disturbed, aimed upwards. That vertical orientation and dynamism of the two boulders expresses the heroic act of the battle itself, all its moral greatness, its optimistic meaning. The sculptural mass is conceived and executed in such a way that it gives the impression of strength, vigor, and victory. From afar, it resembles the natural environment in which the battle took place, but also a stone massif that ignites. Not far from the ossuary where the remains of the fighters are buried and which means the peace and silence of death, rises a sculptural mass imbued with the breath of life and struggle, as a symbol of the negation of death. On the inner sides of the stone masses, highly stylized figures of fighters can be seen, whose presence ennobles and inspires the entire sculpture with human warmth. The penetration between the boulders symbolically represents the penetration of partisan units, and it forms two masses that, through mutual relations, grow into a whole full of defiant strength. The beginning of the works on the arrangement of the Tjentište memorial complex was started in 1967 and its implementation was planned in three stages. However, work on the monument itself began in 1969, and due to financial deficiencies, the realization of the monument was delayed, which jeopardized the plan for its ceremonial opening scheduled for 1971, the 35th anniversary of the revolution. The compositional solution was reflected in the creation of the access plateau that leads from the parking area to the staircase. A new staircase was built that connects the access plateau and the existing memorial - ossuary. Viewed from the front, the newly built staircase represented a symmetrical composition leading to the plateau of the ossuary. The monument itself is composed of two "stone" masses and is positioned on an elevation after the ossuary. Between the two parts of the monument there is a passage that leads to the last segment in the composition and is spatially manifested by the formation of an amphitheater. The amphitheater, as a frequently used element in the memorial complexes that were created in the post-war period, was formed from white concrete strips on which were written the names of the units that participated in the battles on Sutjeska.

3 SPATIAL ANALYSIS OF THE COMPLEX

The method of spatial analysis was applied using various tools, so that while moving along the designed path intended for visitors the different impressions to which the observer was exposed were noted. The noted impulses are related to the perception of the relations that exist between the landscape and the monument itself. Finally, the different levels of "information" that the observer acquires while moving along the designed path were mapped. The monument “Battle on Sutjeska” is monumental sculpture, whose form is

made up of two stone units, which resemble the silhouettes of the gorge, represents an abstract representation of the morphology of the space where the battle took place, emphasizing the harshness of the terrain. The connection between the monument and the environment highlights the interdependence and correlation of form and space, which are such that form determines space and space determines form. From this follows the multiplicity of spatial implications of the monument. These implications do not need to be proven, but it is necessary to point them out and describe the specifics that arise from them [1]. The shape and design of the "arms" of the monument establish relations with the morphological characteristics of the environment and are placed in such a way that they tend towards the tops of the mountains, which symbolizes the exit to victory (Fig. 1). The monument itself carries requirements for the space, more precisely for the landscape. Form presupposes space just as space presupposes form, namely a certain space and a certain form. This once again confirmed the importance of the aesthetic criterion of singularity and uniqueness of each work of art and its environment, which dictates an adequate relationship and approach to space and form from an assumed spatial unity [1].

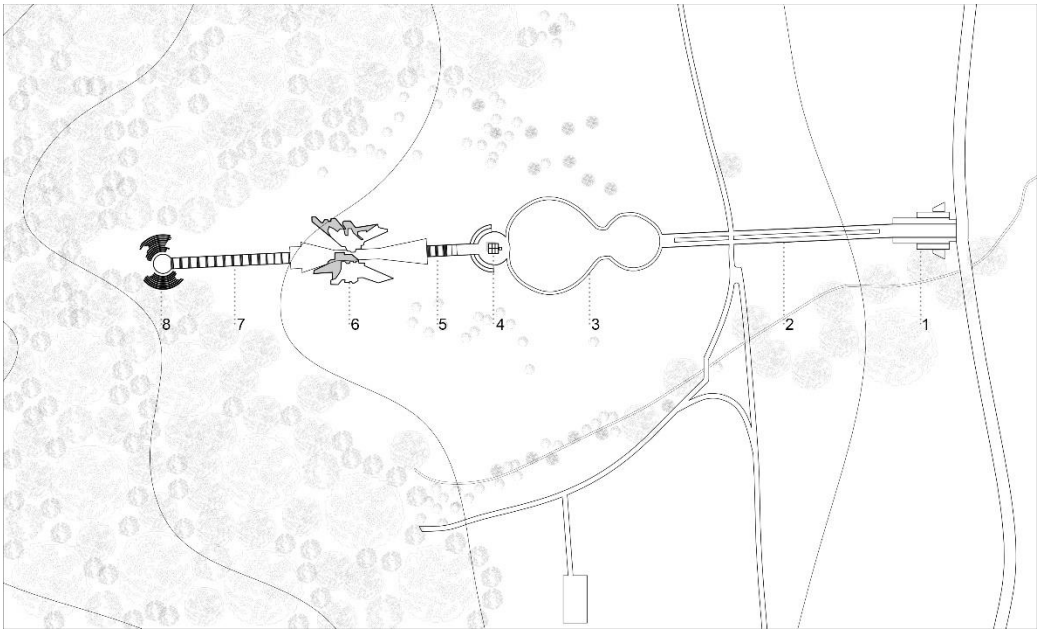


Figure 1. Situational plan
1 - access plateau 2 - path 3 - grand staircase 4 - memorial ossuary 5 - second staircase 6 - monument 7 - third staircase 8 - amphitheater

The interaction between the form of the monument and the landscape is deepened by the symbolic representation of the space between the two entities. The created space "bordered" by the stone units of the monument symbolizes the space inside the units and the rescue of weak and wounded fighters. The very structure of the monument in the part oriented towards the central passage is characterized by the manifestation of reduced anthropomorphic forms, which highlights the diversity of the treatment of the monument from large strokes that determine its external appearance to the representation of segments of the human body in its "inside". With its design and symbolic representation, the monument possesses a high degree of aesthetic values and a narrative character expressed through appearance in space. The modern age has complexly expressed the

aesthetic function as essential for the functioning of art. It is not just an empty aestheticization, but the spirit and thought of modern art situates the aesthetic-content function, that is, the level of spatial relations where the aesthetic is manifested through the content, which as a new visualization forms a new speech that is identical, full and true [1]. Through the described characteristics and realized values, the unique aesthetic, design and symbolic values of the Sutjeska battle monument are highlighted, whose identity of spatial entities and visual foundations is rooted in the uniqueness, authenticity and specificity of the visual perception.

3.1 Views and perception of the complex

The existence of symmetry is highlighted as a dominant term when establishing perceptual relations between the observer and the monument. Namely, the first access plateau was formed around a clearly set axis of symmetry around which it spreads symmetrically with gentle cascades, thus forming a wide access surface. The monument itself, positioned on a hill, although monumental in character and 19 meters high, can be seen from the plateau in the rough outlines of its form with a pronounced contrast of its whiteness against the wooded, green landscape. At this level of perception, with its design, the monument establishes a clear connection with the natural environment and morphological characteristics of the terrain, suggesting the silhouette of mountain outlines. Two branches of the path lead from the plateau to the bottom of the stairs, maintaining the symmetry of the composition with the green grass belt in the middle. At this level of observation, the visitor gets an impression of the relief of the monument's processing and an even stronger connection between the shape of the monument and the space that surrounds it. At the very bottom of the stairs, the monument becomes invisible to the observer due to the morphology of the terrain. The existence of symmetry has been preserved by designing two sets of stairs, although one set is currently destroyed due to a landslide and its reconstruction is planned, with a characteristic circular shape, which overcomes the difference in height between the path and the plateau of the ossuary.



Figure 2. The relationship between monument and landscape - part 1

The staircase is made of stone blocks and leads in a steady rhythm with frequent rest stops to the memorial plateau - the ossuary. The ossuary itself has been preserved according to the original project of Sakib Hadzihalilović, but the plateau around it has been changed and has a circular shape with cascading elevations around the perimeter. The axis of the ossuary represents the axis of symmetry, in the extension of which a staircase is formed that leads further to the monument. The perception of the relief treatment of the monument and the hint of its details becomes noticeable by moving towards the monument (Fig. 2).

By further approaching the contours of the monument seen from the observer's position, the silhouettes of the hilly landscape begin, which represents a direct "scenography" at this perceptual level. On a perceptual level, the shape of the two separate masses of the monument still support the sense of symmetry, while on the level of detail, the need for symmetry has been abandoned by relief processing. The tapering plateau leads the visitor towards the passage between the two masses of monuments and enables the reading of the anthropomorphic relief forms executed in the mass of the monuments. The moment stands out as a turning point in perception when one passes between the two masses of the monument - the form opens up and becomes more sophisticated, changing the initial quasi-symmetrical and monolithic appearance [6]. Side views from the "axis of symmetry" towards the monument, for the first time, the monument overhangs the silhouette of the surrounding landscape, and with the arms of the monument, that is, the wings of the monument, the only background becomes the open sky. The continuation of the movement from the plateau of the monument leads the observer to the staircase that leads to the formed amphitheater. The amphitheater was formed on the basis of the natural characteristics of the terrain morphology by cutting white concrete strips on which the names of the units that participated in the battle were written. Positioned on elevated ground in relation to the monument itself the view from the amphitheater allows to observing the monument from above, while the background is the hilly and wooded landscape on the opposite side of the Sutjeska River (Fig. 3).



Figure 3. The relationship between monument and landscape part 2

Returning to the monument, this landscape becomes a continuous segment of the view, where the dimensions of the monument never go outside the silhouette of the landscape,

but remain within its frame. From the bottom of the stairs, the path leads to the memorial house of Ranko Radović. The path leads over a channel lined with stone and a bridge of very reduced design. By looking at the monument from this distance, the harmony of the form of the monument with the space of the landscape can be read again, with the contrast of the whiteness of the monument and the strips of the amphitheater against the forested areas of the national park.

3.2 Materialization and construction

By accepting concrete as an aesthetically relevant material with the knowledge and skill of its application and processing, the entire construction and final appearance of the materialization of the monument of the Battle of Sutjeska was made in concrete. The concrete structure of the monument was created as a result of the collaboration between the sculptor Miodrag Živković and the architect Đorđe Zloković. The construction of the monument was formed by creating individual concrete elements and their grouping, which created a very complex supporting structure made of "chambers" that bear the main load and around which the final elements of the monument's appearance were formed. The creation of such a complex "hollow" construction of the monument required a very complex system of scaffolding and formwork necessary for the execution of such a specific sculptural and artistic achievement (Fig. 4). Due to spatial organization, the applied structural system possesses significant high load-bearing capacity and the structural efficiency was enhanced and the structure was able to "float" due to the fluctuation in density of the inner structural elements [7].



Figure 4. Construction of the monument

Specialized engineering units of the Yugoslav People's Army were engaged in the construction of the monument, using both the technical equipment of these units and the personnel. The most impressive evidence of the complexity of the formed three-dimensional structure of load transfer and the way of creating the supporting elements of the monument are the photographs taken during the construction of the monument itself. From an artistic and technical point of view, the conformity of the constructive requirements and the potential of the artistic properties of the monument, expressed precisely by the use of concrete, is manifested. Seen from this aspect, and with the aim of perceiving the final appearance of the monument, it is important to understand that concrete surfaces that are not subsequently hidden and that their "non-processing" does not in any way mean their aesthetic degradation. What follows from this approach is the need to use high-quality concrete for the full expression of its artistic values, but also to satisfy the static load-bearing conditions. Pure forms derived from the need for function and construction appear in all their logic - which was also one of the conceptual bases of the pioneers of contemporary architecture [8]. What characterizes the final appearance of the monument and the final processing of the materialization is the visibility of the layout of the board formwork elements used during the pouring of the concrete masses, whereby the size of the applied formwork varies from the largest elements at the base of the monument to the smaller formwork elements applied on the higher parts of the monument. The method of casting concrete elements plays a significant role, perhaps crucial to the final artistic effect, where the properties of the formwork and the workability of the concrete mass are the main influencing factors [8]. The recognizability of the monument of the battle on Sutjeska, in addition to the already mentioned characteristics, is also its whiteness, which creates a contrast against the landscape, and at the same time achieves authenticity in its appearance and the impression it leaves on the observer. The aforementioned characteristics were achieved by the very technology of making the concrete mass by adding additives that achieved the desired whiteness of the monument. The complexity of the constructed construction of the monument and the symbiosis with its appearance embodied in the concrete mass suggest the importance of knowledge and skill in the application and processing of materials while highlighting all the aesthetic and constructive characteristics that the material possesses, an aspect that was respected to the greatest extent and skilfully applied in the case of the creation of the monument to the Battle of Sutjeska.

4 TRANSFORMATION OF THE ROLE OF THE MEMORIAL COMPLEX

The specificity of the function of memorial complexes is their perception as a medium of transmitting social memory, where their role is manifested by transposing the content and fulfilling the function of creating a place of memory [9]. In the context of Sutjeska, passing on social memory and creating a place of remembrance refers to the establishment of relations with the events of the Second World War and the sufferings characteristic of the area where the memorial complex is being built. In the local context, the preservation of the memory of the war appears primarily as an attempt by people to cope with mourning for the dead, where the areas of social action are included: the preservation of memory appears as a business policy, as an artistic process, as a social obligation and as a pedagogical task

[3]. The role of memorial spaces set in this way required the artist, architect or sculptor to create spatial units with a strong character, an authentic and unique narrative of passing on memories and establishing relations with the visitors of the memorial complex. Designing the spatial type of monuments, memorial parks or memorial areas was aimed, among other things, at attracting as many users as possible, especially the younger generation, to authentic locations associated with the *NOB*. Those spatial entities also implied a specific type of reception of social memory, such as the movement of visitors through nature, following a given route that included famous historical locations. What characterizes the monument on Sutjeska is precisely the power of the narrative about the event, the spatial, symbolic and associative connection. In the structure of Sutjeska's interpretation, the supporting elements were victory, willingness to sacrifice and heroism of the partisans with the emphasized participation of partisan units from different parts of the country, i.e. the presence of a general Yugoslav element [3]. The most dominant events related to the existence of the memorial complex are the commemorative ceremonies organized by the state leadership and in the presence of the highest state officials. The first such ceremony and one of the most attended was held on July 4, 1958, marking the 15th anniversary of the Battle of Sutjeska. The ceremony was attended by the president of the state by laying wreaths on the memorial - ossuary and giving a speech, with an estimated attendance of about 70,000 people [3]. Commemorative festivities were also held in the following period, mostly connected by dates to the anniversaries of the battle or the revolution. On the other hand, the Sutjeska memorial complex became part of the tourist offer and the network of tourist attractions related to the NOB in Yugoslavia. Thus, Sutjeska becomes a kind of brand visited by tourists from all parts of Yugoslavia.

The status and condition of the Tjentište memorial complex in the modern moment differs to a certain extent from other memorial spaces dedicated to the NOB in the territory of the former Yugoslavia. Namely, most of the monuments created with the aim of marking the struggle and suffering during the Second World War are mostly in a neglected state, ruined and damaged or even demolished. This, to a certain extent, confirms the views that the official socialist culture of remembrance even with the help of an artistically successful monument and mass visits to such a central place of remembrance could not be passed on to new generations [10]. The Tjentište memorial complex has been under the protection of the Republic Institute for the Protection of Cultural, Historical and Natural Heritage of the Republic of Srpska since 2009, after the decision to designate the Tjentište memorial complex as a cultural asset of exceptional importance [11]. During 2017 and 2018, the reconstruction of the memorial complex was carried out, and on that occasion the monument itself was whitewashed, returning it to its original recognizable whiteness. Also, works were carried out on the replacement of paving on the plateau around the monument and on the staircase that connects the memorial ossuary and the monument itself, as well as on the staircase between the monument and the amphitheater. The importance and relationship to the values of the monument on Sutjeska in the contemporary context is perhaps best evidenced by the fact that the first and original model for the memorial was presented to the world public at an exhibition in the Museum of Modern Art in New York. The artistic values of this sculpture were affirmed before the eyes of the professional and interested public of the West the modern era, which marked the culture of a part of the European in a special way with a convincing visual expression of its time.

5 CONCLUSION

As the starting goal in the creation of this work was the spatial analysis of the Tjentište memorial complex with the research of archival material, an overall picture of the origin and development of the space was created, as well as its role in the process of creating memories of the events of the Second World War. From the aspect of spatial, architectural and sculptural characteristics, the work itself represents an imposing achievement that can be classified in the category of the most representative works of art created in the territory of the former Yugoslavia, made with the theme of marking places of suffering and battles. The dominant characteristic that places this work in that category is the continuity of establishing relations with the environment and landscape. This continuity of established relations is manifested at the macro level and the relationship between the monument itself and the entire Sutjeska National Park, through an abstract representation of the characteristic landscape expressed through the design of the monument. At the micro level, the relations between the monument and the landscape are articulated in such a way that they can be seen from the perspective of the visitors while moving along the projected path and approaching the monument itself. For the understanding of the tectonics and symbolic representation of the monument, a significant segment is represented by the preserved written explanations of the monument author Miodrag Živković himself. The symbolism of breakthrough, victory and freedom that the monument carries is also significant in terms of the role of the monument in the social, political, cultural and sociological aspect, which is evidenced by the photos from the festivities held within the complex. From the aspect of the modern life of the monument and its role, as well as the importance attached to it, the inclusion of the original model of the monument in an integral part of the exhibition in the Museum of Contemporary Art in New York, which to a certain extent confirms the aesthetic quality of the work itself and its perception as a representative example of artistic expression from the modern period from the area of the former Yugoslavia.

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Research paper

SEISMIC PERFORMANCE ASSESSMENT OF AN EXISTING RC BUILDING IN ROZAJE ACCORDING TO EN 1998-3

Anida Murić[1], Jelena Pejović[2]

Abstract

Given that Montenegro is located in a region with a high seismic hazard, assessing the seismic performance and retrofitting of existing buildings is crucial for reducing seismic risk. This presents a significant challenge in modern construction, as most existing buildings were designed according to outdated regulations, making them non-compliant with contemporary seismic standards and necessitating structural retrofitting. This research focuses on the seismic assessment of an existing reinforced concrete (RC) frame building in Rožaje, with the aim of verifying the compliance with the significant damage limit state as defined by the European standard EN 1998-3. The analysis of the existing building, modeled in the ETABS software package, was carried out using non-linear static Pushover analysis. Material and structural nonlinearity characteristics were defined, along with the plastic mechanism and nonlinear loading, all in accordance with EN 1998-3. The Pushover analysis was conducted in 50 steps, during which the predefined plastic mechanism demonstrated the formation of plastic hinges within the structure. The results indicated that while the building does not meet the significant damage limit state, its deformation capacities remain within acceptable limits, whereas shear capacity is exceeded. Consequently, it was concluded that shear retrofitting of specific structural elements (beams and columns) is necessary to meet the EN 1998-3 requirements. FRP (Fiber Reinforced Polymer) materials were identified as the optimal solution for retrofitting. This study provides valuable insights into the seismic performance of similar structures in Rožaje and other Montenegrin cities, offering a basis for improving seismic resilience in line with modern regulations.

Key words: *Seismic assessment, RC building, EN 1998-3, retrofitting, Non-linear static Pushover analysis*

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1. INTRODUCTION

Given that Montenegro is located in a region of high seismic hazard, the assessment of seismic performance and the seismic strengthening of existing structures are of critical importance for reducing seismic risk. Evaluating the behavior of buildings under earthquake loading and ensuring adequate seismic safety prior to the occurrence of a seismic event remains a significant challenge in structural engineering today. Most existing buildings were designed according to outdated codes, such as PIOVS 1981 [1] and Temporary Code 1964 [2], and therefore do not possess adequate seismic resistance. Moreover, they fail to meet the seismic design requirements specified in modern European standards, particularly EN 1992-1-1 [3], EN 1998-1 [4] and EN 1998-3 [5]. Consequently, these buildings require structural strengthening. Assessing the seismic performance for buildings designed according to old codes and designing appropriate retrofit measures to achieve acceptable seismic behavior has become a highly relevant and pressing issue in the field of structural engineering in Montenegro.

As no comprehensive vulnerability assessment of the built environment has yet been conducted in Montenegro, this study aims to contribute to the evaluation of existing reinforced concrete (RC) residential buildings in the municipality of Rožaje. The objective is to assess the seismic performance of a selected representative RC building type, with a focus on verifying the limit state of significant damage in accordance with the EN 1998-3 [5]. The analysis will evaluate both the bending and shear resistance and deformation capacities of structural elements (beams and columns), and propose optimal seismic strengthening solutions for selected components. The proposed retrofitting strategies will emphasize both economic efficiency and ease of technical implementation. By achieving these objectives, the study will provide valuable insights into the seismic safety of existing buildings exposed to earthquakes in the Rožaje area and contribute to a broader understanding of the seismic vulnerability of RC buildings. The seismic performance assessment, particularly the verification of the significant damage limit state as defined by EN 1998-3 [5], will be conducted using a nonlinear static pushover analysis. For the purpose of this study, data on multi-family residential buildings will be sourced from the Municipal Earthquake Protection and Rescue Plan for Rožaje (OPZiS, 2017) [6], as well as available design and planning documentation obtained from the municipal archive of Rožaje.

2. SELECTION OF A REFERENCE RC BUILDING IN ROŽAJE

Based on the analysis of the available planning and design documentation, the building shown in Figures 1, 2, and 3 was selected as a representative example of typical buildings in the municipality of Rožaje. The selected building is a RC frame structure, has base dimensions of 40.75m by 14.0m. It consists of a basement with a height of 2.77m, a ground floor with a height of 3.57m and five floors, each with a height of 2.79m [7]. One of the key factors influencing its selection as the reference building is the well-documented construction history, which provides a solid foundation for a comprehensive seismic assessment. The availability of complete data from the original design documentation allows for a detailed and accurate seismic analysis. In addition to representing a typical frame-structure building found in Rožaje, the selected building is also among the larger structures constructed in recent years, giving it urban significance and making its seismic safety particularly important to the

local community, further justifying its selection for this research. RC frame systems have distinctive characteristics with respect to seismic performance and are among the most commonly used structural systems in seismically active regions. These structures are defined by a skeletal arrangement of beams and columns, offering high flexibility and effective dissipation of seismic energy during earthquake events.

