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 4

September 11 – 12, 2025

Science and Technology Park Niš, Serbia

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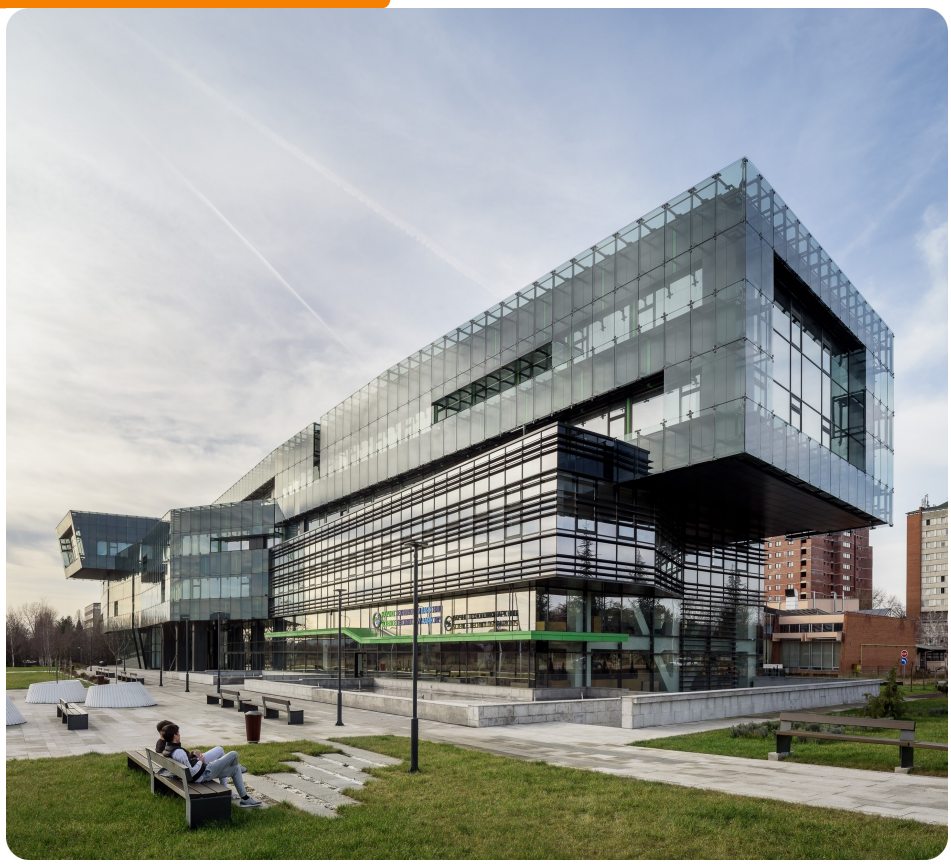

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PREFACE

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

SYNERGY BETWEEN ARCHITECT AND ALGORITHM – THE EVOLUTION OF ARCHITECTURAL DESIGN PROCESS THROUGH DIGITAL TOOLS

Jovana Tomić[1], Sonja Krasić[2], Isidora Mitrović[3]

Abstract

This paper examines how digital tools have transformed the architectural design process – from early CAD systems and parametric modeling to generative design and modern AI-based algorithms. The focus is on the relationship between the architect and the algorithm in shaping architectural solutions. Over time, digital tools have enhanced the precision and efficiency of architectural design. However, with the rise of generative design and multi-objective optimization, algorithms have evolved from being just tools to becoming active participants in the creative process. Through a historical overview and an analysis of tools, the paper explores how algorithms influence form, functionality and energy efficiency while architects retain creative control. The conclusion highlights a hybrid model as the most effective approach in modern architectural design, where the algorithm processes data and optimizes solutions, while the architect sets the creative framework and makes final decisions.

Key words: *Architect, Algorithm, Generative Design, Optimization, Design Process*

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1. INTRODUCTION

Architectural design has historically been shaped by the evolution of tools that allowed architects to express space in accordance with technological capabilities and social conditions. From hand-drawn sketches and physical models to CAD software, parametric systems, and BIM environments, each technological shift not only improved workflow but also influenced how architects think about space, form, and the role of design itself.