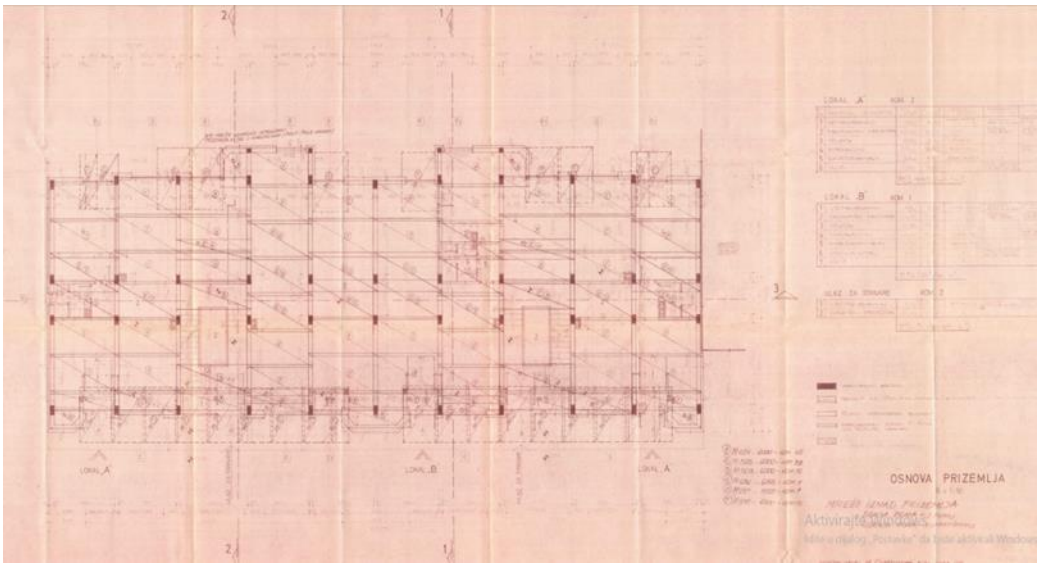


Figure 1. Ground floor plan extracted from the available design documentation

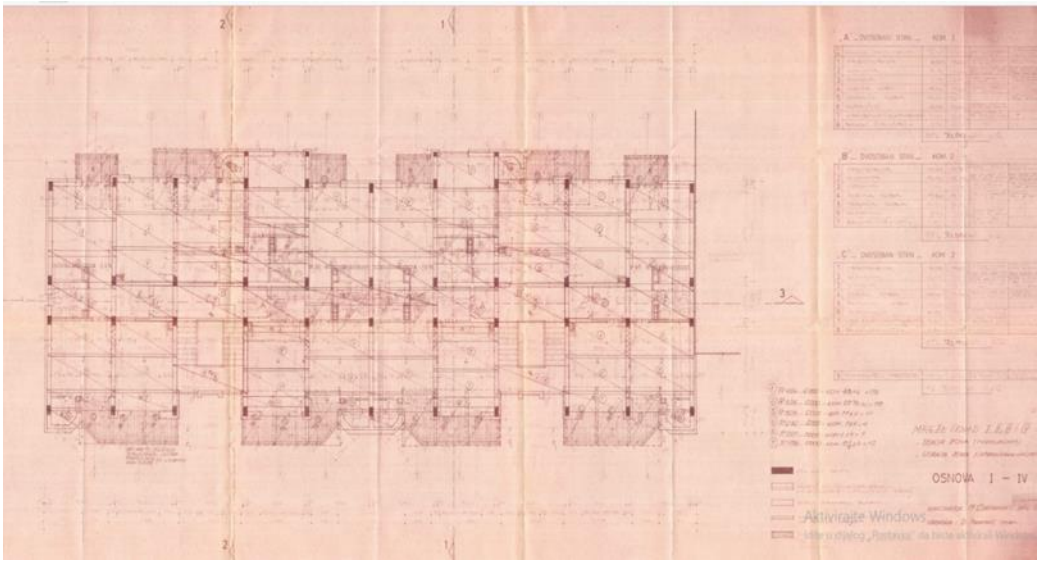


Figure 2. Typical floor plan (Levels I–IV) extracted from the available design documentation

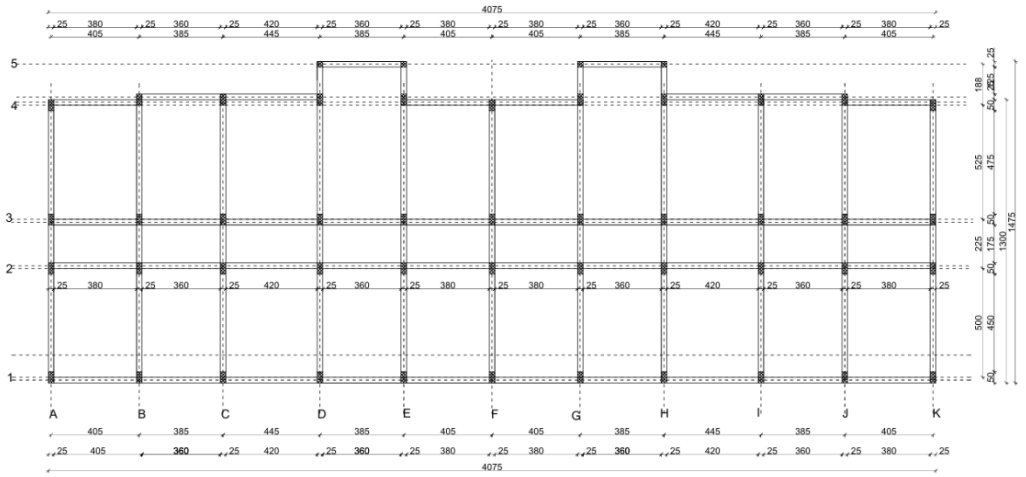


Figure 3. Typical floor plan (Levels I-IV) extracted from the autoCad

Given that the building has been in use for an extended period, serving both residential and commercial purposes, the analysis of its characteristics, seismic resistance, and potential retrofitting methods provides valuable insight into the real challenges and opportunities for enhancing the seismic performance of such structures.

While RC frame structures have advantages in terms of seismic performance, due to their inherent flexibility and ductility, they nonetheless require detailed analysis, particularly when design standards have evolved since the time of construction (in this case, 1985). The analysis of the selected building's frame system will provide valuable insights into the seismic behavior of such structures in Rožaje. Consequently, this research may serve as a reference for similar buildings, not only in Rožaje but also in other municipalities across Montenegro, offering practical recommendations for improving and modernizing seismic resistance in accordance with current standards and techniques. In doing so, the study contributes to the long-term safety of communities and the protection of the urban built environment.

3. SEISMIC ASSESSMENT OF A SELECTED RC BUILDING ACCORDING TO EN 1998-3

Prior to conducting nonlinear static analysis, it is essential to perform a structural condition assessment of the building under investigation. This process involves determining whether the existing structure satisfies the required performance at a defined limit state under the considered seismic action. In this study, the assessment focuses on verifying the Significant Damage (SD) limit state in accordance with EN 1998-3 [5]. Seismic performance evaluation of existing structures requires input data gathered from various sources, including available documentation, field surveys, in-situ or laboratory testing, and measurements. According to EN 1998-3 [5], the data required for structural evaluation should include: (1) identification of the structural system and its compliance with regularity criteria defined in EN 1998-1 [4]; (2) determination of the building's foundation type; (3) classification of soil conditions based on EN 1998-1 [4]; (4) data on global dimensions, cross-sectional properties of structural elements, and mechanical properties of materials used; (5) identification of material deficiencies and detailing inadequacies; (6) information on the seismic design criteria applied

in the original design, including the behavior factor (q-factor), where applicable; (7) description of the current or intended use of the building; (8) updated load assessments reflecting the building's functional use; and (9) data on the type and extent of past and existing structural damage, if any, including records of previous retrofitting measures.

An essential subsequent step in the assessment of an existing structure is the determination of the knowledge level, as defined in EN 1998-3 [5]. Knowledge levels represent varying degrees of reliability in the information collected about a building and are particularly important in the evaluation of existing structures.

Before performing any structural analysis or implementing retrofitting measures, it is essential to determine the achievable level of knowledge. A higher knowledge level corresponds to greater reliability of the analysis results. The selection of an appropriate type of analysis and the corresponding confidence factor, reflecting the accuracy and reliability of the available data, should be based on the established knowledge level. As the knowledge level increases, the confidence factor decreases, leading to a more realistic and accurate assessment of the structural condition.

Three levels of knowledge are defined:

1. Knowledge Level 1 (KL1): Corresponds to a limited amount of information available about the structure.
2. Knowledge Level 2 (KL2): Represents a standard level of knowledge, based on more detailed investigation of the structure, including material sampling and testing to obtain more accurate data on material properties.
3. Knowledge Level 3 (KL3): Corresponds to complete knowledge, based on the most comprehensive investigation and documentation of the structure.

The factors that determine the appropriate knowledge level include: the geometric properties of the structural system and non-structural elements that may influence the structural response; detailing, including the quantity and layout of reinforcement in RC elements; and the mechanical properties of the materials used in the structure.

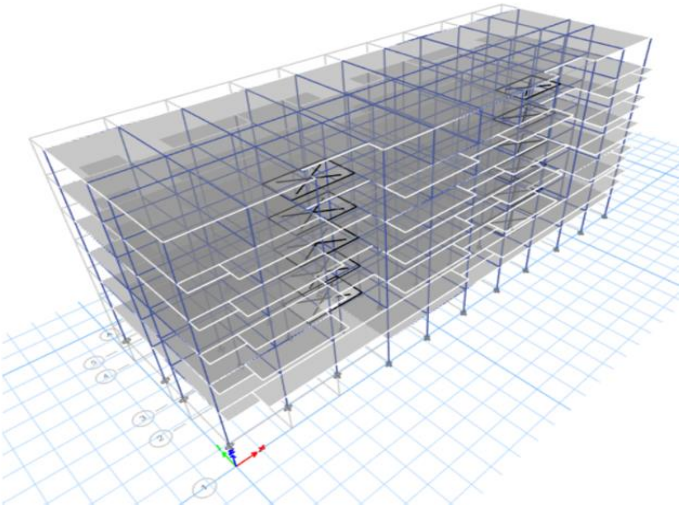
Based on the available design documentation and the analysis of the factors defining the knowledge level, it was concluded that the selected reference building corresponds to Knowledge Level 2 (KL2), i.e., a normal level of knowledge.

The condition assessment procedure can be carried out using general analysis methods specified in EN 1998-1 [4], with modifications outlined in EN 1998-3 [5]. The following types of analyses may be employed: a) Linear analyses: Lateral Force Method and Modal Response Spectrum Analysis; b) Nonlinear analyses: Static (Pushover) Analysis and Dynamic (Time History) Analysis and c) Approach based on the application of the behavior factor (q-factor).

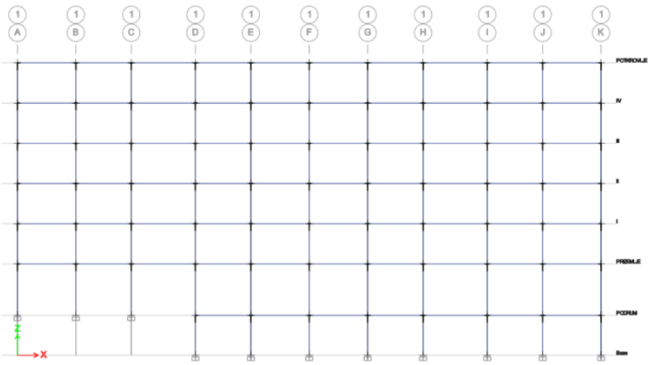
For the selected building, the most appropriate method for obtaining a comprehensive understanding of its seismic behavior is the nonlinear static pushover analysis. This choice is based on the fact that the criteria for applying linear methods, as defined in EN 1998-3, were not fully met. Specifically, the lateral force method did not satisfy the requirements related to the fundamental period of vibration. As a result, modal response spectrum analysis was initially applied, with floor forces calculated according to EN 1998-1 [4]; however, the conditions required by EN 1998-3 [5], which is the focus of this assessment, were still not satisfied. Consequently, nonlinear Push-over analysis was adopted.

3.1. Non-linear modelling

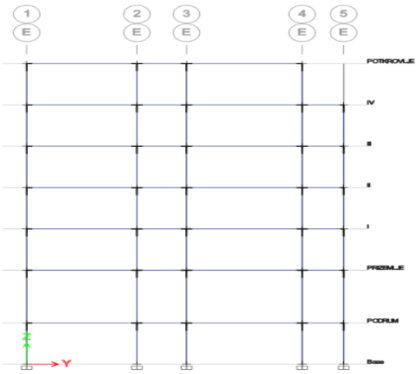
The analyzed RC building was modeled using the ETABS software package [8] (Figure 4). For the purposes of the nonlinear pushover analysis, moment–curvature diagrams were generated within the same software environment. The development of these diagrams required the adoption of nonlinear material properties for both concrete and reinforcing steel. The moment–curvature diagram was used to define the yield moment M_y and the corresponding yield curvature θ_y as well as the ultimate moment M_u and the corresponding ultimate curvature θ_u. To define the properties of confined concrete, it was first necessary to determine the properties of unconfined concrete for the corresponding concrete grade, as presented in Table 1. For the selected building, concrete of class C25/30 was assumed, in accordance with EN 1992-1-1 [3]. Both confined concrete and reinforcing steel were modeled in accordance with the provisions of EN 1992-1-1 [3] and EN 1998-3 [5]. After defining the nonlinear material properties, plastic hinges were assigned to the cross-sections of columns and beams.



(a)



(b)



(c)

Figure 4. a) 3D view of the modeled RC building in the ETABS software package [8], b) Elevation of the X-direction typical frame and c) Elevation of the Y-direction typical frame

Table 1. Properties of unconfined concrete

Concrete class C25/30	
Characteristic compressive strength f_{ck} $[MP_a]$	25
Mean compressive strength f_{cm} $[MP_a]$	3,3
Mean value of the modulus of elasticity E_{cm} $[GP_a]$	31
ε_{c2} [‰]	2,0
ε_{cu2} [‰]	3,5

Figure 5 illustrates the definition of plastic hinge properties for nonlinear analysis in ETABS [8], applied to one of the representative beams. Given that the beam is subjected to a negligibly small axial force and primarily loaded in bending about a single axis, the definition of the plastic hinge requires only a moment–curvature diagram, without the need for interaction diagrams, thus, an M3 plastic hinge is appropriate.

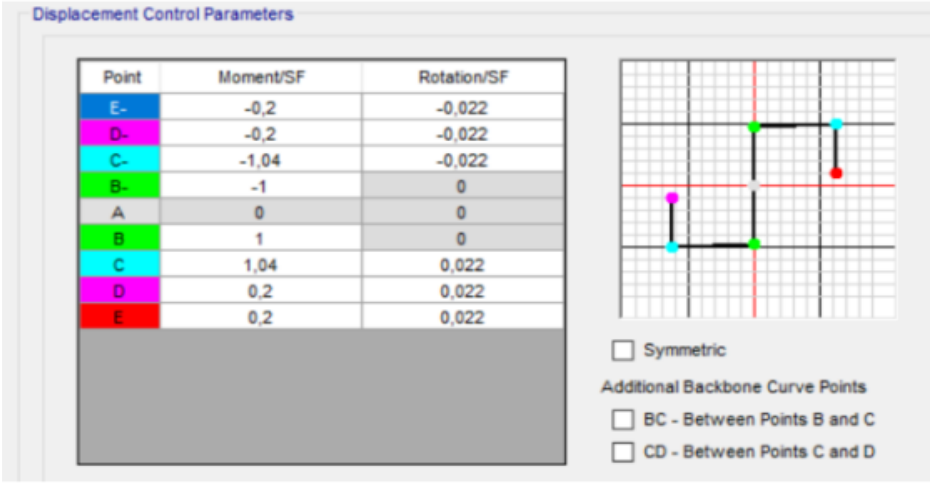


Figure 5. Definition of a beam plastic hinge in the ETABS software package [8]

Figure 6 shows the definition of a column plastic hinge for nonlinear analysis. Since axial compressive force significantly influences column behavior, it is necessary to consider biaxial bending and axial loading. Therefore, a P–M2–M3 plastic hinge is defined for the column, incorporating an interaction diagram that accounts for biaxial bending combined with axial force.

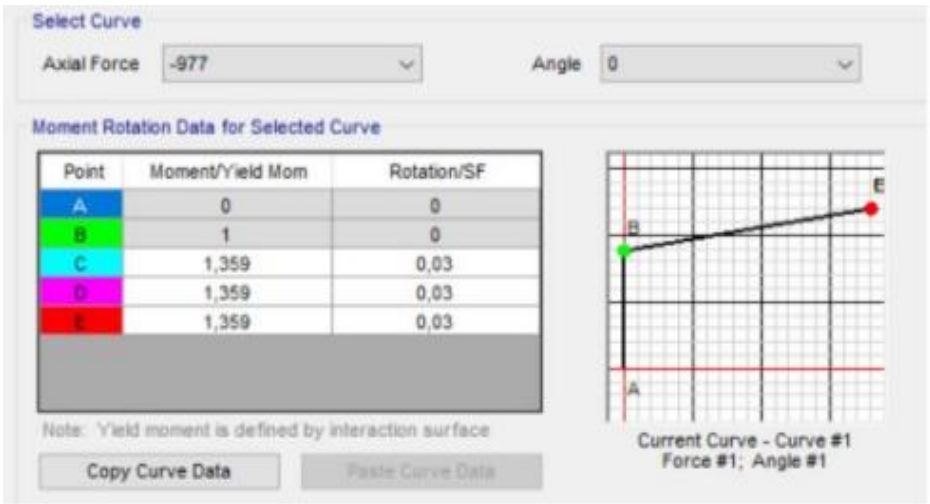


Figure 6. Definition of a column plastic hinge in the ETABS software package [8]

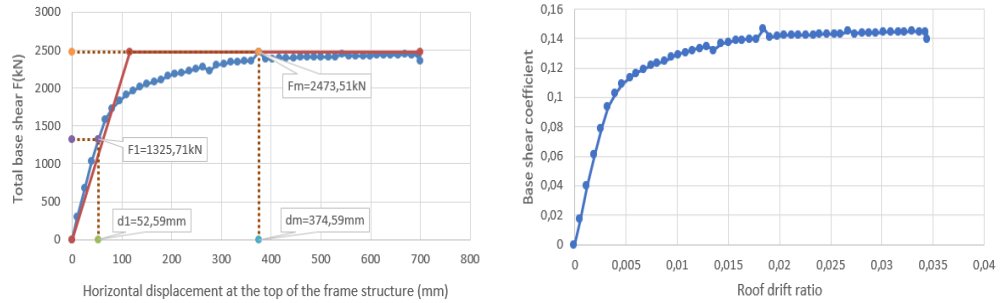
Subsequently, the nonlinear loading was defined. The first step involved the definition of nonlinear gravitational loading. In accordance with EN 1998-3 [5], two load distributions, modal and uniform, were specified for both the X(+/-) and Y(+/-) directions.

3.2. Non-linear static Pushover analysis

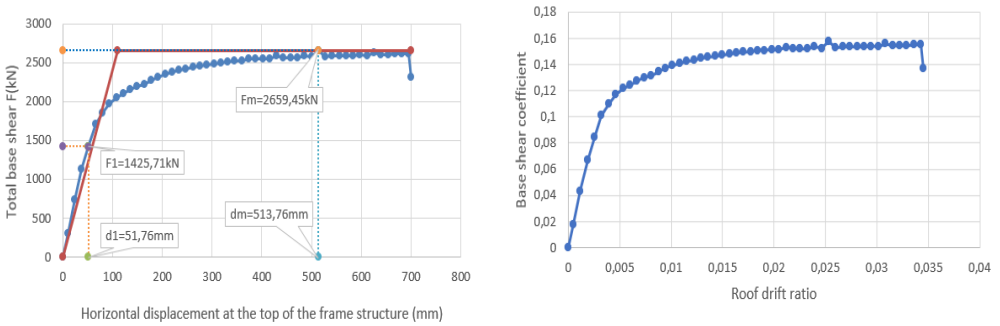
The pushover analysis was conducted in ETABS software package [8]. The outcome of the analysis is the pushover curve, which describes the relationship between the base shear and the displacement at the top of the structure [9]. This curve was used to determine the target displacement, which in turn provided the control displacements required for further structural analysis. The target displacement was calculated in accordance with EN 1998-1

(Annex B) [10], by transforming the multi-degree-of-freedom (MDOF) system into an equivalent single-degree-of-freedom (SDOF) system using the elastic response spectrum.

Figures 7 and 8 present the pushover curves obtained using the ETABS software [8] for both the X and Y directions, considering both lateral load distributions (modal and uniform). These curves were used to determine the control displacements, which served as the basis for the final results.

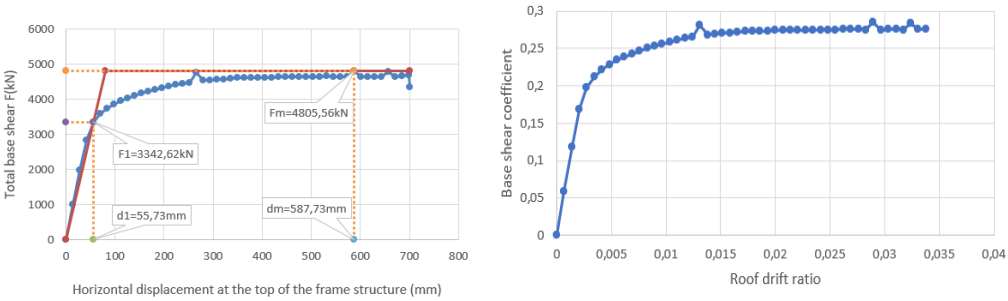


(a)

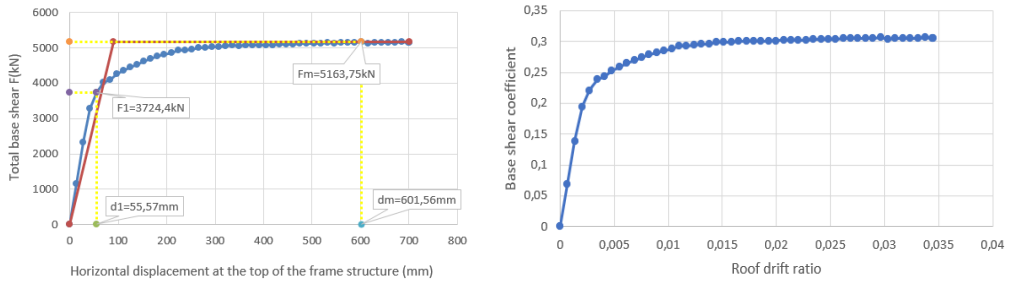


(b)

Figure 7. Pushover curves in the X+ direction: a) modal load distribution and b) uniform load distribution



(a)

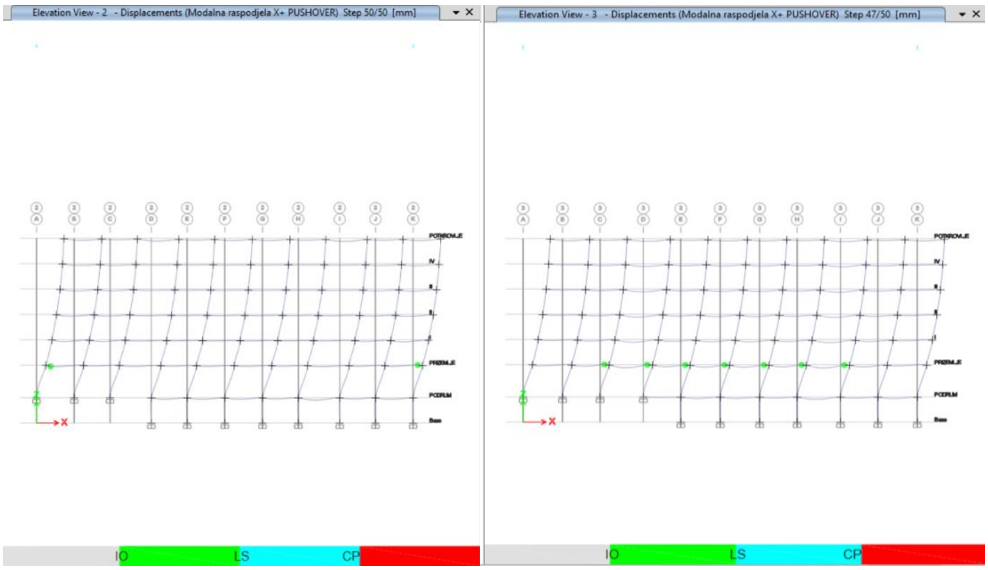


(b)

Figure 8. Pushover curves in the Y+ direction: a) modal load distribution and b) uniform load distribution

Figure 9. illustrates the formation of plastic hinges for modal distribution in X+ direction, shown for the frame along axis 2 at step 50/50 and the frame along axis 3 at step 47/50, respectively. Figure 10 presents the behavior of one of the plastic hinges observed in the aforementioned frames.

Specifically, while the deformation capacities were not exceeded, the shear capacity was surpassed, leading to the conclusion that the Significant Damage (SD) limit state was not satisfied. Consequently, seismic strengthening of certain structural elements (beams and columns) is required, with a focus on enhancing their shear resistance. Since the shear capacity was exceeded, it was necessary to consider structural strengthening in accordance with EN1998-3.



(a) *(b)*

Figure 9. Loading case with "modal distribution X+": a) frame along axis 2 – plastic hinge formation at step 50/50, and b) frame along axis 3 – plastic hinge formation at step 47/50

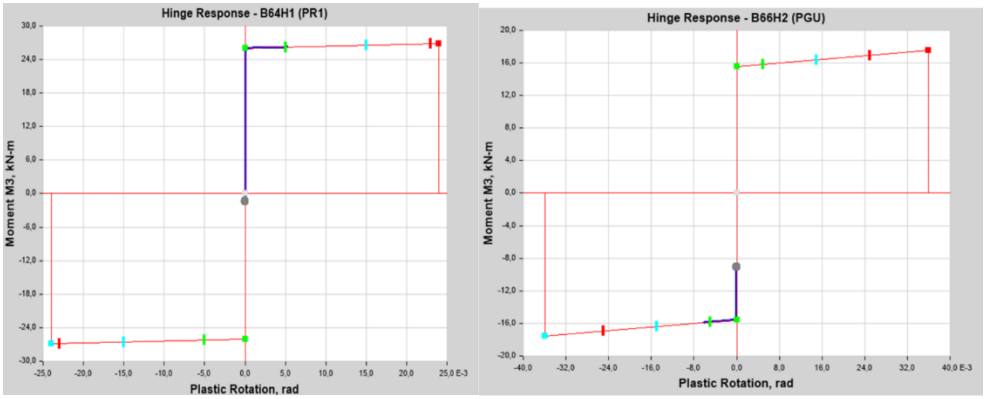
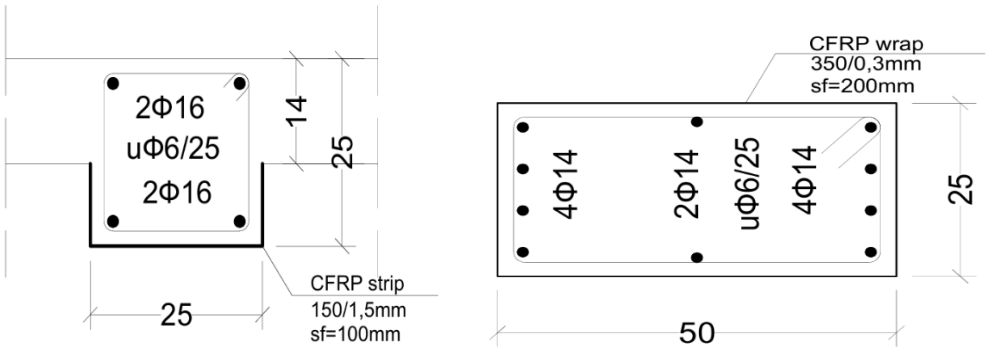


Figure 10. Behavior of one of the plastic hinges – deformation capacities not exceeded

4. SEISMIC RETROFITTING OF RC BUILDING USING FRP MATERIALS

Various strengthening techniques are available for structural elements, including concrete or steel jacketing, confinement with additional reinforcement, and the use of Fiber Reinforced Polymer (FRP) systems such as FRP laminates and wrapping. These methods aim to enhance load-bearing capacity, increase bending and shear strength, and improve deformation capacity. In this study, FRP materials, specifically carbon FRP (CFRP) strips and wraps, were selected as the strengthening solution. A key advantage of FRP-based retrofitting, compared to conventional methods, is the ability to carry out the intervention within a short time frame, even while the building remains in use. Figure 11 illustrates beam strengthening using CFRP strips and column strengthening using CFRP wraps.



(a) *(b)*

Figure 11. Example of strengthening: a) beam retrofitted with CFRP strips, and b) column retrofitted with CFRP wraps

5. CONCLUSIONS

The analysis of the selected building provides important insights into the seismic behavior of such structures in Rožaje. Accordingly, this study may serve as a reference for similar buildings throughout Montenegro, offering recommendations for improving and modernizing

seismic resistance in line with current design practices and technologies, thereby contributing to long-term community safety and the protection of the urban built environment.

The assessment was carried out using nonlinear static pushover analysis, which demonstrated that the deformation capacities were not exceeded. However, subsequent evaluation of shear capacity revealed that, for certain structural elements, shear demands exceeded capacity, indicating that the Significant Damage (SD) limit state was not satisfied. As a result, seismic strengthening of structural elements with respect to shear is necessary to ensure that the structure can adequately dissipate seismic energy in a controlled manner without experiencing brittle failure, given that deformation capacity remains within acceptable limits.

To enhance shear resistance and overall seismic performance, strengthening using CFRP strips was adopted as the optimal solution due to its economic viability and ease of implementation. The use of CFRP materials contributes to increased load-bearing capacity of structural elements without a significant increase in the structure's self-weight.

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Research paper

STRUCTURAL CONDITION ASSESSMENT AND REHABILITATION PROPOSALS - CASE STUDY PARTIZAN SPORTS COMPLEX IN MOSTAR

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Abstract

In this paper structural assessment of Partizan sports complex in Mostar, Bosnia and Herzegovina, is presented. The sports complex was damaged during 1993., and since then did not had significant rehabilitation activities. The complex is composed of three parts: main building, sports ground and locker rooms. Main building and locker rooms are from Austro-Hungarian period and were used as administrative buildings prior to 1920. Afterwards it was used as a sports complex, and a sports ground was added in the middle of the last century. According to UNESCO plan of rehabilitation this complex has high priority for rehabilitation, considering location. Only the sports ground is still in active use, since it did not experience significant damage. The complex was entirely detailly inspected, first by visual inspection, followed by in-situ test to evaluate quality of the materials. In the end, the rehabilitation proposal for the buildings and sports ground with appropriate strengthening methods and new design is presented.

Key words: *rehabilitation, assessment, stone, damage*

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1. INTRODUCTION

Due to its geographical location, the city of Mostar represented an extremely important military and strategic stronghold as early as the period of Ottoman period in Bosnia and Herzegovina. Mostar remained a military center during the period of the Austro-Hungarian Monarchy, the Kingdom of Serbs, Croats and Slovenes and Yugoslavia. Known as the "Military Camp," Mostar had, by the end of the 20th century, four military camps within the city itself (Northern, Southern, Eastern or Konak and Western) [1]. During four decades of Austro-Hungarian period, new modern barracks and fortifications sprang up on the surrounding hills, which to this day remain true marvels of craftsmanship — showcasing near-luxury and extravagance in white dressed stone [2]. The core of the city's defense consisted of the defensive barracks Nordlager (Northern Camp – today Dzemal Bijedic University of Mostar), as well as the Sudlager (Southern Camp, which also housed the military hospital), Westlager (Western Camp — today the University of Mostar) and Ostlager (Eastern Camp — Konak) [1].

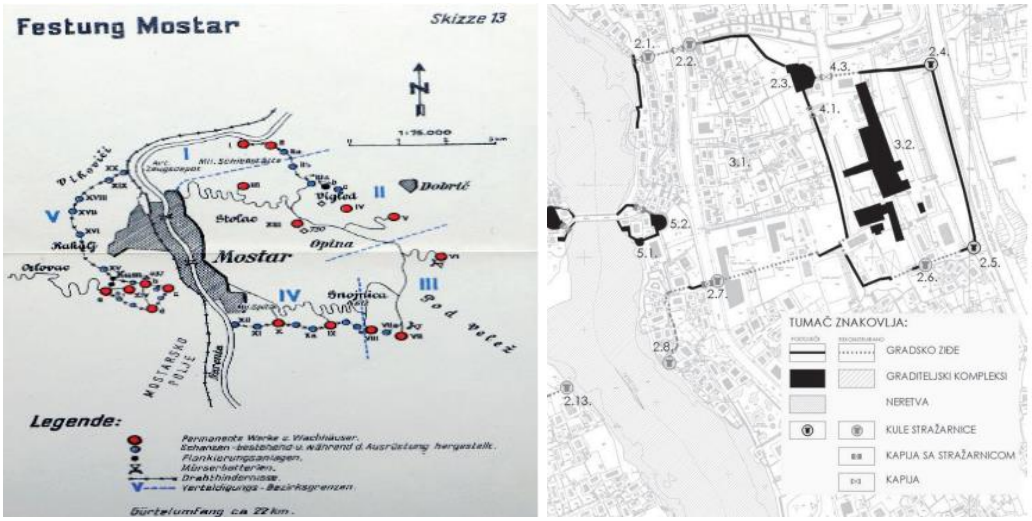


Figure 1. Barracks in Mostar and Konak [1]

The Mostar Konak is a complex that housed the military until the 1990s. Today, the complex — more precisely, its largest building — is home to the Secondary School of Civil Engineering and the Secondary School of Economics. The surrounding buildings, those that have not been abandoned, serve various purposes: an Archive, a Veterans' association and others. The surrounding towers and the open spaces are devastated. The Partizan sports field is located within the Konak complex.

The materials used for the construction of all types of buildings from this period were traditional, such as stone, fired clay products (brick, roof tiles), wood, sheet metal, lead, iron, gypsum, lime and others [3]. Stone, brick, wood and iron (iron beams — traverses) were used as the main materials for the construction of the building's vertical and horizontal load-bearing structures. The stone used for building construction was quarried from local sites (Mukoša), primarily from Tenelija and Miljevina, although for special needs of representative buildings, stone was imported from Brač or from Austria-Hungary [4].

The building was constructed between 1893 and 1901 as part of a higher girls' school. It was built by a businessman, and later the then-mayor of Mostar, Mujaga Komadina, and was

subsequently sold to the municipality. The building served educational and administrative purposes [1].

The Partizan complex is a traditional masonry structure from the Austro-Hungarian period, built from stone and mortar. Parts of the buildings also include sections made of brick and wood, which were used for the construction of the roof and floor structures. The exception are the stands, which were made of concrete. The types of stone found at the Partizan sports field include limestone ("živac") Tenelija and Miljevina stone.

The entire complex consists of four separate parts that together form a single unit. The complex of the Society for Sports Recreation and Physical Education "Partizan" covered an area of 2027 m², of which the courtyard occupied 173 m², the administration building 486 m², the gymnastics hall 242 m² and the field and stands 1126 m².

The structure of the buildings consists of massive stone walls built with lime mortar, with thicknesses ranging from 40 to 60 cm. The floor structures were made of timber, characteristic of the construction period. The building was significant damage and fire during the 1992–1995 period and there were also subsequent fires. Some parts of the complex underwent certain interventions, but it is unclear at which stages they were carried out and for what purpose.

2. CONDITION ASSESSMENT OF THE BUILDINGS

2.1. Visual assessment

The easiest way to collect data about a building is by reviewing the existing project documentation. However, for buildings from the Austro-Hungarian period, such as this one, the documentation is often lost or destroyed. Moreover, due to numerous interventions over the years, the original project no longer accurately represents the current state of the building. Visual assessment of the damaged structures includes precise measurements, a detailed description of observed damages, an assessment of their severity and the conclusion regarding the possibility of continued use of individual parts of the structure [5].

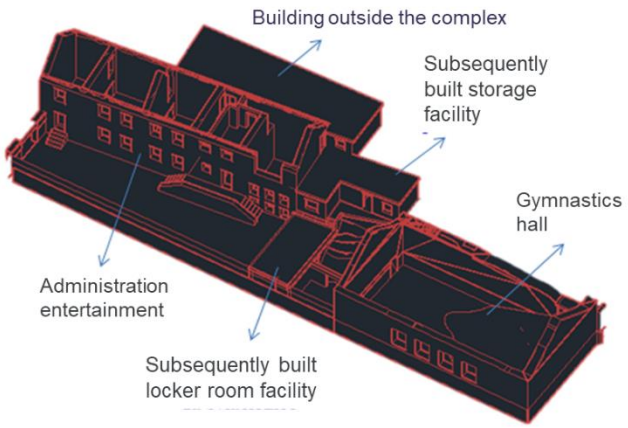


Figure 2. The current state of the Partizan complex

The building, which is assumed to have served for administrative purposes, has a rectangular base with an additional L-shaped part that forms a single unit. The second unit consists solely of the sports field with stands, next to which is another building, for which there is no data regarding its function, but it is assumed that it housed the locker rooms. The administrative buildings are connected to the rest of the complex by stairs leading to the sports field, which is in the courtyard of the third building, i.e., the locker rooms.

Due to the complexity of the "Partizan" complex, we will introduce the following designations for the units:

- Building A – The sports field with stands
- Building B - The administrative building
- Building C – Building intended for the locker rooms

2.1.1. Damage of building A

Upon entering the sports field area, it is evident that there are numerous damages caused by various factors. The stands have various physical damages that occurred from grenade impacts during the war, while the remaining significant damages are due to large tree roots that have destroyed much of the stands. There are mechanical damages as well as significant material loss. The entire wall shows signs of joints washout, the crown (top layers of stone) and the wall cap are missing. The most notable damage on the wall is the damage to the buttress and the damage at the window location—both areas have been identified with dense vegetation, such as trees (Fig.3). The stands consist of concrete slabs 15-20 cm thick, laid on a foundation of compacted earth (Fig.3). An additional issue regularly encountered is the runoff rainwater that flows from the surrounding area, accumulating on the field and causing problems for adjacent buildings. The field is made of concrete slabs, which have been better preserved than the stands, but there are still damages to the surface layers and cracks.



Figure 3. Damage to the wall and stands of building A

2.1.2. Damage of building B

The administration building has significant damage from a fire to which the building was exposed. The eastern and northern external facades do not show major structural failures, except for localized detachment of stone blocks (Fig. 4). The walls are stable and in relatively good condition. The building also shows damage from vegetation that has covered its interior, so the true condition of the building could only be assessed once the rubble and vegetation are removed. However, localized damage around the windows and wall cornices is present throughout the entire wall. Around some windows, the detachment of stone blocks is visible (Fig.4). The detachment of blocks is also visible on the cornices beneath the roof. The existing mortar is in very poor condition, with large sections of the building either missing or damaged, and in some places, it is visibly detached from the wall.



Figure 4. Damage to the walls and interior of building B

The roof of this building was destroyed during the fire and because of the collapse of the wooden structure that it rested on, the material at the support points was crushed. Remnants of the wooden structure are inside the building and the effects of the fire are visible on them. The floor structure also suffered from the effects of the fire and was completely damaged.

2.1.3. Damage of building C

The stone walls are in good condition; however, further testing will determine their actual state in terms of mechanical properties. A large part of the building is missing the mortar and sections of the wall (Fig.5). As for the roof structure and the floor structure, they are completely destroyed. The interior of the building is filled with rubble and vegetation.



Figure 5. Damage of the building C

2.2. In-situ and laboratories testing of materials

An in-situ and laboratory testing of the stone from the interior of the walls were carried out on the Partizan complex with the aim of determining the load-bearing capacity of the existing walls.

In situ analysis with rebound hammer was carried out on B and C buildings, on eight positions, on each building four position with five samples (table 1).

Table 2 presents the results of the testing of the physical and mechanical properties of miljevina stone from the buildings.

Table 1. In situ analysis with rebound hammer

Location/building	1C	2C	3C	4C	5B	6B	7B	8B
Compressive strength (MPa)	22.0	11.8	16.4	19.8	16.0	17.4	18.2	23.2

Table 2. Mechanical properties of miljevina stone

Property	Density (kg/m3)	Compressive dry strength (MPa)	Compressive strength water-saturated (MPa)	Flexural dry strength (MPa)	Absorption (%)	Porosity (%)
Average	1834.45	24.84	17.30	3.18	12.50	22.92

The ultrasonic testing method was applied to the walls of all three buildings in order to assess the uniformity of the material structure, detect voids, cavities and cracks, the obtained results are presented in Table 3.

Table 3. Ultrasonic testing

Sample/building	T	L	v (km/s)
A1	0.00007440	0.00014300	1.92
A2	0.00014400	0.00016200	1.12
A3	0.00007550	0.00012500	1.66
A4	0.00007150	0.00012400	1.73
A5	0.00009610	0.00014800	1.54
A6	0.00007910	0.00012500	1.58
A7	0.00019720	0.00030000	1.52
A8	0.00012600	0.00026000	2.06
B1	0.00003710	0.00005148	1.39
B2	0.00005220	0.00012748	2.44
B3	0.00006740	0.00011000	1.63
B4	0.00011240	0.00021000	1.87
B5	0.00009340	0.00019000	2.03
C1	0.00007300	0.00012700	1.74
C2	0.00004200	0.00011300	2.73
C3	0.00005800	0.00013400	2.30
C4	0.00005600	0.00013500	2.41
C5	0.00004000	0.00007600	1.93
C6	0.00005500	0.00020500	3.73

The results of the testing of Miljevina stone indicate a decline in mechanical properties, caused by exposure to weather conditions over a period of 30 years, as well as by the fire to which Buildings B and C were exposed. To preserve the load-bearing walls in the reconstructed building, it will be necessary to strengthen them or to develop a new load-bearing system, while retaining the existing walls as facade – decorative elements.

3. REHABILITATION PROPOSAL

Following the complete diagnostic assessment of the building—which included collecting existing documentation, an on-site visual inspection, building measurements, and testing of material samples both in-site and in the laboratory—the next step in the restoration of the "Partizan" Sports and Physical Education Complex is the proposal for reconstruction.

The proposed reconstruction of the complex aimed to restore the former glory of the "Partizan" Sports and Physical Education Society, wrapped in a new appearance. The main goal of the reconstruction was to preserve the significance and spirit of the complex, while restoring its original function through modernization [6].

The entire complex is located in the central old zone of the City of Mostar, which is a very demanding site, and it is necessary to ensure access for machinery for clearing and further construction work. Partial demolition of Building B is required and must be rebuilt afterward in order to allow machinery to move freely and clear the site. Demolition is also necessary for the reconstruction of Building A (the stands).

In terms of the construction and repair sequence, the first step is the wall behind Building A, which will be supported with buttresses to stabilize it. Once the retaining wall is reinforced, the reconstruction of the stands will follow, along with the partial demolition and then construction of the playing field. Due to proximity and practicality, the first building to be reconstructed around the field will be Building C, followed by Building B.

Building C is located adjacent to the playing field and will function as a service building for the field, with its original purpose being locker rooms for the two teams on the ground floor (Fig.6). The attic is designed as a gym. The load-bearing issues of the stone walls is solved with designed a skeleton system of reinforced concrete columns and slabs. When renovating the walls, the existing mortar needs to be removed from the surfaces beforehand. Due to the completely destroyed roof, a new wooden roof structure has been designed. The calculation for Building C has been fully performed using the Tower8 software.

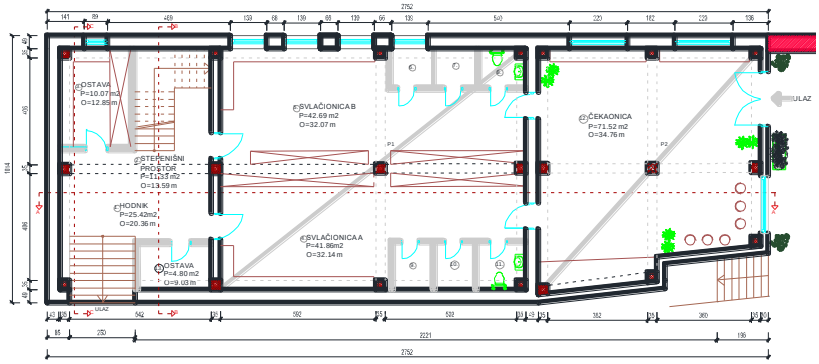


Figure 6. Floor plan of building C

At the entrance to the complex is the largest building, Building B, which is designed as a combination of administrative space and functional space that could be used for various activities. The space on the next floor is envisioned as a gallery space and office area, which would be equipped with a cafeteria and seating area. As with Building C, a skeletal load-bearing system of reinforced concrete columns and slabs, with a wooden roof structure, has been designed. It is also necessary to remove the mortar from the existing facade walls (Fig. 7).

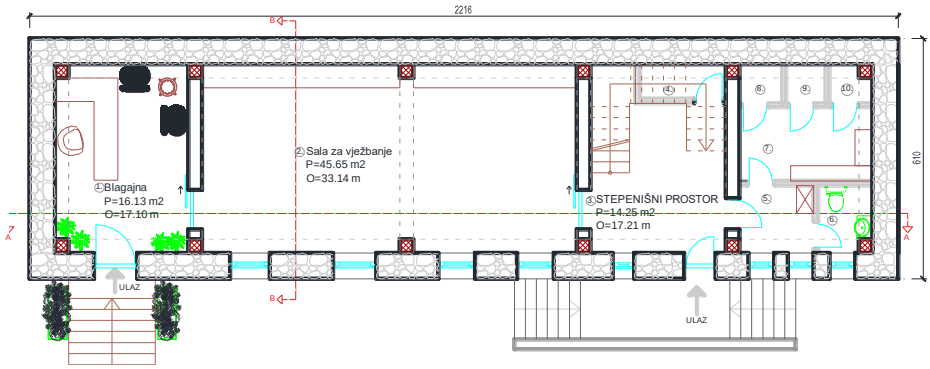


Figure 7. Floor plan of building B

4. CONCLUSION

The paper presents assessment and a proposal for rehabilitation measures for the existing structure of the "Partizan" complex in Mostar. The complex was built during the Austro-Hungarian period and consists of two high-rise buildings and a sports field with stands. The inspection of the buildings and laboratory testing of the stone indicate that the current condition of the structure is low, and that appropriate interventions are necessary before beginning rehabilitation work. The proposed rehabilitation measures include certain modifications to the foundations, load-bearing walls, and floor structures, while the repair of the staircases and the roof is proposed to be carried out as close as possible to their original appearance. The biggest modification involves the floor structures, as they need to be completely rebuilt. In this way, the current masonry structure, which has been exposed to external influences over time and whose load-bearing capacity has been reduced, would be completely relieved; it would only support its own weight, while all additional loads would be carried by the new reinforced concrete structure.

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Research paper

MOSAIC SAMPLING: GENERATIVE SCHEME FOR SPATIAL STRUCTURES DESIGN

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Abstract

Because of their construction efficiency, regular tessellations are standardly applied in the design of discrete spatial structures. However, digital fabrication enables the application of intricate patterns that may be structurally even more rational, such as patterns based on isostatic (principal stress) lines, or the application of patterns inspired by nature. This study explores the potential use of ornamental patterns in the design of spatial structures' mesh geometry. A generative design tactic based on structural form-finding is suggested, wherein structural mesh geometry is created using mosaic samples. While computational form-finding is typically used in spatial structures design, the suggested design tactic is unique because it uses the sampling concept to define a generative system. In this context, sampling is an act of taking a fragment, or a sample, of one design and its implementation in different design solutions. Specifically, a series of mosaic designs were used to derive initial mesh geometry applied to the form-finding of spatial structures. Since form-finding directly links configuration with force in a closed loop, structurally rational designs are produced from the initial mesh patterns derived from mosaics. The effectiveness of the suggested approach was tested through design explorations. Further, the approach may also be extended to other patterns that are not conventionally used in the design of spatial structures.