In contemporary practice, digital tools are no longer used solely for documentation or visualization, they now enable the generation, simulation, and real-time evaluation of design decisions. Generative design and multi-objective optimization have introduced new methodological approaches [1], while the growing integration of artificial intelligence (AI) raises additional questions, not only technical, but also theoretical, methodological, and ethical. It can be argued that architectural practice is undergoing a paradigm shift in which algorithmic systems are no longer passive support mechanisms but active participants in the design process.

According to Branko Kolarević [2], architectural practice has shifted from traditional drawing to form generation through digital processes, while Mario Carpo [3] considers digital tools to be instruments of thought in contemporary design. Robert Woodbury [4] and Wassim Jabi [5] emphasize the importance of the parametric approach in redefining the relationship between form and algorithmic logic. In this context, the increasing presence of AI technologies introduces not only new tools but also a new epistemology in which design can adapt, learn, and evaluate itself based on input data.

This paper explores how digital tools from early CAD systems to contemporary AI models have influenced the redefinition of the architect's role in the design process. Particular emphasis is placed on the current phase of development, in which the architect no longer acts as an isolated author, but rather as a participant in an interactive relationship with algorithmic structures. The methodology is based on a historical-analytical approach and a comparative evaluation, with the aim of assessing their impact on creative autonomy, workflow, and decision-making within the contemporary architectural context.

2. THE EVOLUTION OF ARCHITECTURAL TOOLS AND THE TRANSFORMATION OF PROFESSIONAL PRACTICE

This study applies a historical-analytical method with the aim of examining the evolution of computerization within the architectural profession. The periodization is based on the framework proposed by Michael Fox and Bradley Bell [6], as it provides a clearer insight into the developmental phases of digital tools and their impact on the changing role of the architect.

The analysis is structured across the following chronological phases:

- Prologue (…1972);
- Pioneering (1973-1981);
- Translation (1982-1991);
- Appropriation (1992-2003);
- Experimentation (2004-2012);
- Legitimacy (2013-2018) and
- Paradigms (2019-2024).

Each of these phases reflects specific changes in both software and hardware tools, as well as shifts in how architectural practice is conceptualized. The focus of the research is on the transformation of the architect's role in relation to technology, with particular attention given to the emergence of new methodological approaches in design.

2.1. Prologue (…1972)

This period was marked by a gradual transformation of both architectural tools and the role of the architect. Prior to the advent of computers, architectural documentation was produced manually through sketches and perspective drawings initially using stone and graphite, and later rapidographs, rulers, and drafting tables.

The historical roots of the profession trace back to ancient Egypt, with Imhotep (c. 2650 BCE) representing the archetype of the architect as a universal intellectual figure. In ancient Rome, Vitruvius laid the theoretical foundation for architectural practice, while during the Middle Ages, the architect appeared as a "master mason", simultaneously responsible for design and construction. The Renaissance redefined this role through Alberti and Brunelleschi, positioning the architect as an intellectual and author of design intent. The invention of the printing press facilitated the standardization of architectural drawings, while the 19th-century cyanotype process introduced mechanical reproduction and early automation [6].

In the second half of the 20th century, the development of electronic computers launched a new technological era. The 1957 experimental system PRONTO marked one of the first attempts at digital design. In 1967, the founding of the Architecture Machine Group at MIT by Nicholas Negroponte and Leon Groisser fostered research in interactive and adaptive design. Ivan Sutherland's Sketchpad (1963) became the first graphical software enabling parametric manipulation of geometry and introduced a novel form of on-screen visual representation, allowing real-time interaction between the designer and digital drawing [7]. Douglas Engelbart, in the same period, introduced the computer mouse and hypertext-based interaction. In 1971, Luigi Moretti coined the term "parametric architecture", linking design decisions with mathematical modeling [8]. Minsky and Chomsky's early work in AI and linguistics paved the way for algorithmic design theories, later formalized by Gips and Stiny through the introduction of shape grammars.

Representative architectural projects include:

- The TWA Flight Center, New York City, Eero Saarinen and Associates and
- Olympic Stadium, Munich, Frei Otto and Günther Behnisch.

This period established key theoretical and technological foundations for digital architecture, envisioning the computer not as a replacement, but as an intelligent partner in the design process.

2.2 Pioneering (1973-1981)

This period marks the transition of digital design from experimental laboratories into broader academic and educational practice. Computers became more accessible, and the first software and hardware tools specifically tailored to architectural needs were developed.

The Architecture Machine Group at MIT developed the software URBAN5, which enabled two-way communication between the user and the computer via a linguistic interface. This concept anticipated contemporary ideas of generative design, intelligent

systems, and interactive environments. One of its creators, Nicholas Negroponte, in his visionary reflections, suggested that professional intermediaries in the design process would become obsolete foreshadowing the emergence of artificial intelligence [9]. In contrast, Nigel Cross initiated important discussions on the relationship between humans and machines in design, emphasizing the importance of understanding the cognitive aspects of creativity [10].

At the same time, William J. Mitchell, in his book Computer-Aided Architectural Design, established a theoretical framework for analyzing the relationship between computing technologies and architectural practice [11]. During the same period, George Stiny and James Gips developed the concept of shape grammars, a rule-based system for form generation that would become the foundation for parametric and algorithmic design [12]. Their work was later expanded by Dennis Sheldon and Larry Sass, who introduced these principles into practical software applications.

Don Greenberg of Cornell University introduced the concept of computer visualization, developing some of the earliest digital tools for architectural representation. Simultaneously, Dean Hankes and Richard Stibbs developed software systems for analyzing building energy performance, signaling the future development of BIM (Building Information Modeling) environments, while Charles Eastman laid their theoretical foundations by integrating design and technical data into a unified digital model.

Representative architectural projects include:

- Sainsbury Centre for Visual Arts, Norwich, Foster + Partners and
- Centre Pompidou, Paris, Renzo Piano and Richard Rogers.

This period shaped the foundational concepts of digital design and laid the groundwork for the broader integration of computers into the architectural profession.

2.3. Translation (1982-1991)

This phase marks the shift of digital design from experimental labs to everyday architectural and educational practice. Personal computers became more accessible, while CAD tools moved into offices and schools.

Companies such as Autodesk (AutoCAD) and Graphisoft (ARCHICAD) took leading roles. AutoCAD 1.0 (1982) became an industry standard for digital drafting, while ARCHICAD (1987) introduced the concept of Building Information Modeling (BIM), enabling the integration of graphical and numerical project data. At the same time, tools such as Vectorworks (formerly MiniCAD), FormZ, and 3ds Max (formerly 3D Studio, 1990) emerged, offering advanced 3D modeling, visualization, and animation capabilities.

During this period, the development of digital tools followed two distinct trajectories: one focused on improving existing architectural workflows through efficiency and standardization (e.g. AutoCAD, CADAM), and the other on redefining design approaches through integrated modeling and multidimensional thinking (e.g. ARCHICAD, SONATA, Reflex).

Artistic and research projects such as The Legible City by Jeffrey Shaw and the VPL Research DataSuit illustrate how digital methods, including early forms of AR and VR, were expanding into new areas of creative exploration [13]. At the same time, CAD was formally introduced into academic curricula in the late 1980s, making digital skills an essential part of architectural education.

The Translation phase marks a turning point when CAD tools shifted from technical aids to creative design partners, as computers became instruments for generating, testing, and optimizing architectural ideas.

2.4. Appropriation (1992-2003)

During this period, digital technologies moved from specialized tools to integral components of architectural practice. Architects actively adapted them, often drawing solutions from fields such as aerospace, animation, and industrial design, which encouraged experimentation and a critical rethinking of professional norms.

A notable example from this period is the fish sculpture designed for the 1992 Barcelona Olympics by Gehry Partners, developed using Digital Project [14], an architectural adaptation of the CATIA system. This software enabled parametric control and optimization of complex forms based on structural and material constraints, establishing a foundation for the integration of BIM principles and algorithmically generated architecture.

During the same period, tools such as Rhino, SketchUp, Revit, Blender, and Maya were increasingly adopted by firms like Zaha Hadid Architects and MAD Architects. Notably, the development of Grasshopper, a visual scripting plugin for Rhino, introduced algorithmic thinking and scripting logic into everyday design workflows. The first built example of a parametric design approach was the Waterloo International Terminal in London (1993), developed using MicroStation.

Theoretical discourse during this period further deepened. Bernard Tschumi questioned the relationship between digital tools and architectural theory, while Greg Lynn developed the concept of folding. Through agent-based modeling and swarm behavior, CAAD pioneer Paul Coates defined architecture as a DNA-like system, where simple rules can generate complex forms [15]. In parallel, the concept of “cybertecture” emerged, integrating interactivity, adaptability, and system intelligence. John Frazer defined architecture as a living system capable of learning and evolution [16]. Branko Kolarević identified a new generation of architects who use digital tools not only for form-making but also to integrate design and construction, a process that, according to him, had not been seen since the era of Gothic cathedrals [2].