Key words: *Generative Design, Form-finding, Spatial Structures, Structural Geometry, Sampling, Sampler, Pattern, Mesh, Mosaic*

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1. INTRODUCTION

Application of digital technologies, transfer of knowledge and appropriation of methods, processes and procedures form other disciplines demarcate current architectural discourse, requiring our revision of conventional design processes and design tools. Implications are displacement of design process in the simulative and interactive environment, implementation of hybrid strategies and production of unconventional designs.

This paper presents the research on application of generative strategies in design of discrete spatial structures, grid shells, i.e., structural systems composed of linear elements [1]. Generative design in this paper is related with the discourse of structural performances, since spatial structures are form-active structural typology [2]. Since form of these structures are determined by stresses [3], the sustainable approach to their design is application of form-finding. Respectively, generating space structures represents process in which form emerges through modelling of their physical behavior by applying diverse modelling techniques. In contrast to the conventional designer-controlled process of shaping, forms that emerge from these self-organizing processes are influenced by the design of their boundaries. Instead of explicit decision of the designer, simulations of the influences and constraints manage modification of the model parameters and lead to the improvement of the geometry on the bases of feedback information.

Until the development of digital design and fabrication technologies [4, 5], regular tessellations were mainly used in the design of spatial structures because they were rational from both a design and construction perspective. Application of digital technologies opened opportunities for realization of unconventional spatial structures' mesh designs [6, 7, 8, 9].

The aim of this research is to define and apply generative design strategy based on the concept of sampling. Starting from the premise that mosaic, initially decorative patterns, could be applied for mesh topology of spatial structures, the task was to select patterns that have design potentials, to derive mashes for space structures form the selected mosaic patterns, and generate unconventional designs using form-finding. Additionally, this research contributes to the review of the relation between form and force, by analyzing correlation of mesh topology of equilibrium shapes and stiffness of the structure (deflections), and comparison of structural behavior. Exploration construct that manages this generative process, was implemented by application of computational tools.

This research demonstrates that, though form-finding processes follow precise rules and contain optimization by their natural description, they could be used as creative design tools in architecture. Furthermore, research demonstrates that application of mosaic patterns for construction of mesh topology offers range of possibilities and combination of design processes. Finally, study identifies impact of topology change onto structure's load paths so that these relations can be manipulated through design production.

2. METHODOLOGY

2.1. Form-finding as medium for design of the discrete space structures

Form-finding could be defined as: *Finding shape of equilibrium forces within defined boundaries, and in relation to the defined stress state* [10]. Generally, it represents a method

in which after setting certain geometric parameters, boundary condition, load and desirable stress and deflection constraints, starts a process of finding equilibrium shapes.

Development of form-finding methods is in relation with shape resistant structural typologies [11]. Deployment of lightweight structures, especially from the mid of XX century, in a certain way, provoked engineers to experiment. In that period Otto proposed design strategies inspired by nature [12]. Historical examples of Gaudi, Isler, Otto and others demonstrate that in order to design and test some of their innovative design solutions, they developed original form-finding methods.

Since 1960s the constraints manual experiments were replaced by more efficient, reliable, precise, and flexible computational simulations based on numerical methods. Design in computational environment, facilitated simultaneous analysis of diverse design demands, setting of large number of goals in form-finding processes, and explorations that are frequently on the interactive bases, implying change of the role of form-finding tools from problem-solvers to from-explorers.

The distinction between form-finding techniques could be made with respect to the medium on analogue and digital; or with respect to the concept on analytical (geometrical and mathematical), experimental (inverted chain models, tension and pneumatic membranes), and others (sculptural forms, simulation of the shells form nature). Generally, form-finding methods could be based on principle of the inverted chain, stress control concept or structural optimization.

In their simplest set-up form-finding methods both analogue and digital generate catenary curves or simple hanging forms. The hanging chain models are fascinating by their variety, structural performance, reduction to the minimal in terms of material use and resources and their peculiar aesthetics. Together these perimeters represent the common basis of a potential design or design concept and characterize its grade of sustainability.

Particle-Spring System (PS) is computational form-finding method applied in this work.

2.1.1. Particle-Spring System

Particle-Spring was applied for form-finding in the context of architecture by Kilian and Oschendorf in 2005 [13]. This system is initially developed for computer graphics [14]. Programs for animation use this technique, for animation of elasticity or plastic deformations of solids and creation of visually realistic preview of physical effects. In last decades it found application in modelling of physical performances of architectural systems. In this basis a number of conceptual design tools that enable experiments through simple digital models were developed.

Like in all dynamic equilibrium methods, in PS problem of dynamic equilibrium is reduced to static equilibrium problem (systems in the steady state), so obtained solution is equivalent to the static equilibrium. PS is Lagrangian based mesh method, i.e., the model is composed of the set of points that change their position.

PS system is composed of two elements: (1) dimensionless points in space – particles that are connected with (2) linear elastic rods – springs. Each spring has its rest length, i.e., span between two particles that it connects and stiffness that is assigned to the spring as the dampening factor. PS enables modelling variety of influences. Usually, in form-finding processes gravitational influences are modeled, or influences of the air pressure that replicate experiments with pneumatic models.

In the case of form-finding of equilibrium shapes due to the influences of self-weight (as in the case of this research), total mass of the system is modeled as concentrated mass in the particles. The value of the mass as well as initial non-equilibrium mash configuration are set at the beginning of the process. Influenced by the force particles start to move, mash starts to deform and oscillate. Because these displacements can quickly bring system in unstable state, in the case of modelling gravitational influences, it is necessary to specify dampening coefficients. After setting of oscillations resultant form represents approximate equilibrium shape of given system (Figure 1).

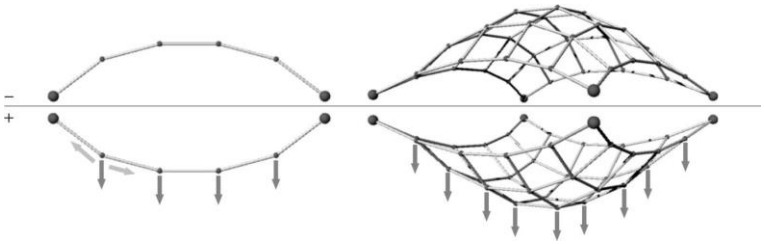


Figure 1. Particle-Spring setting into catenary form

Implementation of PS concept enabled creation various digital design environments. CADenary, created in 2002 on MIT in collaboration of several researchers, represents and example [15]. Its environment enables interactive three-dimensional visual research and dynamic simulations of catenary chains and meshes. Application of PS library in Processing programming language was also widespread option. Pikar developed Kangaroo Physiscs, plug-in for modeler Rhinoceros which is currently one of the most used tools in physically informed design processes.

2.2. Sampling as exploration construct

Creation processes frequently use strategies of transpositions of creative elements, such as intertextuality or appropriation. Sampling represents act of taking a fragment, or sample, of one design and reusing it in creation of new design solution. Through originally related to the music, sampling strategy is used in this research for design exploration in architecture. In Killian (2006), design exploration is described as steering the design using the design explorer through a solution space, where the target of the design coevolves with the driver, the design and the design space itself.

Without intention for generalization, design exploration could be described as two stage process. In the first stage the task is to focus and define design problem, to abstract and create set of rules and constraints, and to turn them into exploration system. The task of second stage is to exercise exploration system according to the rules and constraints. Design exploration concept of sampling, outlined in the paper, follows this scenario.

Applied sampling strategy, enabled exploration of design potentials of mosaic pattern in construction of initial mesh topologies for form-finding of discrete space structures. In this constellation mosaic patterns represent samples that are transferred from decorative arts to the context of architecture (Figure. 2). The modes of transposition of patterns could be from literal copying of compositions to a more abstract derivation of principles and finding of systematic solutions. The aim is realization design solutions with describable structural performances and aesthetic attributes.

Sampling was implemented through definition of design explorer – sampler and application of design elements – samples.

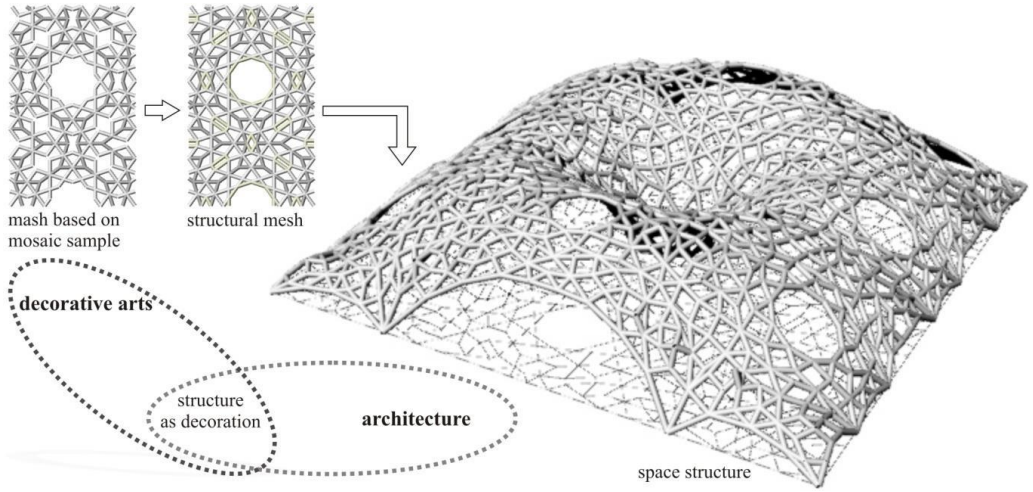


Figure 2. Sampling concept

2.2.1. Sampler

Sampler represents a computationally implemented design-driver. This design tool uses pattern samples in generation of mesh topology for form-finding of discrete space structures. In this work, mesh topologies are derived from the original patterns, but functionally of the sampler could be extended to modify original patterns in many different ways or to synthesize new ones.

Since the task of sampler is production of mesh topologies and form-finding, it is organized into a hierarchy of progressively more complicated data structure. At the bottom lay samples, individual patterns, at a particular rate and resolution. Samples may be arranged by defining rules of the repetition of the basic elements – polygons, allowing single or small number of elements to form tessellations. Parameters may be added to define how polygons are distributed in tessellations, as well as parameters that regulate change of the bar length and determine mesh density.

The sampler reproduces samples, as the first step of its algorithm. In the more developed version sampler could be synthesizer, a software that generates patterns algorithmically from mathematically described geometric elements. Sampler applies any of defined pattern samples and offer editing allowing designer to modify and process the design and apply a wide range of effects, which makes it a powerful and versatile design tool.

After generating mesh based on mosaic pattern the task is to conduct form-finding. Underlying form-finding techniques is particle-spring (PS), interactive computational method. As a result of this physics informed process emerges equilibrium form of space structure (Figure 3).

2.2.2. Samples

Samples represent patterns underlying generated mesh topologies. Samples are composed of regular or irregular polygons, and every tessellation could be decomposed on

simple building blocks. Compositions could be: (1) *original samples* patterns co-opted from mosaics applied without modifications in design, (2) *re-samples*, custom patterns made by designer; (3) *synthesized samples*, computer generated artificial patters that resemble original.

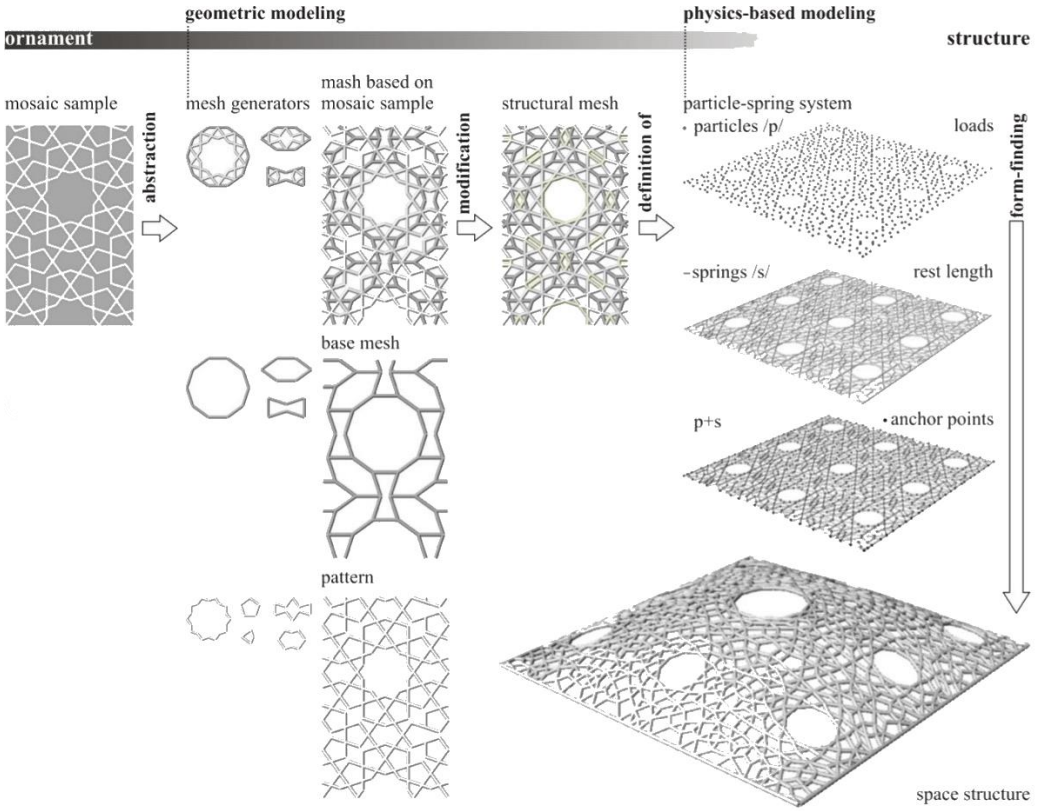


Figure 3. Flowchart of the process

Samples can be edited. Sampler should facilitate creation of costume elements, in order to enable for the designer to manipulate elements to match other part of the composition. Manipulation of elements is to extend range of their applicability. For example, to meet structural demands certain patterns must be modified by introduction of additional elements.

3. RESULTS

Previous methodology was applied to explore structures created form different mesh topologies for the same boundary conditions – supports and loads. Conventional regular mesh patterns, irregular mosaic patterns, and their combinations are applied for production of designs. Besides mesh topology, PS system require definition of spring stiffness and geometric lengths. Changing the parameters of the system influences the geometric shape outcomes as well as force distribution.

Generally, design exploration could be realized through the variation of the supports, loads (masses of the nodes), the length and strength of the springs, topology of the mesh and related discretization of load. Starting from the rectangular base 10x10m, defined

supports along edges, and self-weight load case, the task was to monitor what happens with structure's form for different mash topologies.

To test correlation between form and mesh topology in self-organizing equilibrium structures variations of mesh topologies for the same hanging model surface were applied. The range of exploration covers regular tessellations, and irregular derived from mosaic patterns. The overview and the comparison of the results as well as the possibility of targeted selection are exploited as the basis for creative applications.

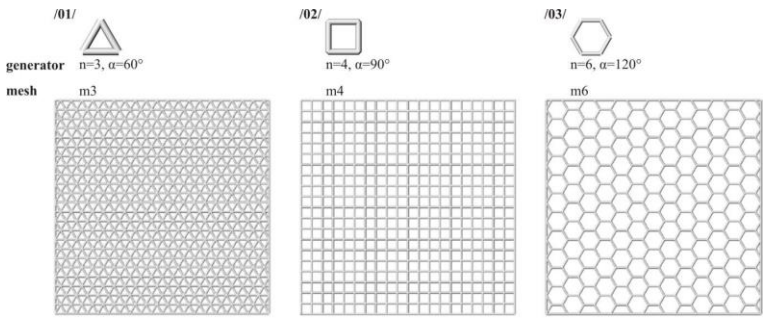
Modeling of structural was realized by application of PS system. First step in modeling of the system is definition of initial configuration. Initial configuration is described by the set of particles and rods/springs that connect them. In the next step points in which system is fixed are determined. Because the length of the spring cannot be anticipated, for the practical reasons identical loads are assigned to all nodes, in spite of the fact that varying the rest length of the spring imply that assignment of the identical values for the mass to each particle is wrong (i.e., particles that connect longer elements should be more loaded because they represent self-weight of the bigger part of the structure).

To demonstrate effectiveness of suggested approach several example patterns were selected. We started from regular patterns, composed of triangular, quadrilateral, and hexagonal polygons (Figure 4a). These patterns frequently represent underlying of base mesh in mosaic design. In the structural design these meshes are commonly applied.

Semi-regular pattern composed of triangular, quadrilateral, and hexagonal polygons that represents base mash, mosaic tessellation composed of irregular polygons and their composition were examined in this work (Figure 4b). Since these patterns does not represent conventional mesh in structural design, to produce mashes that meet structural demands modification were performed (Figure 4c).

After setting all model parameters, program generates flexible geometry, which deforms in order to take its equilibrium position. The obtained form represents schematic preview of the real structure. Of all parameters that determine equilibrium form and that could be varied such as position of the supports, number of nodes, number of geometric segments, length of spring elements, in this research we tested influence of the load path.

The generative system was implemented by application of Kangaroo Physiscs plug-in for Grasshopper, a visual programming editor for Rhinoceros modeler. Results of design explorations are for regular patterns are presented in Figure 5 and mosaic patterns in Figure 6a and modified mosaic patterns in Figure 6b.



(a)

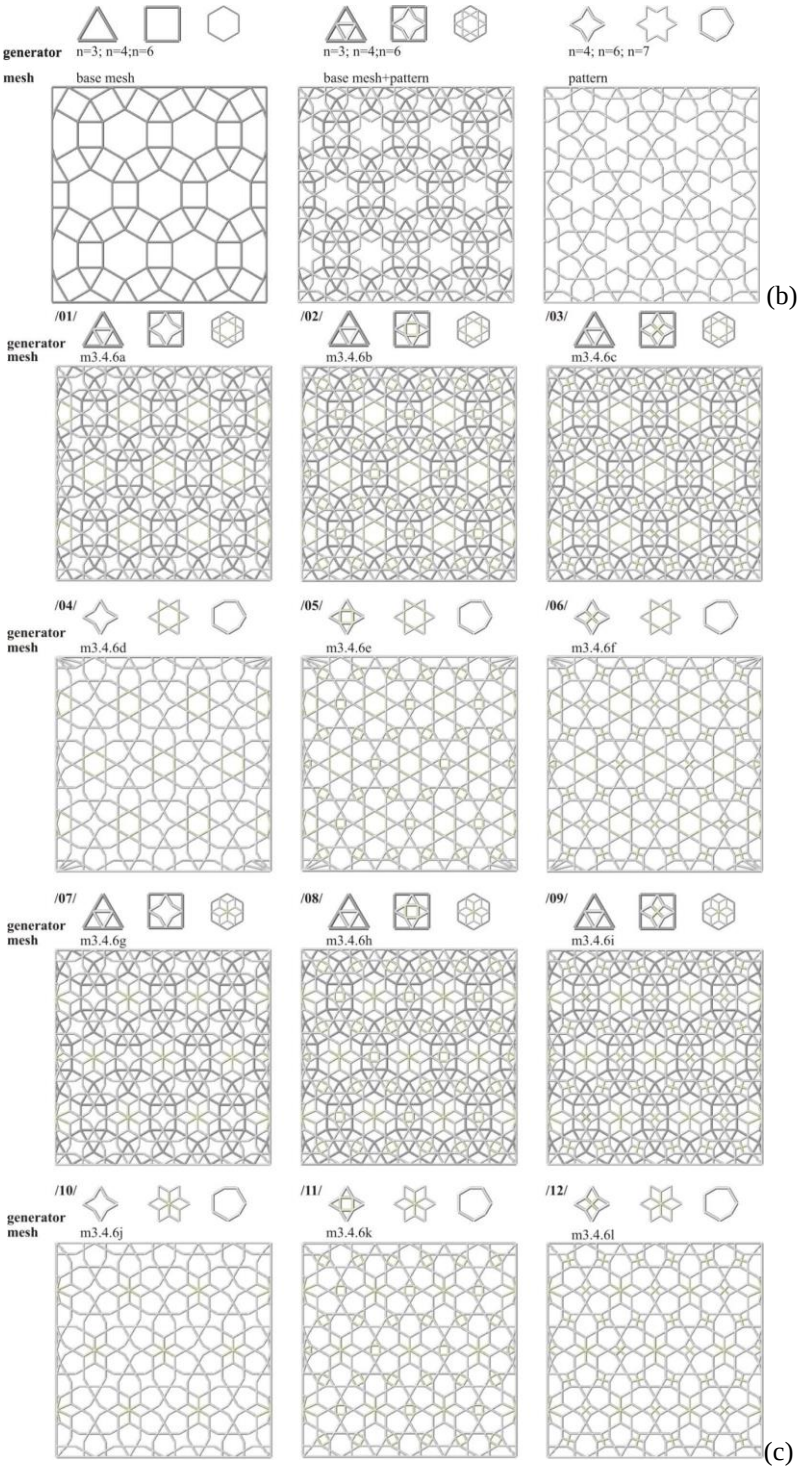


Figure 4. Samples made of regular (a) and irregular polygons (b,c)

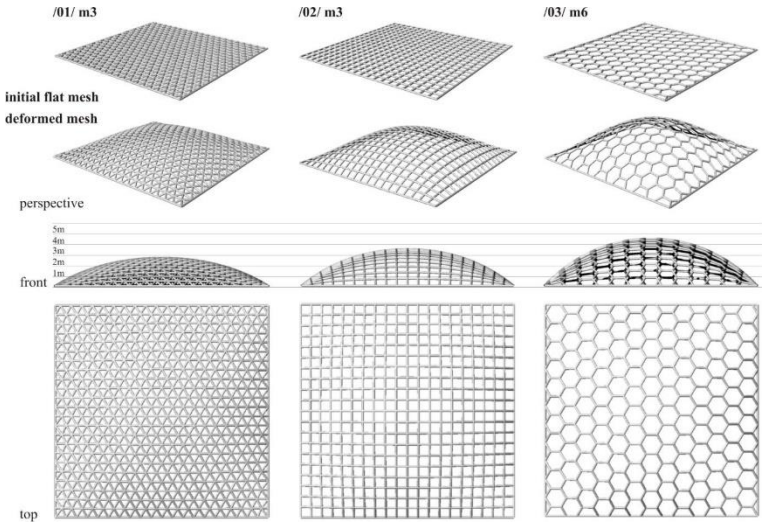
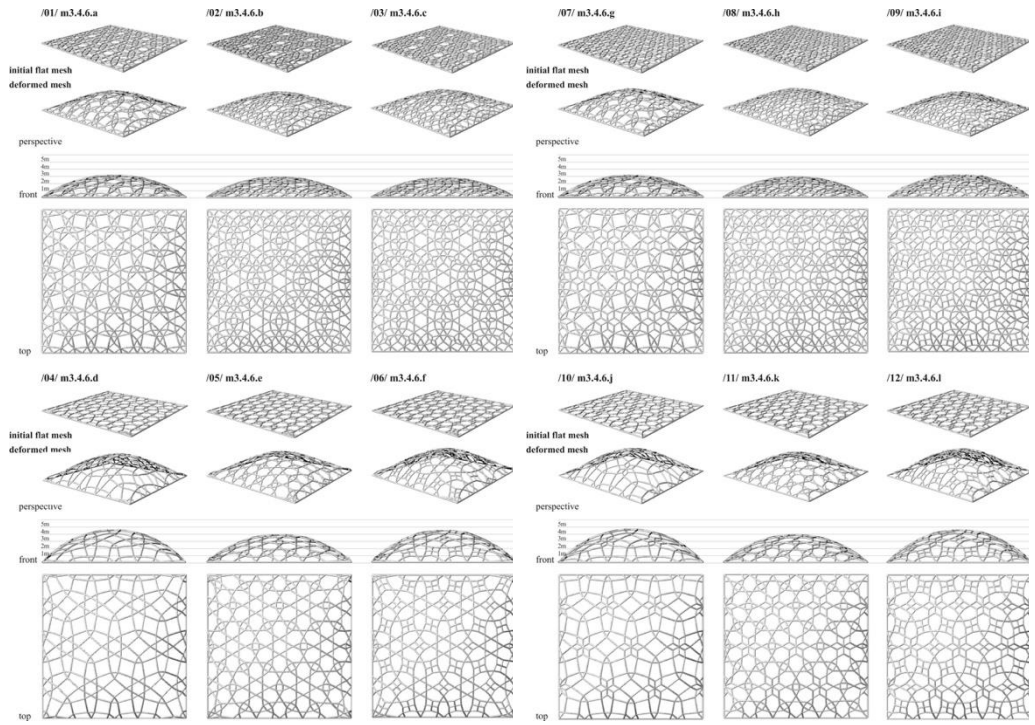


Figure 5. Result from form-finding for different topologies for the same plan, based on conventional regular meshes



(a) (b)

Figure 6. Result from form-finding for different topologies for the same plan, based on mosaic samples

4. DISCUSSION

Construction of the physical based models represents essential part of the design of spatial structures. Within this paper we investigated application of the computational methods

in design. In this approach we replace the absolute goals of optimization with interactive, iterative approach which means use of same underlying algorithms. Such approach allows designers to selectively deviate from optimal solutions and explore design variations, found through discovery rather than precise analysis. Applied design approach enables designers to conduct explorations that overcome exclusively aspect of visualization. This research illustrates opportunities of form-finding techniques in design of equilibrium shapes, with the note that it is not simple to predict behavior of the real structure on the basis of the obtained results.