Institutional support for digital architecture strengthened during this period. Networks such as ACADIA, eCAADe, CAAD Futures, and SIGraDi were established and became actively engaged, along with the creation of the CUMINCAD database. In 2003, the first issue of the International Journal of Architectural Computing (IJAC) was published.

The phase of appropriation thus marked not only technological advancement but also a profound cultural and epistemological transformation of architectural practice.

2.5. Experimentation (2004-2012)

During this period, the concept of parametric design gains clear theoretical and methodological articulation, establishing itself as a specific form of computer-aided design. Although its foundations had been laid earlier, only now does it acquire a defined status within architectural theory and practice.

Key figures of this phase, Mark Burry, and Patrik Schumacher, develop different approaches and interpretations. Mark Burry is particularly known for implementing CAD technologies in the construction of complex structures, such as the Sagrada Familia, significantly enhancing precision and efficiency. Patrik Schumacher introduces the term “parametricism” as a theoretical and aesthetic framework of the 21st century, based on variability, connectivity, and formal adaptability [17].

At the same time, algorithmic approaches are gaining momentum. The publication Programming Architecture by Paul Coates offers an introduction to the use of programming languages for form generation. In his book Elements of Parametric Design, Robert Woodbury develops a methodology grounded in operations and systems logic, bridging architecture and computer science [4]. Wassim Jabi and Kostas Terzidis expand this discourse with generative techniques such as evolutionary strategies, cellular automata, swarm intelligence, and shape grammars, introducing algorithmic processes into design [5].

This period also marks the rise of digital fabrication and visual scripting. Although programming languages had been present earlier, visual coding within modeling environments now becomes a key design tool. John Maeda laid the groundwork as early as 1996, while Marc Fornes promoted visual scripting as a core method of parametric modeling. Designers increasingly recognize the agency of tools: the design system is no longer neutral but consists of interconnected elements, i.e. designer, code, user, robotic systems, and context. Design becomes a process of interaction, participation, and algorithmic adaptation. This approach culminates in tools such as Rhino and Grasshopper, which enable visual linking of geometric parameters and algorithms. The integration of Python and C# scripting opens up space for the development of custom design methodologies.

Simultaneously, technological transfer from other industries continues to shape architecture. Building automation, remote control, and spatial personalization become everyday realities, driven by advances in sensor technology and computational power. By the end of this decade, digital tools become an integral part of everyday practice in most globally relevant architecture firms.

Representative architectural projects include:

- Beijing National Stadium, Herzog & de Meuron and
- Heydar Aliyev Center, Baku, Zaha Hadid Architects.

The transformation phase is characterized by an intense drive toward research, coding, and experimentation, where design and technology converge into an integrated and coherent architectural practice.

2.6. Legitimacy (2013-2018)

This period marks the transition of digital practice from an experimental to a validated phase, characterized by localized and applied research directions. Digital tools become standard in architectural practice, used not only for form generation but also for analysis, simulation, and decision-making.

Mario Carpo emphasizes that digital tools in this period became instruments of thought rather than mere production means. He notes that contemporary architectural practice relies on searching, simulation, and data analysis, enabled by widespread access to information and digital resources [3]. Symbolically, the founding of OpenAI in 2015 signals a new direction in which algorithmic intelligence enters the creative industries, including architecture. In his book Parametric Design for Architecture [4], Wassim Jabi provides practical examples and scripts, highlighting the shift in design thinking toward algorithmic and systemic logic, while Patrik Schumacher continues to advocate for “parametricism” as an architectural approach in his extension of The Autopoiesis of Architecture.

The focus shifts toward biologically inspired and ecologically oriented approaches. The development of biomimetics opens new avenues of research based on insights from robotics and material science. Michael Hensel, Achim Menges, and Michael Weinstock view nature

as a sophisticated engineer whose principles should be transferred into architecture through adaptive and evolutionary systems. In this context, Gordon Pask, in the introduction to An Evolutionary Architecture, states that the architect is no longer the designer of a predetermined form, but rather a catalyst for evolutionary processes in which buildings evolve like organisms [18]. This logic leads to digital morphogenesis, inspired by dynamic, nonlinear, and non-repetitive patterns found in nature.