The starting topology and geometry represent the main interface for specifying the final form. Regular grids are often a starting point, or randomized triangulated meshes when using standard mash approach such as Delaunay triangulation. Due to their simple repetitive geometry and constant node valence, the most common default mashes are the quad grids. But they are not particularly well suited for form-finding. Take, for instance the case of an equally spaced rectangular grid, fixed at its four corner points, with an equal load distribution assumed using particles of equal mass. The mesh distorts extremely as it moves towards an equilibrium state.

Different mesh topologies, iterative re-mashing strategies, as well as iterative parameter adjustments could account for the possible deformations of the geometric mesh during the form-finding process. This does require a more complex set-up. Alternatively, one can set a topology and geometry close to the expected and result to reduce this deformation. Still, changing the mesh topology has a major impact on the resultant form, and so steering the design through topological variation is a regularly the most influential of all steering methods.

In comparison to the linear chains, structural behavior of the mesh is more complex. There is no one unique load path, multiple paths between supports and loads are possible, and no single determined solution exists. With the increasing mesh density, the behavior of the structure approximates that of the shell. The load paths in the spatial structure are very much dependent on the topology of the mesh and the geometry of the individual members. By changing of the topology, a singular dominant load paths could be avoided.

In the PS system the performance and dimension of a structure is integrally connected with its topology. Deformations of the spring could vary in dependence of it position in the mesh, so at the end of form-finding, mesh that was composed of elements that initially had equal length becomes mesh with elements of diverse lengths. Springs near supports frequently have larger deformations, which represents consequence of that all forces act in the particles that are hanged on the supports and could be corrected by increasing the stiffness of the springs.

In his research Isler find out that the 90% of the loads in his shells are traveling into the supports in the corners of his shells. The edge supports receive only a fraction of the weight. This is due to the varied stiffness of the shell areas and subsequent variant resistance to loading [16]. The optimization of compression-only structures does not guarantee evenly distributed loads. In his research Kilian explored influence of the topology in form-finding centenary forms [15]. Previous research demonstrate that change of the topology considerably influences efficiency of form.

This research demonstrates that mesh topology has a substantial effect on the form of the structure and on the distribution of forces within it. The mesh topology fundamentally influences the performance of the structure. Implying that optimization of the structure should not be restricted to finding of the most efficient form for a given topology, but to finding the

most optimal topology for a given load case as well. Novel topology can challenge the starting conditions.

Topology studies may be a way to steer the design towards desired results with topologies reflecting the expected flow of force more closely. A change in the topology can have significant impact onto load paths in a structure. Therefore, the design cannot stop at optimizing geometry but has to address the optimization of topology as well. This could lead to introduction of topology-finding of structure in addition to form-finding.

5. CONCLUSION

Within this research we applied sampling concept in form-finding. We also examine influence of the topology on the resulting global structural form. Application of proposed strategy opens up infinite range of possibilities in creating of space structures with new architectural qualities like shown in case studies and experiments, leading to larger issues of goals for design intent rather than structural performance alone.

Computational form-finding techniques are usually conceived to simulate behavior of physical models. Advantages of current and emerging digital technologies expanded interest of the designers for unconventional space structures. The goal of proposed design strategy is to use computational methods to achieve more integrative design solutions, and to extend the canon of forms established through conventional analytical techniques.

In this research we used several patterns, to illustrate effectiveness of proposed design approach. Further development of the design strategy concept proposed in this paper is towards expanding vocabulary of patterns and development of computational tools. The expansion of the pattern vocabulary could be achieved by development of the comprehensive library/repository of patterns and generation of synthetic samples.

Sampling is not restricted to application of pre-existing patterns. Genetic coding could be applied for creation of artificial patterns and construction of dynamical complex generative system with a capacity to produce endless variations. Creating artificial DNA of mosaics could represent basis for generation of practically infinite number of different patterns. Like any morphogenetic process, it is based on a software to produce non-repeatable designs. From the rang of synthesized patterns the selection of design configuration could be done in order to both fit aesthetical and structural performance criteria.

The use of sampling could be controversial, because it opens the question of originality. While some may argue that sampling lacks originality, others may view it as a form of innovation. In any event, it is worthwhile to conduct additional research on how design might change as a result of applying different approaches and transferring design elements.

ACKNOWLEDGMENTS

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Research paper

APPLICATION OF THREE REGRESSION METHODS FOR FILLING MISSING VALUES OF ANNUAL MAXIMUM DAILY PRECIPITATION

Nikola Đokić[1]

Abstract

This study examines the effectiveness of three regression methods – multiple linear, random forest, and log-linear (gamma) when applied to annual maximum daily precipitation data sets to fill in missing values. Gridded observations data of extreme daily precipitation, sourced from the Digital Climate Atlas of Serbia platform, were utilized for this study in the area of Niš. The dataset, which is complete for the period 1950–2020, was intentionally modified to simulate missing data. These artificial gaps, or 'holes,' were introduced systematically at the beginning, end, and randomly selected locations within the dataset. The data omission was carried out incrementally at rates of 5%, 10%, 15%, and 20%. The performance of the methods for completing incomplete series was evaluated in terms of standard metrics like the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). The results indicated a commendable performance across all evaluated methods, even when addressing 20% missing data. Notably, multiple linear regression emerged as the most effective technique among those tested.

Key words: *Missing Data, Precipitation, Regression Methods, Gridded Datasets*

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1. INTRODUCTION

Effective planning and management of water resources rely on the availability of reliable and precise precipitation data collected from meteorological stations [1]. Precipitation data is commonly gathered using rainfall gauges, which are regarded as the primary source of precipitation observations. These instruments provide direct measurements of precipitation at specific locations [2, 3]. However, precipitation data is frequently incomplete. The incompleteness of precipitation data may be due to instrument failure, measurement errors, or other factors. The presence of missing data in rainfall time series can significantly impact the accuracy of statistical analyses [4]. A common approach to address this issue is to discard the years or periods that contain missing data. However, this strategy may lead to significantly reduced sample sizes or can obstruct an accurate characterization of the upper tail of the distribution of the random variable [5]. An alternative approach involves supplementing the target station with data from appropriate nearby stations.

Various techniques have been developed to estimate and reconstruct missing data, which can be generally divided into three categories: empirical methods, statistical approaches, and function-fitting techniques [6]. The methods described for addressing missing data aim to enhance the accuracy and reliability of hydrological models. Techniques such as the regional weighting method, linear regression, Kriging, etc., are used in practice to fill in monthly and annual rainfall data [7]. However, due to the significant spatial variability of extreme precipitation, such techniques are not recommended for filling daily and sub-daily precipitation [6]. Since daily and sub-daily precipitation data serve as inputs for hydrological models, selecting an appropriate method for estimating missing values is crucial. Previous research has discussed the use of multiple linear regression [8], simple substitution [9], the Theil method [10], and machine-learning algorithms [11, 12] for this purpose.

This study evaluates the effectiveness of three methods for filling artificially induced gaps in annual maximum daily precipitation data from the period 1950 to 2020. The methodologies under investigation include Multiple Linear Regression (MLR), Random Forest (RF), and Log-Linear Gamma (LLG) regression techniques. Gridded data representing the annual maximum daily precipitation at nine locations across the city of Niš, sourced from the Digital Climate Atlas of Serbia, were utilized.

2. MATERIALS AND METHODS

This chapter defines the specific location of the investigation and provides a detailed explanation of the techniques used to fill the data series. It also describes how the so-called "holes" were intentionally introduced into the complete sequence of daily precipitation records. Validation was conducted by comparing the reconstructed values with the actual omitted precipitation data.

Due to the insufficient density of observation stations with available daily precipitation data, a suitability test for filling in incomplete sequences was conducted using a grid network sourced from the Digital Climate Atlas of Serbia [13].

2.1. Study Area and Data

Niš, one of the oldest cities in the Balkans, is located in southern Serbia and serves as an important economic, cultural, and geographical hub. Positioned at the crossroads of Central

and Southeast Europe, Niš has historically been a gateway between Eastern and Western civilizations. The city lies at 43°19′N latitude and 21°54′E longitude, with an elevation averaging 194 meters above sea level. The following figure (Figure 1) includes the location of the research area on the territory of the Republic of Serbia, with a detailed overview of the positions of 9 significant points from the gridded observations of the Digital Climate Atlas of Serbia, which are located over the city of Niš.

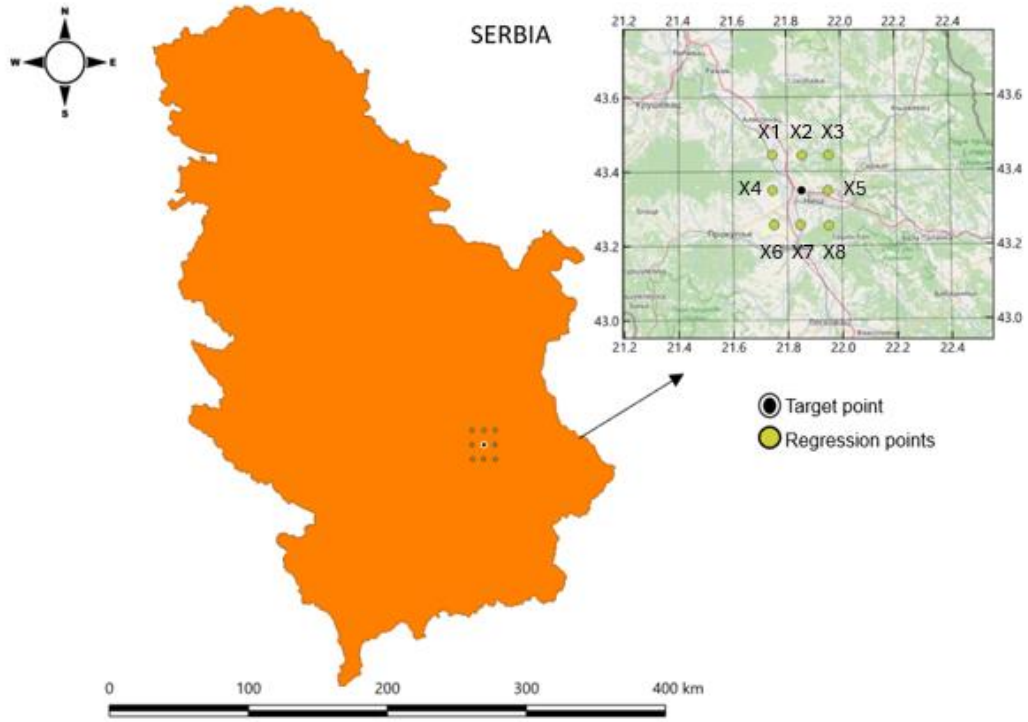


Figure 1. Study area with eight regression and one target point gained from the Digital Climate Atlas of Serbia

Gridded meteorology refers to meteorological data that is organized into a structured grid format, rather than being based solely on individual weather station observations. This approach allows for consistent spatial and temporal coverage, making it useful for climate modeling, weather forecasting, and environmental research [14].

The grid of the atlas was formed based on the measured climatic variables at meteorological and climatological stations in Serbia, which were then interpolated to a regular grid of points, with a horizontal distribution of ~10x10 km. Annual maximum daily precipitation data in the period 1950-2020 were used from the climate atlas of Serbia. An "intervention" was conducted on the complete dataset, resulting in the removal of 5 %, 10%, 15%, and 20% of the data from the beginning, from the end, and in random places. A total of 36 incomplete data series were obtained in this manner. Such an intervention was carried out only at one (central/target) measurement point, to further establish a regression based on intact data from the 8 nearby points. Used regression techniques are detailed below.

2.2. Regression methods

2.2.1. Multiple Linear Regression

MLR is a statistical method used to analyze the relationship between a dependent variable and two or more independent variables. It extends simple linear regression, which only deals with one independent variable, to handle multiple predictors [1, 15]. The missing data (*Yi*) is estimated from the following equation:

$$Y_i = b_o + \sum_{i=1}^{n}(b_i X_i) \quad (1)$$

where Yi is the estimated rainfall data, Xi is the observed rainfall value of the ith surrounding point, and bi, b1, …, bn are the regression coefficients.

2.2.2. Random Forest Regression

Among its many uses, RF is a reliable technique for regression, prediction, and classification. By sampling the training data at random, it builds several decision trees and uses a bagging process to determine which trees produce the best predictions [16]. In 2001, Breiman presented an expansion of this algorithm [17].

RF works well for producing predictive models for tasks involving both regression and classification. Binary decision trees, specifically Classification and Regression Trees (CART), are the foundation of this approach. Software XLstat was utilized to carry out RF regression [18]. The number of trees, the mtry value, and particular tree parameters like minimum node size, minimum child size, and maximum depth are among the parameters that XLstat needs to know. Longer computation times result from using more trees, even though this improves model stability. To lessen the chance of overfitting, the maximum depth parameter limits the trees' complexity. When building individual decision trees, the mtry parameter indicates how many features are chosen at random at each split.

The following parameter values were used:

- Forest parameters: Sampling (Random with replacement); Method (Random Input); Sample size (71); Number of trees (300),
- Stop conditions: Construction time (300); Convergence (50),
- Tree parameters: minimum node size (2); minimum son size (1); maximum depth (30); mtry (3); CP (0,0001).

2.2.3. Log-Linear (Gamma) Regression

Log-linear regression is one of the specialized cases of generalized linear models (GLM). The 'linear' in the name means the model's presumption of a linear relationship between the input and output variables. And 'log' refers to the model's use of a logarithmic transformation of the input data before fitting it into a linear equation. GLM offers considerable flexibility in assuming the distribution of ‘errors’ about the mean response. They handle response variables that follow different distributions, and in this case, the gamma-distributed data is used. Applying a logarithmic transformation to variables in a regression model is a widely embraced technique for addressing scenarios where a non-linear relationship intricately intertwines the independent and dependent variables. This method allows for a more coherent interpretation of the data, enabling analysts to uncover patterns that might otherwise remain obscured. By re-scaling the variables, one can often reveal a clearer, more linear relationship, transforming complex interactions into more manageable and visually

interpretable forms [19]. This transformation accommodates nonlinear relationships in the data, resulting in a more accurate prediction of those relationships. In the log-linear model (2), the literal interpretation of the estimated coefficient b_i is that a one-unit increase in *X* will produce an expected increase in log *Y* of b_i units. In terms of *Y* itself, this means that the expected value of *Y* is multiplied by e^{bi}.

$$logY_i = b_o + \sum_{i=1}^{n}(b_i logX_i) \quad (2)$$

2.3. Methods Performance

The efficiency of the filling data was compared using three different error indices: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination R^2. The error measures were used to compare the estimations with the observed values. The three error indices are given as follows:

- Mean absolute error (**MAE**)

The Mean Absolute Error (MAE) stands out as a crucial metric in the realm of model evaluations, revered for its clarity in quantifying estimation errors. This powerful measure provides straightforward insight into the magnitude of errors, allowing researchers and analysts to gauge the precision of their predictions. As highlighted by Willmott and colleagues in 2009, the MAE is a recommended method for assessing accuracy [20]. The MAE is computed using the following equation:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{Y}_i - Y_i\right| \quad (3)$$

where $\hat{Y}_i$ is the observed value of the rainfall data from the target point.

- Root mean square error (**RMSE**)

RMSE measures the difference between the estimated and observed values. The best method gives the lowest computed value of the RMSE. The RMSE value varies from 0 to +∞. The RMSE is computed using the following equation:

$$RMSE = \sqrt{\sum_{i=1}^{n}\frac{(\hat{Y}_I - Y_I)^2}{n}} \quad (4)$$

- Coefficient of determination (**R^2**)

The **coefficient of determination**, denoted as **R^2**, is a statistical measure used in regression analysis to assess how well a model explains the variability of the dependent variable. The R^2 is computed using the following equation:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})\cdot(Y_i - \bar{Y}_i)}{\sqrt{\sum_{i=1}^{n}(\hat{Y}_i - \bar{Y})^2 \cdot \sum_{i=1}^{n}(Y_i - \bar{Y}_i)^2}} \quad (5)$$

where $\bar{Y}_i$ and $\bar{Y}$ are the average precipitation values of estimated and observed data, respectively.

3. RESULTS AND DISCUSSION

The following table (Table 1) summarizes the values of error indicators (RMSE, MAE, and R2) for all three applied regression techniques and all considered incomplete sets of precipitation data, with omission from the beginning (B), end (E), and in random (R) places along strings.

Table 1. Values of different error indices: mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination R^2 for three different regression methods and different types of omission datasets

Rate of omission	Perf. metrics	Regression method: MLR			RF			LLG		
		Omission: B	E	R	B	E	R	B	E	R
5%	RMSE	1.42	0.82	0.89	1.51	2.50	4.92	1.45	2.33	1.70
	MAE	1.16	0.68	0.70	1.35	2.27	3.19	1.14	2.26	1.56
	R^2	0.94	1.00	0.99	0.90	0.91	0.99	0.92	0.99	0.98
10%	RMSE	1.31	1.18	0.79	5.32	4.41	1.14	10.68	5.23	10.37
	MAE	1.01	1.00	0.61	3.33	3.91	0.81	4.92	3.66	5.35
	R^2	0.99	1.00	0.99	0.94	0.92	0.93	0.98	0.94	0.94
15%	RMSE	1.19	1.01	0.90	4.62	4.15	3.06	7.87	4.12	4.38
	MAE	0.96	0.84	0.74	2.98	3.20	2.16	3.78	2.49	2.52
	R^2	0.99	0.99	0.99	0.94	0.90	0.96	0.96	0.94	0.96
20%	RMSE	1.03	0.89	0.66	4.75	3.59	3.31	9.85	3.78	7.05
	MAE	0.74	0.72	0.59	3.33	2.62	2.15	5.13	2.38	2.90
	R^2	1.00	0.99	0.99	0.95	0.91	0.93	0.89	0.94	0.95

From the previous table, it can be seen following:

- The largest errors are obtained using the LLG model, where RMSE goes up to 10.68 mm,
- The smallest errors are obtained using MLR for all considered cases,
- RF regression gave satisfactory results, with the biggest RMSE value of 5.32 mm,
- The error values did not strictly increase as the number of missing data in the series increased, moreover, the smallest errors were registered in the case when multiple linear regression was used over the series with 20% of missing data.

The computational results showed that classical statistical methods such as MLR performed excellently, as also noted by Sattari M.T. and Kusiak A. in their work [1], as well as Hasanpour Kashani, M., and Dinpashoh, Y. in their study [21].

In the following Table 2, a correlation matrix between the included regression (X1-X8) and target points (T) is shown, for the case where the smaller errors are found.

Table 2. Correlation matrix of the nine considered locations

	X1	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**T**
X1	**1**	0.981	0.963	0.977	0.874	0.964	0.926	0.241	0.885
X2	0.981	**1**	0.994	0.992	0.939	0.976	0.966	0.274	0.945
X3	0.963	0.994	**1**	0.983	0.951	0.973	0.970	0.270	0.951
X4	0.977	0.992	0.983	**1**	0.941	0.988	0.979	0.256	0.952
X5	0.874	0.939	0.951	0.941	**1**	0.932	0.969	0.269	0.993
X6	0.964	0.976	0.973	0.988	0.932	**1**	0.985	0.255	0.940
X7	0.926	0.966	0.970	0.979	0.969	0.985	**1**	0.268	0.973
X8	0.241	0.274	0.270	0.256	0.269	0.255	0.268	**1**	0.260
T	0.885	0.945	0.951	0.952	0.993	0.940	0.973	0.260	**1**

It can be seen that all but the last eighth point have a strong correlation with each other.

Standardized coefficients, also known as beta coefficients, are used in regression analysis to compare the relative importance of predictor variables. They are calculated by standardizing the data so that all variables have a mean of 0 and a standard deviation of 1. This allows for direct comparison of the effects of different variables, regardless of their original units of measurement. In multiple regression, standardized coefficients help determine which independent variables have the greatest impact on the dependent variable. A higher absolute value of a standardized coefficient indicates a stronger influence on the outcome [22]. The following figure (Figure 2) shows the values of the standardized coefficients for the eight predictors used with a 95% confidence interval. Blocks shaded in a lighter blue represent locations with a more significant influence in the regression model, while darker shades indicate a smaller influence.

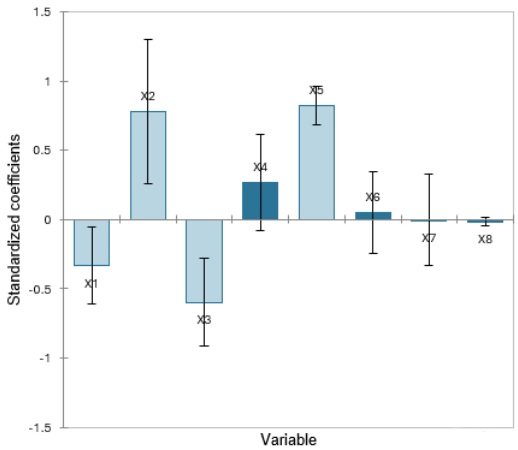


Figure 2. Values of the standardized coefficients of predictors with a 95% confidence interval

From the figure above, it can be seen that X5 has the strongest influence (0.78), because it has the highest standardized coefficient, meaning it contributes the most to predicting the dependent variable. Conversely, X7 and X8 have the lowest coefficients - their impact on the prediction is minimal.

4. CONCLUSION

In the study reported in this paper, the annual maximum daily precipitation data at the nine locations from a grid network sourced from the Digital Climate Atlas of Serbia are considered. Each point/location contains complete data strings, with intentional holes introduced at the central point in various locations along the string, resulting in 36 new strings for this point. Three different methods were applied to fill artificially induced missing data. The results demonstrated that the MLR method is well-suited for estimating missing precipitation data, even in cases where 20% of the data is missing. RF had satisfactory but not as good results as MLR, while LLG indicated that in some cases, it can give a weaker forecast of potential values of extreme precipitation. This work represents a respectable example of how incomplete precipitation datasets can be supplemented, indicating that a more conservative approach is potentially better than newer techniques involving the application of artificial intelligence and machine learning to solve such problems.

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Research paper

DIY ACTIVITIES ON MULTI-FAMILY APARTMENT BUILDINGS IN NIŠ, SERBIA: BEAUTIFICATION OR DEGRADATION?

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Abstract

Housing is not only a physical structure, but also a process that has an important function in the lives of individuals. Do-it-yourself (DIY) concept in multi-family residential architecture involves apartment users conceptualizing, planning and executing a range of activities related to functional, structural, energy, aesthetic, or other home improvements. Apartments that have been improved by their residents have a greater use value because they express their specific needs. Such housing gives residents a stronger sense of belonging. Alterations of the apartments do not necessarily mean dissatisfaction of the occupants. Instead, it could show how people would like to make their home unique. This paper uses the case of Niš, Serbia to analyze patterns of home-related DIY activities in multi-family housing architecture. By observing the exterior of multi-family apartment buildings throughout the city of Niš, different forms and levels of DIY activities of the occupants were identified, from the smallest, visual and aesthetic ones to the more significant ones, which included more complex functional alterations. They were classified into eight groups: balcony/loggia glazing, creating a private open space, construction of a canopy, opening the entrance from public area, window replacement, installing sun shading, installing safety protection on windows and private open spaces, and painting activities on the façade. Although it is undeniable that the originality of architectural design is diminished by involving users in architectural shaping and aesthetics, the residential environment gains a personal touch. On the other hand, too many individual interventions can lead to the so-called visual pollution, which is reflected in the devastation and degradation of the architectural environment. To avoid significant changes and degradation of the appearance of an apartment building during the use phase and to protect the architect's original idea and design, certain regulatory and technical guidelines and restrictions should be introduced. Also, for most DIY interventions on a building, if users want to implement one, they could be offered a unique model, thus keeping the change in the appearance of the building under control.

Key words: *Do-it-yourself Activity, Multi-family Apartment Building, Originality, Individualization, Visual Pollution*

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1. INTRODUCTION

The do-it-yourself (DIY) concept in multi-family residential architecture involves a wide range of activities related to functional, structural, energy, aesthetic, or other apartment modifications that users undertake for the purpose of some type and form of apartment improvement. The user of an apartment in a multi-family residential building is usually not known in advance, so it is impossible for each housing unit to fully meet all the demands, needs and aesthetic preferences of future users. Designing according to the principles of flexibility can be an adequate answer to this problem, although it primarily focuses on the functional aspect of the arrangement of the apartment and rarely includes visual-aesthetic aspect.

Reaching for DIY activities on the apartment can be a consequence of the desire for some kind of home improvements, especially considering that DIY tasks are frequently less expensive than hiring a professional. However, they do not necessarily mean that the users were dissatisfied with the quality of their housing unit but can also be the result of the need to express creativity and originality, as well as personal satisfaction [1]. DIY tasks could include leisure activities at home that are craft-oriented, the most obvious rewards of which are enjoyment and a sense of pride, but the concepts of thrift and saving are also associated with DIY, making it an activity undertaken out of economic necessity or savings [2].

Any alterations that residents make to the external appearance of the apartment can contribute to achieving a certain degree of personalization and individualization, and it can also be said that the residential environment thereby acquires its own personal touch. However, the user's action on the architectural form of the residential building undermines the originality of the architect's design. Thus, on the one hand, there is a violation of the geometric and aesthetic harmony defined by the design, and on the other hand, an increase in the viability and suitability of the environment for users [3]. Insufficient control of space personalization can lead to extremely pronounced personal preferences of the residents. Such interventions in the outdoor space also open up the problem of aesthetic or visual pollution [4], that is, the inappropriate and unsatisfactory appearance of the residential environment. This category is difficult to precisely define or measure, but it should certainly be expected since multi-family residential building houses many users with different needs, educational levels, acquired habits, financial capabilities, aesthetic criteria, etc.

2. OBJECTIVE AND METHOD OF THE RESEARCH

This paper deals with the analysis of forms and patterns of home-related DIY activities that can be observed on the exterior of multi-family residential buildings in the city of Niš, Serbia. For the purposes of this research, DIY activities include a series of measures that apartment users undertake on their own or with the help of professional teams, bypassing the original architectural design, i.e. disrupting the original appearance of the building. By observing the exterior of multi-family apartment buildings throughout the city, different forms and levels of DIY activities of the occupants were identified. They cover a wide range from the smallest, visual and aesthetic changes to more significant ones, including more complex functional alterations. They were classified into eight groups: balcony/loggia glazing, creating a private open space, construction of a canopy over a private open area, opening the

entrance from public area, window replacement, installing sun shading, installing safety protection on windows and private open spaces, and painting activities on the façade.

The user's motives (goals pursued) that led to resorting to these DIY activities are classified into three categories: functional improvement of the apartment, structural and energy improvement of the apartment and aesthetic improvement of the external appearance of the apartment. On the other hand, the applied DIY measures affected the buildings according to certain aspects, also classified into three groups – functional aspect, structural energy aspect and aesthetic aspect – with the fact that the user's motives and goals for applying a certain measure and the effects of that intervention do not necessarily fall into the same category. So, for example, the user's desire may be to functionally improve the configuration of the apartment, but as it is also evident on the facade of the building, the effect of such an intervention also falls into the category of changes in the aesthetic appearance of the building.

3. RESULTS

DIY activities, most common on the exterior of multi-family residential buildings in the territory of the city of Niš, were for the purposes of this research classified into eight groups of different levels and scope of interventions. The motives and goals of the users for engaging in certain DIY activities were diverse, and the final effects of the applied measures affected different aspects of the building. Both the goals and effects of DIY measures were classified into three categories. Table 1 gives an overview of the most common DIY activities observed on apartment buildings in Niš, to which of the listed categories the goals of the application of the measure belong, as well as to which of the listed categories the effects of the application of the measure belong.

Table 1. Overview of the most applied DIY activities in apartment buildings in Niš

	Functional aspect		Structural-energy aspect		Aesthetic aspect	
	goals	effects	goals	effects	goals	effects
Balcony/loggia glazing	X	X	X	X		X
Creating a private open space	X	X				X
Construction of a canopy	X	X		X		X
Opening a new entrance from public area	X	X		X		X
Window replacement			X	X		X
Installing sun shading	X	X	X	X		X
Installing safety protection	X	X			X	X
Painting activities on the façade					X	X

3.1. Balcony/Loggia Glazing

Loggias and balconies are the most dominant form of private open areas of residential units in multi-family residential buildings, and their role is multiple. These spaces not only physically expand the apartment, but also complement it functionally and can be suitable for various outdoor activities – dining, resting, children's play, sunbathing, socializing, studying, growing plants, etc. They refine the apartment, increase its use value and improve its quality.

Glazing balconies and loggias involves closing them with transparent elements that can be partially or completely opened. The newly formed space of the apartment can be heated or unheated. In the first case, this space can be transformed into a new, separate room (bedroom, living room, dining room, kitchen, etc.) or it can be added to the room with which the loggia/balcony had a functional connection. If the glazed loggia/balcony is not heated, its purpose remains mostly the same as before glazing, with the difference that it becomes protected from external influences such as heat, noise, wind and dust. In both cases, the glazing of the balcony/loggia changes the thermal properties of the facade envelope of the building [5]. Glazing of the open areas of the apartment, which is carried out as a DIY measure, without the existence of regulatory and technical guidelines and restrictions, can lead to a violation of the originality and recognition of the facades. This is especially evident when the building has many differently glazed open areas of the apartments (application of different glazing systems, different design of partitions, different materialization, different profile color, different glass color, etc.), which seriously disturbs the original harmony and aesthetics of the building. The application of this DIY measure concerns the functional aspect, as well as the structural/energy and aesthetic aspects of the building. (Figure 1)



Figure 1. Examples of glazing loggias and balconies in apartment buildings in Niš, source: B. Stoiljković

3.2. Creating a Private Open Space

To satisfy the primordial human need for access to light, air and sunlight, open areas in the form of loggias, balconies, terraces, etc. are envisaged in multi-family housing, representing compensation for yards of single-family houses. Such spaces are often at the top of the priorities of those who choose an apartment. Unfortunately, in the domestic conditions of modern multi-family housing, despite the wishes and demands of users, private open spaces are a category that is often subject to strict economic restrictions. So, many apartments, regardless of their size and configuration, were designed and built without associated open spaces. The subsequent construction of open areas in the form of balconies implies the application of more serious design, structural and building measures and such interventions affect the functional, structural and aesthetic aspect of the building. Also, there have been cases of apartments characterized by direct contact between private and public area area (such as, for example, apartments on the ground floor, apartments next to a flat roof), so that the associated open space is formed on part of the adjacent public area. Although unregulated in terms of ownership (such subsequently added space is not registered as part of the area of the residential unit), the fact is that by creating an accompanied open area, the quality and use

value of the apartment is significantly improved. An open-air space was created where people can stay and engage in outdoor activities. In addition, creating areas with quality greenery can also contribute to the aesthetic appearance of the entire building. (Figure 2)

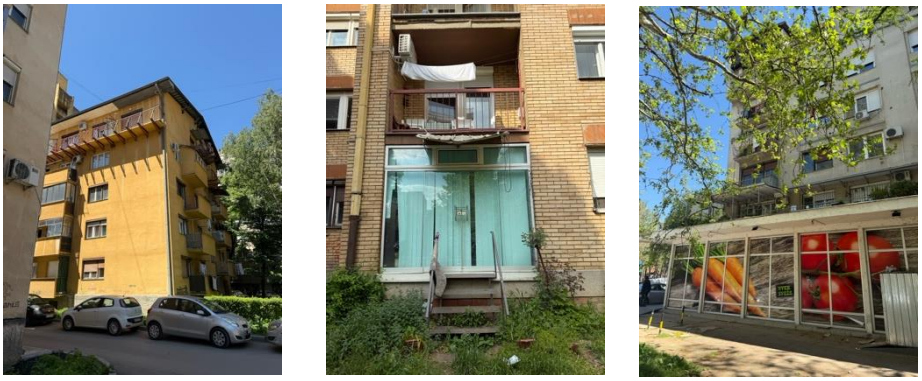


Figure 2. Examples of creating private open spaces in apartment buildings in Niš, source: B. Stoiljković

3.3. Construction of a Canopy over a Private Open Area

The open areas of a dwelling play a vital role in fulfilling various functional, ecological and aesthetic functions. These functions are influenced, among other things, by the different preferences and needs of the occupants [6]. If balconies and loggias are changed, the facades of buildings will be visually altered or even degraded, temporarily or permanently. It is a fact that a covered private open area has a higher utility value than one that is not – the canopy protects users from atmospheric precipitation and excessive sun exposure, protects against dust, and increases privacy. Therefore, it is not surprising that the users need to additionally "protect" their open areas with the subsequent construction of the canopy, if this was not envisaged by the original design. Newly installed canopies are mostly made of light materials – sheet metal, plastic, glass – placed over a light metal or wooden structure and often act as temporary structures of low aesthetic value. It is even very common that the design and materials used for a canopy do not contribute to the primary purpose of such a structure. Also, there have been cases of closing such balconies after the construction of the canopy, with glazed partitions or sun shading elements, which additionally makes the original building façade cluttered. Unfortunately, such interventions very often greatly reduce the aesthetic quality of the building. (Figure 3)



Figure 3. Examples of construction of canopies over private open areas in apartment buildings in Niš, source: B. Stoiljković

3.4. Opening a New Entrance from a Public Area

Unlike a multi-family housing building where there is one entrance to the building, while the entrances to all units are through common, semi-public spaces, family houses have individual entrances, which is considered a great advantage. Moreover, the entrance to the family house is usually visible from inside the house, which has an exceptional psychological advantage because it allows the resident to see the visitor before he appears at the door, and thus prepare for a possible meeting with him, which is usually not possible in multi-family housing buildings [7]. Although separate entrances in apartment buildings can easily be provided to the apartments on the ground floor, due to the proximity of the public area, the usual design schemes for apartment buildings in Niš do not include this. Although rare, practice shows that users of ground floor apartments can see this advantage of the apartment's position and, with subsequent intervention, ensure access to their apartment from the public area. The case of opening a new entrance is much more common when the apartment on the ground floor or a part of it was converted into a business, commercial or service facility, so it is desirable that such an entrance be visible and accessible from the public area for functional and economic reasons. In both cases, the applied measure significantly changes the original appearance of the facades. (Figure 4)

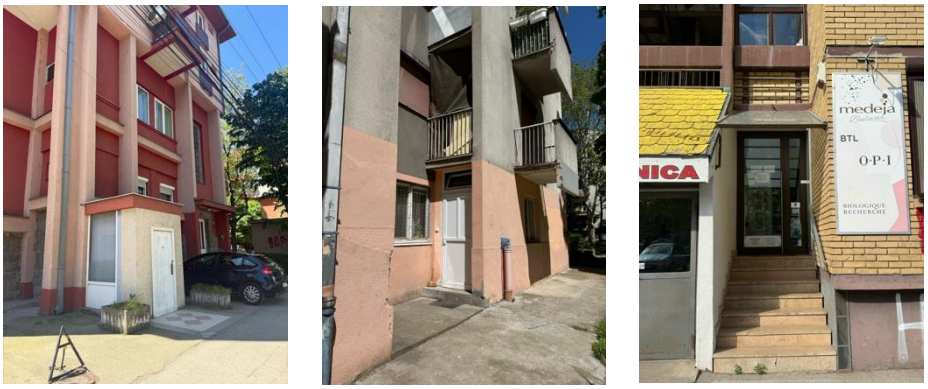


Figure 4. Examples of opening a new entrance from public area in apartment buildings in Niš, source: B. Stoiljković

3.5. Window Replacement

Replacing windows and balcony doors in apartments is a measure that is applied to improve energy efficiency in buildings. The residents undertake it mainly in older apartment buildings where the existing windows are of poor quality or worn out to reduce energy consumption, but also to improve the overall comfort, especially thermal, contributing in this way to a creation of a healthier place [8]. The quality and performances of new windows will depend on the profile material, profile system, type of glass, window fittings, window schedule, etc. However, what has the biggest impact on the appearance of the building is the design of the new windows. It is not a rare case that the new window schedule differs from the existing one, and even that the position, shape, and dimensions of the new windows differ, which significantly impairs the original appearance of the building. Also, examples can be seen where the material and color of the new windows profile are different compared to the original. Like many other DIY interventions, this one is not subject to regulatory control and restrictions, so after applying this measure to different units of the same building, a facade with extremely pronounced personal preferences of the residents can be obtained. (Figure 5)



Figure 5. Examples of window replacements in apartment buildings in Niš, source: B. Stoiljković

3.6. Installing Sun Shading

Installing sun shading devices over windows, loggias or balconies are one of the most common DIY measures that can be seen on apartment buildings in Niš. Solar shading systems influence daylight levels in a building and the view to the exterior environment; they also reduce solar gains and modify thermal exchanges through the glazed building envelope. Therefore, shadings affect the building energy use for lighting, heating and cooling, and the occupants' visual and thermal comfort [9]. Sun shading on the windows of older apartment buildings in the form of fabric curtains, which had completely lost their shading properties over time, needed to be replaced. On the other hand, the installation of sun shading is not always a standard measure even in recently built apartment buildings, so the residents resort to various home-made activities in this regard. Thus, all over the city, you can see the most diverse forms of applied sun shading measures on the facades of multi-storey residential buildings. When we talk about shading devices placed over windows, they are mostly different models of roller shutters, of different materials and colors. Less commonly, other types of installed shading devices can be seen, such as fixed or movable bris-soleils. Sun shading installed on balconies or loggias can be roller shutters, fixed or movable fabric awnings, straw or bamboo blinds, but also various knocked together structures. Similar to other DIY activities on facades, the implementation of this measure can lead to clutter on the facades and visual pollution. (Figure 6)

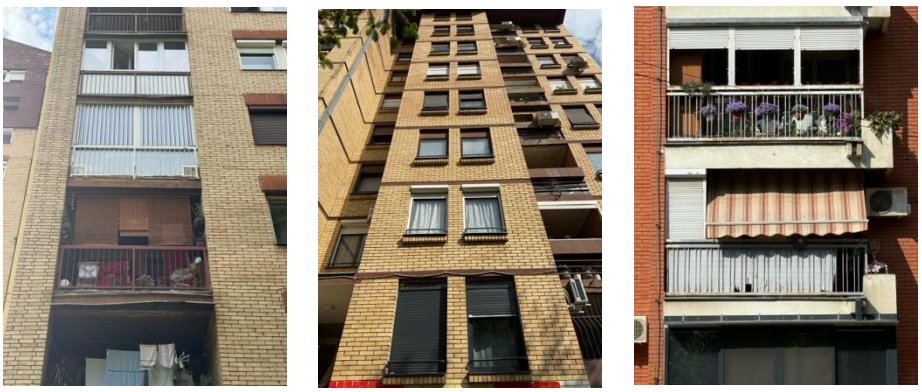


Figure 6. Examples of installing sun shading in apartment buildings in Niš, source: B. Stoiljković

3.7. Installing safety protection on window and open areas

Apartments on the ground floor of buildings are often considered less safe due to their proximity to the ground. This is especially emphasized in those parts of the building that are oriented towards quieter, more secluded or less frequented public open spaces. Users of such apartments often resort to installing some kind of barrier over windows or on loggias and balconies, to protect their property and belongings from external threats. On the other hand, households with small children living on higher floors also resort to this measure, in order to protect their youngest from falling from a height. A metal grille attached to a wall is the most used safety protection device on apartment buildings. However, these grilles can pose a problem – as a visual element on the facade of a building, due to the obstruction of the view of the surroundings, and especially if they are located at an emergency exit [10]. Protective grilles are generally made of steel, aluminum or iron. While ensuring safety is an undeniable benefit of installing grilles, the impact of implementing this measure on the exterior appearance of a building is questionable, especially when different grille designs are applied to a building. Regarding the obstruction of evacuation routes, the use of movable grilles could be a solution. (Figure 7)



Figure 7. Examples of installing safety protection on window and open areas in apartment buildings in Niš, source: B. Stoiljković

3.8. Painting activities on the façades

The human need for home is not only a need for physical protection, but also a demand for identification with a specific space. As a multi-family housing building contains a larger number of units, the apartment loses its spatial and visual identity and becomes part of a system of the same or similar units, and the identification of residents with the apartment becomes difficult. When a person can contribute to the formation and creation of a given space through their activities, they have the opportunity to become attached to it and consider it their own [11]. Viewed in this context, the exterior wall – the facade – becomes a rich and complex field for the possibility of satisfying various human needs. The simplest and most effective element of identification on buildings is the application of color. Color is perceived on facades before some other elements (material, texture, decoration...) and significantly contributes to the achievement of visual identity. Residents sometimes apply this measure on the part of the facade that belongs to their apartment, and most often on the part that is accessible to them, namely loggias and balconies. Such unsystematic use of paint on the

facade generally does not enhance the beauty of the building, and if applied by a large number of users, it can easily lead to clutter. (Figure 8)

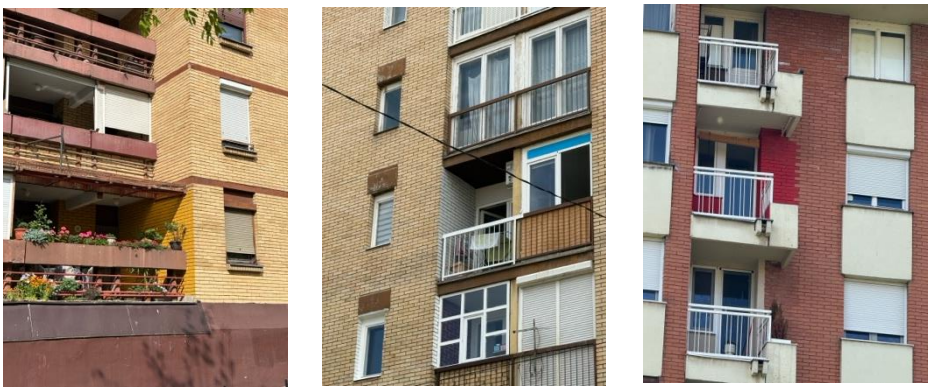


Figure 8. Examples of painting activities on the façades in apartment buildings in Niš, source: B. Stoiljković

4. CONCLUSIONS

DIY activities in multi-family housing occur when apartment users decorate, modify, build, maintain, or repair any part of their home themselves. DIY projects can range from very small, quick and relatively inexpensive one-off interventions and repairs to more significant structural, functional and aesthetic changes that usually involve a lot of time, high costs and skills. Users' motives for resorting to DIY measures can be described as functional, structural/energy and aesthetic. Whichever motif it belongs to, if its effects are visible on the exterior of the building, they affect the aesthetics and appearance of the building. Although such interventions can contribute to easier identification of users with their dwelling and give residents a stronger sense of belonging, in many cases they can make the facade cluttered, deteriorated, disfigured and certainly far from the designer's original idea.

Bearing in mind the most common DIY measures taken by the residents, and in order to prevent potential disruption and spoil of the facade and aesthetics of the building, some conclusions and design guidelines can be drawn. Regarding the loggia/balcony glazing, especially in places with adverse external influences (wind, noise, dust), this can be envisaged by the design, so that all loggia/balcony glazing on the building is identical. In that case, it should be possible to open the loggia/balcony completely, so that users can use them as a truly open area. Furthermore, the users could be offered a design for the open area glazing, so that if they opt for that measure, the effects on the facade would be controlled. Having a private open area is one of the most important qualities of the apartment, its envisagement by the design should not be called into question at all; the open surface has an essential role in realizing various functional and ecological functions. To make the use value of private open space more significant, it is desirable to design it so that it is covered, with sun shading devices, and to ensure privacy. Moreover, sun shading devices are a necessity on all windows oriented towards the sun's rays. In addition, the windows on the lower floors could have uniform safety protection in those parts of the building where it is necessary, with the possibility of their removal if they are on the evacuation routes. Also, as for other subsequent interventions on the building, the users could be offered a unique model if they decide for this measure themselves. Regarding the visual recognition of residential units on the facades, it is possible to envisage the visual separation of individual units, a

certain level and form of their independence, so that they can be recognized and that their users can identify with them, thus realizing the right to be different from other users.

In general, in order to avoid that an apartment building significantly changes its appearance during the use phase, certain regulatory and technical guidelines and restrictions should be introduced and the architect's original idea and design should be protected.

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Review paper

APPLICATION OF SUSTAINABLE MATERIALS IN FOUNDATION ENGINEERING

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Abstract

Growing demand for sustainable construction methods has led to increased interest in using environmentally friendly materials in foundation engineering. This paper explores the potential applications, advantages, and challenges of using sustainable materials in foundation construction. The aim of the study is to compare sustainable alternative materials, such as recycled aggregates, geopolymers, and bio-binders, with traditional foundation materials.

The methodology includes a review of the literature and comparative analysis in the field of sustainable foundation materials. Their mechanical properties, durability, and environmental impact are analyzed. The results indicate that many sustainable materials exhibit superior performance in terms of load-bearing capacity and longevity, while reducing carbon footprint and natural resource consumption.

The study highlights the need for further research, standardization, and regulatory support to enable wider adoption of these materials in foundation engineering. By integrating these materials into geotechnical practice, the construction industry can contribute to the development of sustainable and resilient infrastructure.