In practice, BIM technology is increasingly used as a real-time parametric system, while AR and VR tools enable immediate spatial evaluation and user experience testing.

Representative architectural projects include:

- Morpheus Hotel, Cotai, Zaha Hadid Architects and
- Louvre, Abu Dhabi, Jean Nouvel.

The phase of legitimacy represents mature and systematic use of digital tools as a standard part of architectural practice, accompanied by growing collaboration between academic institutions and the professional sector.

2.7. Paradigms (2019-)

This period marks a turning point in architectural practice, shaped by global challenges such as climate change, health crises, and social inequality. Instead of being limited to form generation, digital tools are now applied to broader challenges including ecological concerns, healthcare, poverty reduction, and urban development.

A key shift in this phase is the integration of artificial intelligence into the design process. Tools based on deep learning models, such as ChatGPT, DALL·E, and Midjourney, have evolved from visualization aids into active design collaborators. Mario Carpo refers to them as “thinking machines,” while theorists like Matias del Campo, Patrik Schumacher, and Neil Leach [17] define AI as a new aesthetic and theoretical paradigm in architecture.

Figure 1. Fast and realistic massing visualization using AI models trained on Zaha Hadid Architects-specific datasets [19]

In practice, offices such as Foster + Partners and Zaha Hadid Architects [19], [20] (Figure 1) leverage AI to analyze user spatial behavior, encode spatial semiotics, and incorporate synthetic datasets into early design stages. Simultaneously, platforms like Veras, Firefly, and Midjourney assist not only in generating photorealistic visuals and stylistic variants but also in optimizing spatial configurations.

Models such as GPT and GAN further transform the architect’s role. While GPT systems (e.g., ChatGPT) offer cognitive assistance in ideation and decision-making, GAN models raise questions of authorship and aesthetic control. This marks a shift from formal authorship to process-based collaboration, i.e. a transformation explored by authors like Philip Bernstein and research collectives such as the Neural Network Group.

Another defining element of this period is the widespread use of digital twins—virtual replicas of buildings that simulate and respond to real-time data. When integrated with BIM technologies, they enable comprehensive performance monitoring, from energy efficiency and structural behavior to user experience. Platforms such as ARCHITEChTURES, Hypar, and Digital Blue Foam support this data-driven approach by generating and evaluating design scenarios interactively.

The paradigm is thus shifting from the architect as a sole creator to a collaborative curator, working alongside intelligent systems. The central question is no longer what AI will become, but rather how architecture can actively shape its evolution.

3. RESULTS

To examine the evolution of the architect–algorithm relationship, this study analyzes chronological phases across five parameters: dominant tools, defining characteristics, key software, the evolving role of the architect and representative projects (Table 1).

Table 1. The evolution of architectural design process through digital tools

Prologue (... 1972)	
Dominant tools	Manual tools: stone, graphite, rapidographs, drafting tables
Defining characteristics	Gradual shift from manual to early digital tools; theoretical and conceptual foundations of digital architecture
Key software	PRONTO, Sketchpad
The evolving role of the architect	From master builder to intellectual author; emergence of computer as intelligent partner in design
Projects	The TWA Flight Center, Olympic Stadium, The Fun Palace
Pioneering (1973–1981)	
Dominant tools	Experimental digital systems, light pens, early CAD tools
Defining characteristics	Rise of experimental digital tools and interactive environments; emergence of parametric thinking and algorithmic logic
Key software	URBAN5, early visualization tools
The evolving role of the architect	Experimental collaborator; architect begins shaping the interface between human and machine
Projects	Sainsbury Centre for Visual Arts, Centre Pompidou
Translation (1982-1991)	
Dominant tools	CAD software, early 3D modeling, AR/VR
Defining characteristics	CAD adoption, BIM emergence, 3D modeling integration, digital tools in education
Key software	AutoCAD, ARCHICAD, Vectorworks, FormZ, 3D Studio
The evolving role of the architect	From draftsman to design partner; focus on simulation and coordination
Projects	The Legible City, The VPL Research DataSuit
Appropriation (1992-2003)	
Dominant tools	Parametric design tools, scripting, digital fabrication
Defining characteristics	Digital tools integrated into design and construction; experimentation; rise of scripting and fabrication logic
Key software	Rhino, Grasshopper, CATIA/Digital Project, Maya, Processing
The evolving role of the architect	Author-coder; from form-maker to system thinker
Projects	Fish, International Terminal Waterloo, Water Pavilion

Experimentation (2004-2012)	
Dominant tools	Parametric modeling, visual scripting, digital fabrication
Defining characteristics	Theorization and expansion of parametricism; rise of interactive design, custom scripting, and fabrication systems
Key software	Rhino +Grasshopper, Processing, Arduino, Revit, Maya, Python/C# plugins
The evolving role of the architect	System designer and experimenter; interactive participant
Projects	BMW Welt, Beijing National Stadium, Heydar Aliyev Center
Legitimacy (2013-2018)	
Dominant tools	Standardized parametric tools, BIM, environmental simulation
Defining characteristics	Digital tools become validated and institutionalized; integration of design and construction; data-driven design
Key software	Revit, Grasshopper, Ladybug, Dynamo, BIM 360, Unity
The evolving role of the architect	Strategic integrator and collaborator
Projects	Morpheus Hotel, Harbin Opera House, Louvre Abu
Paradigms (2019-)	
Dominant tools	Generative AI, digital twins, real-time simulation, AR/VR
Defining characteristics	AI as design partner; shift to performative and data-driven architecture; cognitive collaboration with algorithms
Key software	ChatGPT, Midjourney, Stable Diffusion, ARCHITEChTURES, Hypar, Digital Blue Foam, Veras
The evolving role of the architect	Strategic guide of data and co-designer with AI
Projects	ZHA AI experiments, Foster + Partners ARD, Delve urban simulations, synthetic data set-driven designs

Architectural tools have evolved significantly, from primitive manual instruments such as stone and graphite, through technical drafting and CAAD systems, to contemporary scripting, parametric modeling, and AI-based platforms. They now influence not just the process, but also the architect's design logic and creative mindset.

In the early phases, the computer was perceived as a technical assistant, primarily used for precise drawing and visualization. The architect retained full control over the design process, while the computer's role was limited to reproduction and accuracy, without any substantial impact on design logic.

The Appropriation phase marks the first significant shift. The architect now becomes an author-coder, using digital tools not only for representation but also for generating form and experimenting with construction. This stage introduces a bidirectional interaction with software, where the design process increasingly depends on scripting and parametric rules.

Rather than a linear progression, we observe an increasingly deep integration of algorithms into the creative process, with the architect acting as a guide rather than a sole author. In the Experimentation phase, the architect's role shifts from formative to strategic. Instead of directly shaping the final outcome, the architect defines system behavior, sets goals, and analyzes solutions generated by the algorithm through iterative processes. Design becomes a negotiation between human intuition and computational evaluation.

The Legitimacy phase brings the institutionalization of algorithmic thinking. BIM systems, analytical platforms, and performance-driven tools introduce complex models into everyday

practice, expanding the architect's role from shaping to coordinating, evaluating, and integrating systemic decisions.

In the current Paradigms phase, a cognitive symbiosis emerges between human and machine. Artificial intelligence is no longer used merely as a tool, but as an active participant in decision-making. It generates, analyzes, optimizes, and proposes solutions, while the architect assumes responsibility for the ethical, cultural, and strategic framework within which the algorithm operates.

The synergy between architect and algorithm has thus evolved into a model of co-authorship, in which architectural form is no longer solely the product of human intent, but the negotiated outcome of a dynamic interplay between cognitive intuition and computational intelligence.

4. DISCUSSION

The synergy between the architect and the algorithm, originally analyzed through the historical periods defined by Michael Fox and Bradley Bell [6], creates an opportunity for a new classification. Instead of basing the timeline solely on technological progress, the proposed framework focuses on the level of interaction between human and algorithm. This approach allows for a more precise understanding of the evolving roles, authorship, and responsibility within digital design. The proposed classification is presented in Table 2.

Table 2. The phases of interaction between architect and algorithm in the design process

Phase	Architect–Algorithm Relationship
Technical Assistance	The architect leads the process/ the algorithm serves as a tool supporting traditional methods
Initiating the Dialogue	The architect sets the rules/ the algorithm responds – the dialogue begins to take shape
Coordinated Collaboration	Decisions emerge through mutual evaluation/ responsibility and control are shared
Creative Partnership	The architect and the algorithm generate solutions together as equal partners in synergy

In contemporary practice, the emphasis is increasingly shifting from the final form to the design process itself, prompting a renewed consideration of authorship, control, and responsibility in workflows supported by algorithmic methods.