Key words: *Sustainable materials, foundation construction, recycled aggregates, geopolymers, environmental impact*

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1. SUSTAINABLE BUILDING MATERIALS: IMPACTS ON PERFORMANCE, HEALTH, AND ENVIRONMENTAL OUTCOMES

The growing environmental consciousness of recent years underscores the imperative to design and construct buildings that prioritize ecological integrity and resource efficiency. Rapid population growth and escalating demands for housing necessitate careful planning to ensure that basic settlement needs are met while preserving natural systems and safeguarding resources for future generations. In this context, community-driven models that integrate green construction principles with affordable housing solutions have emerged as a vital strategy for mitigating the impacts of climate change. Such approaches emphasize energy conservation, the reuse of rainwater, the optimization of natural light and ventilation, and the use of locally sourced, renewable materials that minimize embodied energy, reduce pollution, and pose fewer health risks. By adopting circular design frameworks that interlink energy, water, and material flows, these projects not only enhance environmental performance but also raise occupants' awareness of sustainable living practices [1].

Concrete alternatives are emerging to address the high carbon footprint of ordinary Portland cement. Recycled aggregate concrete replaces virgin coarse aggregate with crushed demolition waste, maintaining comparable compressive strengths while diverting material from landfills [2]. Fly ash and slag-based binders leverage industrial by-products to substitute up to 50% of cement clinker, yielding mixtures with lower embodied CO_2 and enhanced long-term durability [2]. Geopolymer concretes synthesized from aluminosilicate precursors offer an additional pathway, demonstrating up to 80% lower life-cycle emissions when activated with alkali solutions derived from industrial residues [3].

Interior finishes and non-structural elements play a vital role in occupant health and well-being. Natural clay and lime-based plasters regulate indoor humidity through hygroscopic buffering, inhibit mold growth, and contain no synthetic binders or plasticizers [4]. Low-VOC paints and coatings often water-borne and derived from plant oils or mineral fillers minimize off-gassing of formaldehyde and other harmful compounds, improving cognitive performance and reducing sick-building symptoms by up to 50% in green-certified offices [5]. Flooring options such as cork and reclaimed hardwood not only close material loops but also provide acoustic damping and thermal comfort underfoot, further enhancing the indoor environment without reliance on petrochemical-derived plastics [6].

2. FUNDAMENTAL PRINCIPLES OF FOUNDATION ENGINEERING: ANALYSIS OF TRADITIONAL AND MODERN FOUNDATION SYSTEMS

Foundation engineering is a critical sub-discipline of civil and geotechnical engineering that deals with the design and construction of structures that safely transfer loads to the ground. At its core, the design of a foundation involves an understanding of soil behavior, load distribution, and structural interaction with the subsurface environment [7]. Its primary objective is to ensure that buildings, bridges, and other civil works remain stable and serviceable throughout their intended lifespan. The fundamental considerations in foundation engineering include load magnitude and distribution, soil and rock properties, groundwater conditions, and the interaction between the structure and the supporting ground [8]. Over the centuries, foundation systems have evolved from traditional methods-such as isolated pad

foundations, raft foundations, and timber piles-to modern systems that incorporate advanced materials, prefabrication techniques, and innovative installation methods like helical and screw piles.

Well-designed foundation must account for potential settlement both immediate and time-dependent (consolidation). Settlement analysis requires understanding the soil's compressibility and the rate at which pore water dissipates under applied loads. Engineers also consider lateral earth pressures when designing retaining structures or foundations adjacent to steep slopes. In summary, the fundamental principles of foundation engineering revolve around load distribution, effective stress analysis, and the prediction of soil–structure interaction under various environmental and loading conditions.

2.1. Traditional Foundation Systems

Traditional foundation systems have been developed over centuries and are primarily based on empirical observations and classical mechanics. Common traditional systems include spread footings (or isolated pad foundations), strip foundations (Figure 1), and raft (or mat) foundations. For example, spread footings are designed to distribute the load over a large area to avoid overstressing the underlying soil [8]. These foundations typically involve the use of reinforced concrete poured in situ, sometimes combined with masonry elements in older constructions.

Another well-established traditional method is the use of timber piles, which were historically driven into the ground to support structures in soft or wet soils [9]. In ancient construction practices, stone pedestals and trench foundations were used to level structures and provide a stable support base. Despite their historical significance, many traditional systems have limitations. Their performance is often affected by soil heterogeneity, variable workmanship, and, in some cases, the susceptibility of materials (e.g. timber) to decay or deterioration over time.

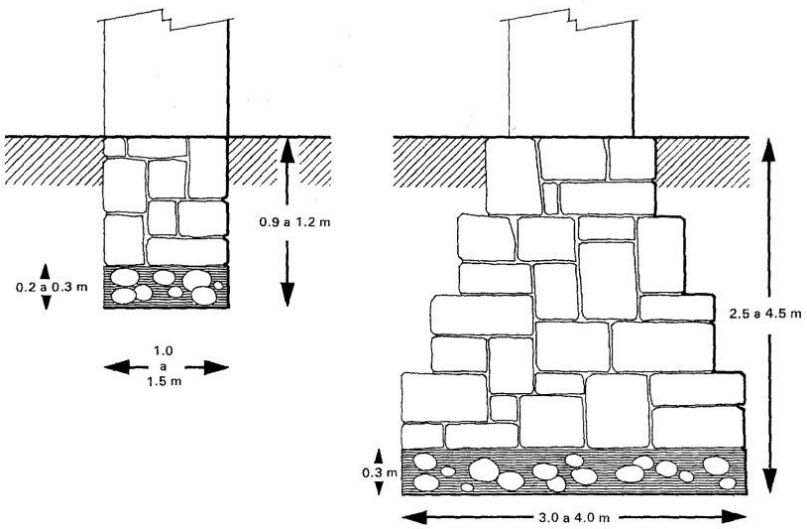


Figure 1. Strip foundations in Ancient Greek architecture [9]

Traditional systems generally rely on local materials and labor-intensive construction techniques. Although they have a proven track record, these methods sometimes lack the precision required to control differential settlements and may not adequately address modern

seismic or dynamic load requirements [7]. However, the simplicity and robustness of traditional systems continue to influence contemporary practices, particularly in regions where modern construction methods are not feasible due to economic or resource constraints.

2.2. Modern Foundation Systems

Modern foundation systems have emerged as a result of advances in materials science, computational modeling, and construction technology. One of the key features of modern foundations is the incorporation of prefabricated components and specialized piles, such as helical and screw piles, which are manufactured offsite under controlled conditions [10]. These systems benefit from high precision and quality control, which contribute to improved performance in terms of load distribution and resistance to environmental factors such as soil expansion and seismic forces.

Modern methods also make extensive use of computer-aided design (CAD) and finite element analysis (FEA) to predict the interaction between the foundation and the soil accurately. For instance, advanced modeling techniques allow engineers to simulate time-dependent soil behavior and the effects of moisture fluctuations on expansive clays, leading to more effective mitigation strategies [11]. Furthermore, modern foundations often incorporate composite materials, including high-performance concrete and steel reinforcement, to enhance durability and reduce settlement under variable loading conditions. An example of such a system is the foundation of the Burj Khalifa, which demonstrates the integration of high-performance materials and advanced analysis techniques (Figure 2).



Figure 2. Burj Khalifa Tower Foundation system [12]

An important aspect of modern foundation systems is sustainability. With an increasing focus on minimizing the environmental impact of construction, modern designs aim to reduce material wastage, improve energy efficiency, and lower the overall carbon footprint. Innovations such as 3D printed concrete elements and the use of recycled materials exemplify the move towards more sustainable construction practices, while also providing economic advantages through reduced construction time and labor costs.

2.3. Comparative Analysis

The evolution from traditional to modern foundation systems reflects both technological advancements and a growing emphasis on precision, performance, and sustainability in foundation engineering. While traditional foundations have served as the backbone of construction for centuries, their limitations in terms of quality control and adaptability to diverse soil conditions are becoming increasingly evident. Modern foundation systems, underpinned by advanced modeling techniques and innovative materials, offer improved performance, enhanced durability, and a lower environmental impact. The integration of numerical analysis tools and sustainable practices in modern foundation design not only enhances the safety and serviceability of structures but also contributes to the efficient use of resources-a critical consideration in today's construction landscape.

3. SUSTAINABLE MATERIALS IN FOUNDATION ENGINEERING

Sustainable development has become a critical consideration in the engineering profession, necessitating that fundamental infrastructure be developed with minimal environmental degradation and long-term economic, social, and environmental viability in mind. In foundation engineering, the selection and use of sustainable materials is a key component in achieving these objectives. Sustainable materials not only reduce the overall environmental footprint of construction but also enhance the resilience and durability of geotechnical systems in the face of evolving climate and socio-economic challenges.

The overarching objective of sustainable engineering is to integrate technical systems harmoniously into both natural and human-made environments, without impairing the operational integrity of either domain. This integration must be achieved across multiple scales: local, regional, and global to ensure that engineered solutions contribute positively to environmental stewardship, economic viability, social equity, and sound design principles [13].

Accordingly, sustainability in engineering can be conceptualized as a dynamic equilibrium among four interdependent pillars: engineering design, economy, environment, and equity often referred to as the "Four E's" of sustainable development (Figure 3).

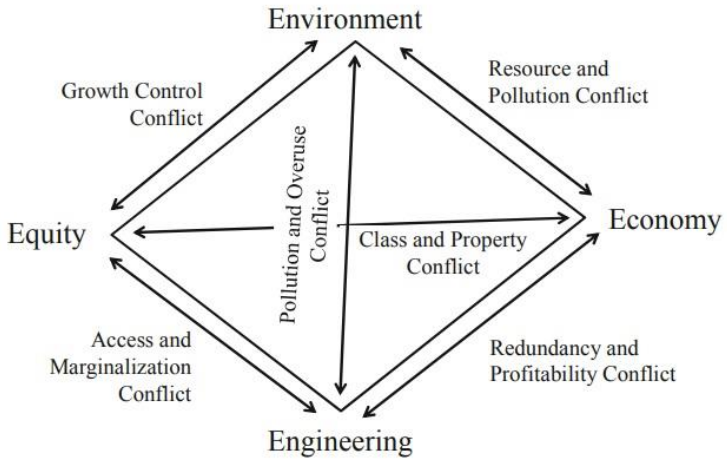


Figure 3. The four E's of sustainability in engineering projects [13]

In line with the four E's framework (engineering design, economy, environment, and equity) several sustainability objectives can be integrated into geotechnical engineering practice. These include early involvement of all stakeholders during the planning phase to establish a shared understanding of sustainability goals, such as pollution reduction and the use of environmentally friendly alternative materials [13].

The integration of sustainable materials into foundation engineering also requires overcoming several technical and logistical challenges. One primary concern is ensuring that substitute materials meet established performance criteria, particularly regarding strength, deformation behavior, and resistance to environmental degradation.

3.1. Recycled Aggregates

The mechanical behavior of recycled aggregates when used in foundation engineering has been the subject of various investigations. Researchers have demonstrated that, with proper processing and quality control, recycled aggregates (Figure 4) can exhibit compressive strengths and stiffness values comparable to those of conventional materials. Nonetheless, challenges remain in ensuring consistent material properties due to the heterogeneous nature of recycled components. The variability inherent in recycled aggregates necessitates rigorous testing protocols and the development of standardized criteria to ensure that they meet the structural demands imposed by building foundations [14]. Moreover, several studies have highlighted the importance of pre-treatment processes, such as washing and sorting, to remove impurities that could compromise the aggregate's performance. These pre-treatment methods not only enhance the mechanical properties of the recycled material but also extend its service life within geotechnical applications.



Figure 4. Recycled aggregate [15]

The foundation of a building is fundamentally concerned with soil–structure interaction, where the chosen materials must provide adequate load-bearing capacity and stiffness while maintaining long-term durability. When recycled aggregates are employed in such settings, they must be evaluated against performance criteria that include settlement behavior, resistance to dynamic loading, and durability under environmental stressors. Recent experimental and numerical studies have provided encouraging results, indicating that recycled aggregates can be successfully integrated into foundation systems with proper design adjustments. In particular, the use of recycled aggregates in sub-base layers or as a component of blended granular mixtures has shown to mitigate issues related to variability and enhance overall performance [14].

The adoption of recycled aggregates in the foundation of buildings signifies a noteworthy step toward the realization of sustainable construction practices. By integrating recycled aggregates, the construction sector can simultaneously reduce its environmental impact and

meet the performance requirements of modern engineering. As the body of research expands, further refinements in material processing and design strategies will undoubtedly contribute to overcoming current limitations, thereby ensuring that recycled aggregates continue to evolve as a reliable, sustainable material option in the foundational engineering domain [16].

3.2. Geopolymers

Geopolymers have emerged as a sustainable alternative to conventional cementitious binders, offering significant potential for foundation engineering applications. Their synthesis involves the alkaline activation of aluminosilicate precursors often industrial by products such as fly ash or slag to form a hardened binder with high compressive strength, chemical stability, and resistance to thermal and acid attacks. These characteristics make geopolymeric materials particularly attractive in building foundations, where durability and long-term performance are critical under various loading and environmental conditions [17]. In addition to their advantageous mechanical properties, geopolymers present a lower embodied energy and substantially reduced carbon dioxide emissions relative to traditional ordinary Portland cement, thereby contributing to a more sustainable construction paradigm. The microstructure of cement lime stabilised soils is typically dominated by flaky calcium-silicate-hydrate (CSH) crystals, which form a cementitious paste that coats and binds individual soil grains, fills pore spaces and thereby enhances interparticle bond strength (Figure 5. a). In sulfidic environments, the same treatment often yields expansive ettringite crystals within interparticle voids, leading to volumetric swelling and increased porosity (Figure 5. b) [18]. In foundation applications, the implementation of geopolymeric binders offers several technical benefits.

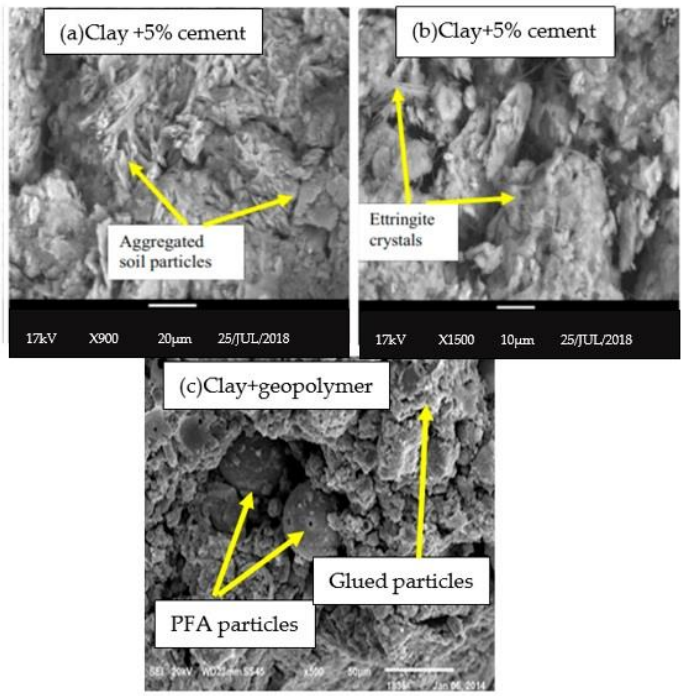


Figure 5. SEM of Stabilised Clays (a) 5% Cement-stabilised Clay (b) 5% Cement-stabilised Clays Showing Ettringite Crystals (c) PFA Stabilised Clay [18]

Their rapid strength development is conducive to early load-bearing capacity, a critical factor in foundation construction while their refined pore structure enhances resistance to the ingress of deleterious agents such as chloride ions and water, thereby mitigating durability concerns. However, the heterogeneous nature of the precursor materials demands robust quality control measures and standardized protocols to ensure consistency in mechanical performance and long-term stability. Research indicates that optimizing the mix design and curing regime is essential to harness the full potential of geopolymers in structural contexts, particularly under cyclic and sustained loads commonly experienced by building foundations [19]. Ongoing studies are focused on bridging the gap between laboratory-scale performance and field applications, ensuring that geopolymers can reliably replace conventional materials without compromising structural integrity. The evolution of geopolymer technology thus aligns closely with global initiatives aimed at reducing the carbon footprint of the construction industry, while simultaneously enhancing the resilience and service life of foundational systems. As geopolymers continue to demonstrate promising results, their integration into foundation engineering is poised to redefine sustainable practices in the built environment.

3.3. Geosynthetics

The integration of geosynthetics into foundation engineering has significantly transformed traditional construction practices by enhancing soil stability, reducing settlement, and improving load distribution. Recent studies have demonstrated that geosynthetic materials, such as geotextiles, geogrids, and geomembranes, provide multiple functions including reinforcement, separation, filtration, and drainage, improving the performance of foundation systems. Figure 6 illustrates two common manufacturing methods of geosynthetic clay liners (GCLs), which are widely used for reinforcement and hydraulic barrier applications in foundation engineering. Their high tensile strength and resistance to chemical degradation enable the effective reinforcement of weak soils and mitigation of differential settlement, resulting in enhanced soil-structure interaction under varying environmental conditions [20].

The use of geosynthetics contributes to sustainable construction practices by reducing the reliance on conventional materials, which in turn lowers the overall environmental impact. Despite promising laboratory and field outcomes, the successful application of these materials requires standardized design methodologies, robust quality control, and ongoing research to ensure long-term durability and performance [21]. Collaborative efforts among researchers, industry professionals, and regulatory agencies continue to refine installation techniques and material properties, further solidifying the role of geosynthetics as a cost-effective and environmentally responsible solution in modern foundation engineering.

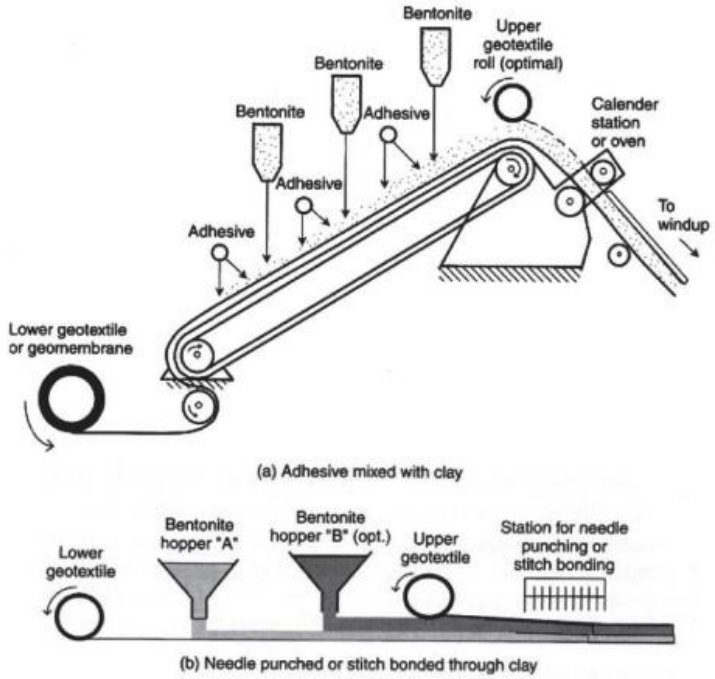


Figure 6. Methods of manufacturing different types of geosynthetic clay liners [20]

3.4. Bio-Based Materials and Mycelium Composites

Bio-based materials, particularly mycelium composites, are increasingly recognized as innovative alternatives in foundation engineering. Derived from renewable resources—such as lignocellulosic substrates colonized by fungal mycelium—these materials boast lower embodied energy and reduced carbon emissions compared to conventional cementitious systems. Early research indicates that, with optimized processing, mycelium composites can achieve suitable compressive strength and thermal insulation properties for certain foundation applications [22]. However, challenges including moisture sensitivity, long-term durability, and variability in mechanical performance persist, necessitating rigorous quality control and standardized testing protocols to ensure their reliability under the sustained loads typical in building foundations.

The incorporation of bio-based materials into foundations supports sustainable construction by reducing reliance on non-renewable resources and promoting the circular economy through waste minimization and reuse of organic by-products [23]. Laboratory evaluations have provided promising insights into the potential of these materials as environmentally friendly alternatives in foundation design, though further interdisciplinary research is required to refine material formulations and processing techniques. The integration of mycelium composites not only contributes to the reduction of environmental impact but also offers economic benefits by potentially lowering lifecycle costs associated with maintenance and material replacement. As ongoing collaboration among material scientists, structural engineers, and sustainability experts advances this field, bio-based materials are poised to emerge as a viable, cost-effective solution for enhancing the sustainability of building foundations [24].

3.5. Case Studies and Applications in Foundation Engineering

The application of sustainable materials in foundation engineering is becoming increasingly important, and through specific case studies, it is possible to observe their actual performance, advantages, and challenges in practice.

3.5.1. Sustainable Pile Foundations

Recent studies have demonstrated that sustainable materials can be successfully integrated into foundation systems, particularly in pile foundations. A quantitative sustainability indicator system has been developed for comparing resource consumption and environmental impacts between drilled shafts and driven piles. The life cycle assessments (LCA) performed on these systems indicate that by incorporating sustainable materials—such as recycled aggregates and supplementary cementitious materials—the environmental footprint of pile foundations can be substantially reduced while maintaining or even exceeding technical performance requirements [25]. For instance, using fly ash as a partial substitute has shown to decrease both the embodied energy and CO_2 emissions associated with the concrete used in pile foundations.

3.5.2. Geopolymer Foundations

A case study from a recent project in Europe evaluated the performance of geopolymer-based concrete in the construction of a deep foundation system. The project used a geopolymer mix with a high replacement level of Portland cement by fly ash and slag. Field monitoring indicated that the geopolymer foundations exhibited comparable load-bearing behavior to traditional concrete foundations, while the LCA results highlighted a reduction of up to 40% in CO_2 emissions [3]. The increased durability under aggressive environmental conditions further underscored the long-term benefits of adopting geopolymer systems in foundation engineering.

3.5.3. Economic and Technical Benefits

Beyond the environmental advantages, sustainable materials can offer significant economic benefits. A reduction in raw material costs due to the use of industrial by-products, coupled with a potential decrease in lifecycle maintenance costs, can improve the overall cost efficiency of foundation projects. Additionally, sustainable materials tend to exhibit enhanced durability, reduced permeability, and better chemical resistance—factors that contribute to extended service life and lower repair frequencies. These benefits are particularly important in infrastructure projects where long-term performance and reliability are critical.

4. CONCLUDING REMARKS

This study demonstrates the growing relevance and applicability of sustainable materials in foundation engineering. Through an in-depth analysis of recycled aggregates, geopolymers, geosynthetics, and bio-based composites, it is evident that these materials can provide technical performance on par with or superior to conventional solutions, while significantly reducing environmental impact. Their potential to reduce embodied carbon,

enhance durability, and lower long-term maintenance demands makes them a compelling alternative in the context of sustainable infrastructure development.

However, the transition toward widespread use of sustainable materials in foundation systems is not without challenges. Variability in material properties, lack of standardization, and uncertainties in long-term performance under complex loading and environmental conditions remain key barriers. Rigorous testing protocols, enhanced quality control, and context-specific design methodologies are essential to overcome these limitations.

Future advancements in material science, coupled with regulatory incentives and interdisciplinary collaboration, are likely to accelerate the adoption of sustainable alternatives in geotechnical practice. By integrating these materials into design and construction strategies, the foundation engineering community can play a pivotal role in addressing global sustainability targets, thereby fostering infrastructure that is not only structurally sound but also environmentally responsible and economically viable.

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Research paper

ONE-YEAR SULFATE ATTACK: INFLUENCE OF CERTAIN FACTORS ON THE CONCRETE PROPERTIES

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Abstract

A large amount of aggressive ions, especially sulfate ions, is present in the soil and groundwater as well as in marine environment, which could lead to the deterioration of underground and offshore concrete structures in those areas. In the last few decades, the problem of the sulfate attack on building materials and structures has attracted considerable attention and is considered very important issue. Regardless of the increased interest and research, there is always a need for further research both because of the complexity of the sulfate attack and the long-term effect itself. The aim of the research presented in this paper is to try to determine the impact of the selected factors and their combination on certain properties of concrete using a mathematical-statistical analysis "Factorial Experiment", which evaluates its sulfate resistance after one year of exposure to 5% sulfate solutions (Na_2SO_4 and $MgSO_4$). The considered parameters included in this are the type of cement (CEM I and CEM III), the water-cement ratio (0.55 and 0.38) and the type of aggregate (river and aggregate from recycled concrete), while the selected properties through which sulfate attack is monitored are capillary absorption, length change and change in compressive strength. Based on the results of the analysis, it is difficult to draw a clear conclusion about the influence level of the key factors of selected properties for evaluation the sulfate resistance of concrete mixtures for the observed sulfate exposure period of one year, but it provides a contribution to further studies in this topic.

Key words: *sulfate attack, compressive strength, length change, capillary water absorption, factorial experiment*

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1. INTRODUCTION

The rapid development of the construction industry has accelerated the consumption of natural resources and generated large amounts of construction and demolition waste (CDW). As a consequence, the enormous amount of construction waste has become a burning issue in energy and the environment [1]. Although several countries recycle around 80 % of CDW such as Japan, the Netherlands, and Germany, there are some developing countries with an average recycling rate of 20 % to 40 %. Accordingly, promoting the use of recycled aggregate (RA) from the CDW into new concrete as a replacement for natural aggregate is an essential priority [2]. Using recycled concrete aggregate (RCA) has significant environmental benefits, in addition to conserving natural resources, reducing the need for disposal of this waste and achieving sustainable development. The use of supplementary cementing materials (SCMs) also may reduce the environmental impact and energy consumption of concrete used for construction.

In recent years, researchers have begun to focus on the degradation of concrete containing RCA due to external sulfate attack. Concrete structures such as basement walls, bridge piers, ground slabs, and tunnel linings often exhibit severe scaling and spalling [3] due to the action of sulfate ions from soil and water, thereby reducing the durability of concrete. This damage due to sulfate attack can be viewed as chemical sulfate attack and physical sulfate attack. The degradation of concrete subjected to sulfate attack in the fully immersed condition is largely attributed to the chemical reactions between the ingress of sulfate and the unreacted phases and hydration phases of cements. The creation of these products is associated with the volume expansive products of ettringite and gypsum [1]. Concretes with recycled concrete aggregate have been shown to be more sensitive to the effects of sulfates than conventional concretes due to the high water absorption and the presence of adhered mortar, but this can be improved by adding, for example, SCMs, by mixing with cements that already contain mineral additives, such as CEM III or using of a lower w/c ratio [4].

Although research in the field of sulfate attack has been very intensive in the last few years, due to the large number of factors that influence the entire problem, not much is still known and more work needs to be done on this problem. This paper attempts to help in this and to contribute to the understanding of this topic and extend the life of concrete structures exposed to the aggressive attack of sulfates. Namely, an attempt was made to show, by using the mathematical tool of a factorial experiment, which of the adopted parameters (cement type, water-cement ratio and type of aggregate-natural or recycled) contributes the most to the properties through which the resistance of concrete to sulfate attack is monitored. The factors that were chosen are the change in compressive strength, the length change and capillary water absorption.

2. EXPERIMENTAL

Eight concretes were prepared and their resistance to sulfate attack was determined by immersing specimens after the specified initial curing in 5% Na_2SO_4 and 5% $MgSO_4$ solutions. The concrete specimens were completely immersed in the solutions and the sulfate solutions were changed every 90 days. Lime-saturated water was used as the

reference solution. The specimens were tested according to previously determined testing program.

2.1. Components materials and mixture proportion

To assess the influence of different parameters on sulfate resistance of concrete, the following component materials were used:

- Cement: Portland cement CEM I 42.5R (Lafarge-BFC Serbia, γ_{sc}=3100kg/m^3) and Low heat/Sulfate resistance cement CEM III/B 32.5N LH/SR (Lafarge-BFC Serbia, γ_{sc}=2650kg/m^3),
- Aggregate: fine aggregate (river aggregate, 0/4 mm) and coarse aggregate (river aggregate, 4/8 and 8/16mm and recycled concrete aggregate, 4/8 and 8/16mm),
- Admixture: HRWRA ("SikaViscoCrete 3070", γ_s=1090kg/m^3 and "SikaViscoCrete 5500HP", γ_s=1090kg/m^3 "Sika"- Switzerland,) and
- tap water.

Designed compositions of concrete mixtures and their labels are shown in Table 1.

Table 1: Mixture proportions of concrete in kg/m^3

Concretes	m_c (CEM I)	m_c (CEM III)	m_v	$m_{a,f}$	$m_{a,c}$	m_{spk}	w/c
NPC1	350	-	192.5	930	858	-	0.55
NPC2	423	-	161.0	936	864	5.9	0.38
NMC1	-	338	186.0	936	864	0.7	0.55
NMC2	-	416	158.0	937	865	2.5	0.38
RPC1	350	-	192.5	20.2	874	803	-
RPC2	425	-	162	20.5	880	813	3.4
RMC1	-	338	186	20.5	881	813	-
RMC2	-	414	157	20.5	881	814	3.3

m_c-quantity of cement; m_v-quantity of water; $m_{a,f}$-quantity of fine aggregate; $m_{a,c}$-quantity of coarse aggregate; m_{spk}-quantity of super-plasticizer; w/c-water-cement ratio

2.2. Curing, specimens preparation and labels

Initially all specimens were cured in lime-saturated water for 28 days. After that period, compressive strength was determined by testing three specimens from each mixture. One third of the remained specimens were transferred to containers with 5 % Na_2SO_4 and another third in 5 % $MgSO_4$ solution where they were stored until testing period of 180 and 365 days. The last third of specimens were submerged in lime-saturated solution for the same period.

For testing of compressive strength at the age of 180 and 365 days cylinders ∅100 mm and H=100mm were chosen. The length change was measured on prism-shaped specimens with dimensions 100x100x500 mm^3 until choosen periods while capillary

absorption was determined on plate-shaped specimens, the dimensions 150x150x75 mm^3, for the same time. Specimens from each mixture were categorized in three series and labelling with five letters in the following way: those with the first letter "E" were cured in lime-saturated water solution, those with "N" were immersed in 5% Na_2SO_4 solution and those with "M" were stored in 5% $MgSO_4$ solution. The second letter in the label ("N" or "R") indicates the type of aggregate (natural or recycled). The third letter refers to the type of cement: "PC" stands for CEM I and "MC" stands for CEM III. And the last letter denotes w/c ratio:"1" is for w/c=0.55 and "2" is for w/c_2=0.38.

2.3. Methods

Compressive strength was tested according to EN 12390-3 [5] before the specimens were immersed in sulfate solutions and after storing them in these solutions for choosen period. For each compressive strength, three specimens were used. Length change was determined according to the procedure given in UNI 11307 [6]. For each mixture and each solution, three prisms were measured once a week until the above-mentioned observed periods. Testing of capillary water absorption were performed on specimens before were immersed in sulfate solutions and at chosen time. Determination of capillary water absorption was done by procedure given in SRPS U.M8.300 [7]. Before testing, samples were conditioned at standard laboratory air temperature and humidity for 14 days. Surface area subjected to water was cca 225cm^2. Measurements were conducted after 1, 5, 15, 30 minutes, 1, 4, 9 and 25 hours. The results were expressed as water absorption in kg/m^2 and presented values are average of three specimens.

3. RESULTS AND DICSUSSION

3.1. Compressive strength

The average results of concrete compressive strength after 180 and 365 days of immersion in $MgSO_4$, Na_2SO_4 and lime-saturated water are presented in Figure 1a for mixtures with NA and in Figure 1b for the mixtures with RA.

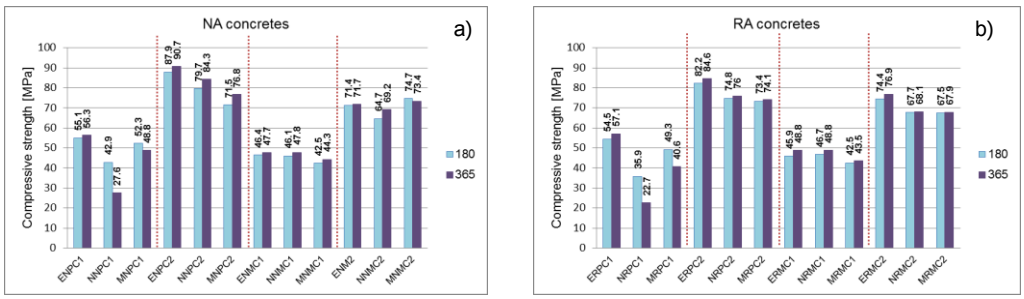


Figure 1. Compressive strength of concrete mixtures at 180 and 365 days a) NA concrete mixtures; b) RA concrete mixtures

Based on the results shown in the Figure 1 it can be concluded that almost all concretes have a decrease in compressive strength or a slight increase compared to the corresponding reference specimens, for both ages, but this is within the limits of up to 10%.

The exception is concretes with CEM I and w/c=0.55 for both types of aggregates, where is this difference greater.

3.2. Length change

Length change results of reference concrete specimens as well as specimens immersed to Na_2SO_4 and $MgSO_4$ solutions after 180 and 365 days are shown in **Error! Reference source not found.**2.

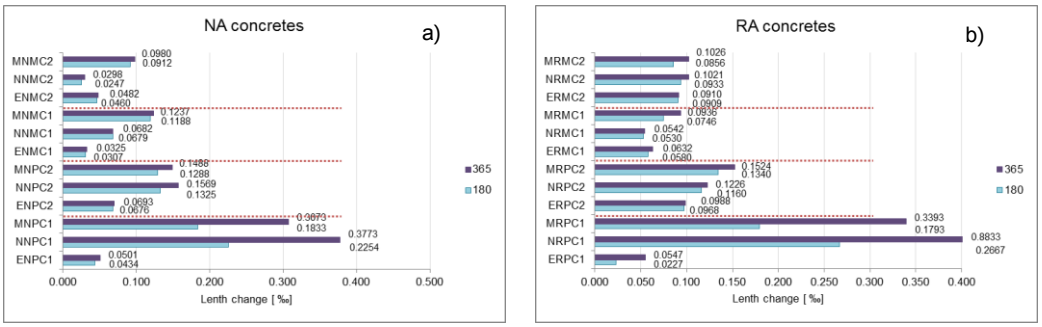


Figure 2. Length change of concrete mixtures at 180 and 365 days a) NA concrete mixtures; b) RA concrete mixtures

Based on the measured values of the length change of specimens exposed to sulfate solutions after 180 and 365 days, it can be concluded that the dominant length change is observed in concrete mixtures with CEM I and w/c=0.55 in both sulfate solutions. All other concretes have a length change within acceptable limits.

3.3. Capillary water absorption

Results of capillary water absorption at 25 hours in kg/m^2 on all observed specimens after 180 and 365 days immersed in sulfate solutions are presented in Figure 3.

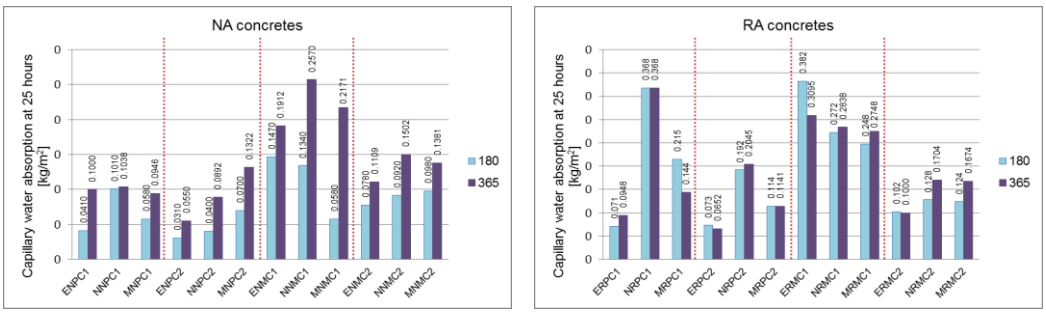


Figure 3. Capillary water absorption of concrete mixtures at 180 and 365 days a) at NA concrete mixtures; b) at RA concrete mixtures

It is difficult to find any regularity in this property, but it can be seen that all concretes with NA have higher capillary absorption values after 365 days, while this is not the rule for concretes with RA.

3.4. Factorial experiment

The influence of selected factors such as the type of cement, water-cement ratio and type of aggregate used in this experiment, as well as their combination, on certain properties of concrete determined after 180 and 365 days immersed in sulfate solutions was carried out using the "multi-parameter" analysis "Factorial experiment", which basically consists of appropriate mathematical and statistical procedures with the aim of obtaining a mathematical model of the process.This type of analysis enables the verification of the hypothesis about the existence of a relationship between the observed properties of concrete and various influencing factors. Factorial analysis can be used to define the relative size of the influence of various parameters, and based on their "significance" the simplest analytical form can be formulated. Each influential factor (type of cement, water-cement ratio and type of aggregate) is assigned a level of consideration that includes values of +1 or -1[8].

The results of the analysis of the influence of the mentioned parameters on the compressive strength are given in Figure 4 according to time exposure and solutions type.

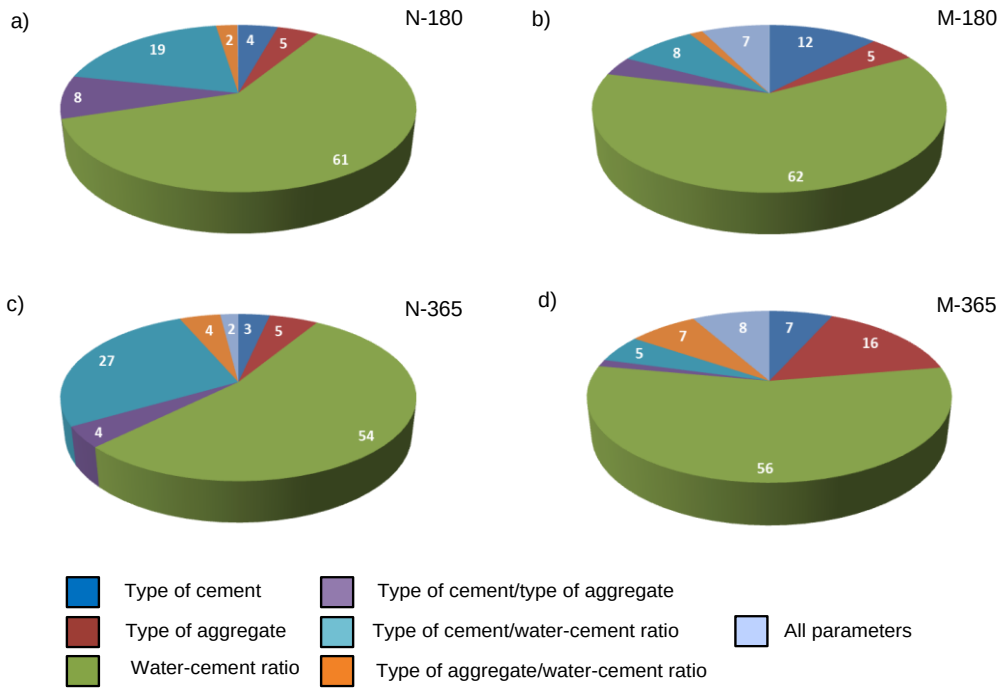


*Figure 4. Results of analysis using a factorial experiment in the case of **compressive strength** a) 180 days immersed in Na_2SO_4, b) 180 days immersed in MgSO4, c) 365 days immersed in Na_2SO_4, d) 365 days immersed in MgSO4,*

Based on the results of the compressive strength analysis (Figure 4), the water-cement ratio is by far the dominant parameter in all cases, regardless of the time of exposure to the sulfate solution or the type of solution. The next parameter that has an impact on this observed characteristic is the combination of cement type/water-cement ratio, in specimens

exposed to Na_2SO_4, while in the case where the specimens are exposed to $MgSO_4$ cement (at 180 days) or aggregate type (at 365 days).

The results of the analysis of the influence of the choosen parameters on the length change of the specimens are given in the Figure 5.

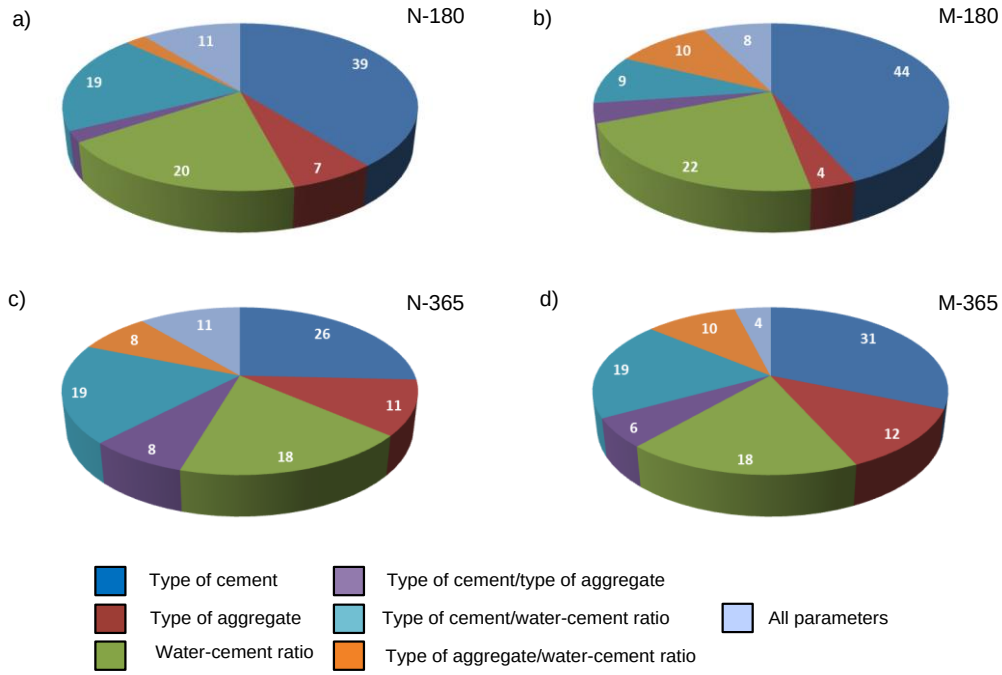
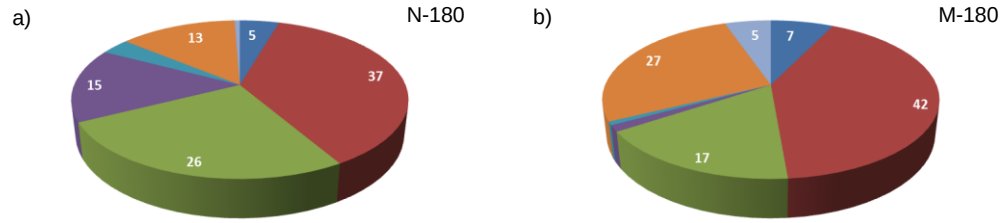


Figure 5. Results of analysis using a factorial experiment in the case of ***length change*** *a) 180 days immersed in Na_2SO_4, b) 180 days immersed in MgSO4, c) 365 days immersed in Na_2SO_4, d) 365 days immersed in MgSO4,*

The results obtained and presented in the Figure 5 indicate that in the case length change, the dominant parameter is the cement type (more in the case of 180 days), followed by the water-cement ratio or the combination of cement type/water-cement ratio (at 365 days).

The results of the analysis of the influence of the mentioned parameters on the coefficient of capillary absorption are given in the Figure 6 for both ages and both solutions.



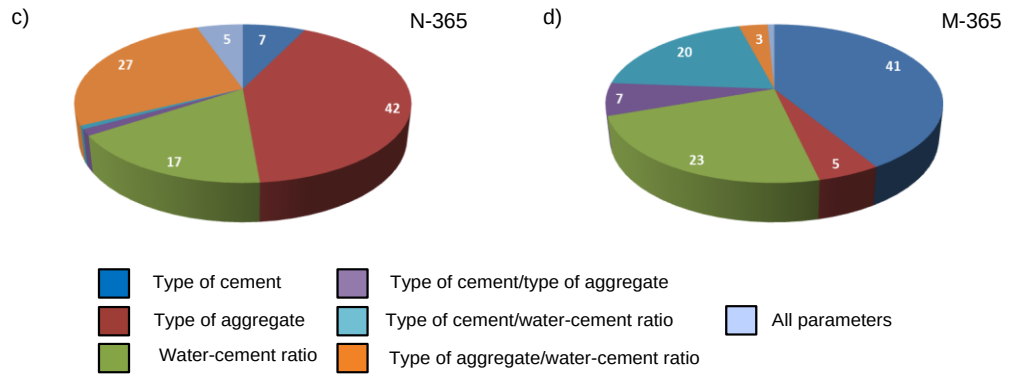


Figure 6. Results of analysis using a factorial experiment in the case of ***coefficient of capillary absorption*** *a) 180 days immersed in Na_2SO_4, b) 180 days immersed in MgSO4, c) 365 days immersed in Na_2SO_4, d) 365 days immersed in MgSO4,*

Based on the results shown in Figure 6, it is difficult to draw a single conclusion, but some rules can be observed. Namely, in the case of exposing specimens to the both solutions for 180 days and the Na_2SO_4 solution for 365 days, the parameter that has the greatest influence on the observed property is the type of aggregate, followed by the water-cement ratio in the case of Na_2SO_4 or the combination of aggregate/water-cement ratio. When we consider a period of 365 days of exposure in the $MgSO_4$ solution, the dominant parameters are completely different. Thus, the type of cement is dominant, followed by the water-cement ratio.

5. CONCLUSION

Based on the analysis conducted on the magnitude of the influence of selected parameters on certain properties of concrete exposed to sulfate attack, the following conclusions were drawn:

- **Compressive strength**: in all observed cases (both sulfate solutions, Na_2SO_4 and $MgSO_4$, and both ages of 180 and 365 days), the water-cement factor has by far the dominant influence. After it is the type of cement in the case of Na_2SO_4 solutions, regardless of age, while in the case of $MgSO_4$ solutions, it is the type of aggregate or the type of cement.
- **Length change**: in all observed cases, the dominant influence on the observed characteristic is the type of cement. It is followed, with a small difference, by the combination of parameters cement/water-cement factor in all cases except for the $MgSO_4$ solution for 180 days.
- **Coefficient of capillary absorption**: the parameter that has the greatest influence on this observed property in all cases is the type of cement except in the case of $MgSO_4$ and age of 365 days. The parameter that follows this dominant one is variable for all observed cases.

As can be seen, it is difficult to make a single attitude and conclusion about the dominant influences of certain parameters in the case of observing the resistance of concrete under the attack of 5% Na_2SO_4 and $MgSO_4$ after 180 and 365 days and that they

depend on both the observed characteristic and the type of solution and the exposure time. This is certainly a move towards understanding the behavior of concrete under sulfate action and further work should be done to study and increase the resistance and durability of concrete exposed to this aggressive influence.

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