A central question arises: how can architectural authenticity be preserved in the context of automation? While algorithmic approaches offer numerous advantages, they simultaneously present significant challenges. Branko Kolarević [2] notes that relying on automated processes may result in forms stripped of authentic expression, neglecting both local and cultural context. Earlier generations of digital tools such as ArchiCAD, SketchUp, or 3ds Max also demonstrated that poor mastery of a tool can limit creativity. In such cases, the software may shape the final form more than the architect's intent, turning the tool into an invisible co-author. These limitations echo the contemporary issues associated with AI, suggesting a continuity in the challenge of preserving authorship and intentionality across technological shifts. Recognizing this continuity helps reinforce the relevance of hybrid models, which aim to balance tool-driven efficiency with the designer's creative control—both in earlier tools and current AI systems.

Furthermore, the growing influence of algorithms on design decisions raises critical ethical and practical questions: who is the actual author of a solution generated by a system, and where does responsibility lie in this new model of shared authorship? These concerns are reflected in current debates on the ethics of AI in architecture [21], where the line between technical assistant and co-author is increasingly blurred, challenging traditional roles.

In response to these challenges, hybrid models of design have gained traction. These models combine algorithmic optimization with the architect's critical, intuitive, and creative judgment. While this paper does not empirically prove the superiority of such models, it proposes them as a compelling direction for further research. In this context, Mustapha El Moussaoui [22] emphasizes that artificial intelligence should not replace architects, but relieve them of repetitive tasks, enabling greater focus on cultural and conceptual dimensions of design.

Ultimately, the key question is no longer whether artificial intelligence will shape architecture, but how architecture will shape the development of artificial intelligence. As Mario Carpo [3] asserts, power lies in shaping the algorithm itself. The architect's ability to design the tools they use, rather than accept them passively, not only preserves creative agency but also defines the ethical boundaries of emerging design paradigms.

5. CONCLUSION

This paper examined the evolving relationship between architect and algorithm through historical phases and proposed a classification based on the degree of their interaction. Rather than framing digital architecture solely through technological progress, the proposed framework emphasizes issues of authorship, control, and responsibility.

The typology enables a better understanding of the shifting role of the architect from traditional author to active co-participant in increasingly algorithmic design processes. The discussion addressed both the benefits and challenges of algorithmic methods and placed them within a broader historical context. Parallels between earlier design tools and AI-driven systems reveal a continuing need to balance computational capability with creative autonomy. This continuity is visible not only in AI-based platforms but also in earlier tools such as ArchiCAD or SketchUp, where limited mastery could constrain creativity and unintentionally shift authorship toward the software. Such examples strengthen the case for hybrid models that combine architectural intent with computational power.

In light of these insights, the hybrid design model is proposed not as a final conclusion, but as a hypothesis for further investigation. The future relevance of architecture may depend on the profession's capacity to shape, rather than merely adopt, the digital tools that now co-author the built environment.

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Research paper

COMPARISON OF EVAPOTRANSPIRATION METHODS IN NOVI SAD FROM 1980 TO 2015

Rastislav Trajković[1], Marija Milićević[2]

Abstract

Evapotranspiration (ET) is a key process in hydrology, agriculture, and managing water resources. It affects numerous processes, including irrigation planning and climate research. In this study, the temperature-based variation of Penman-Monteith (PMt) and the Hargreaves (HARG) equation were compared to the standard Penman-Monteith (PM) method for estimating ET. The data used for the calculation of evapotranspiration was collected from the meteorological station in Novi Sad during the time period from 1980 to 2015. ET results were statistically analyzed using Pearson's correlation coefficient (r), the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), index of agreement (d), root mean square error (RMSE), mean absolute error (MAE), relative squared residual (RSR), relative error (RE), and percent bias (PBIAS). Findings in this study showed r=0.99, r=0.99 for PMt and HARG, respectively. For PMt RMSE equaled 0.24, and for HARG RMSE=0.41. Moreover, findings showed MAE=0.17 for PMt and MAE=0.32 for HARG. A high r value and low RMSE and MAE values indicate that PMt is more reliable than HARG method. The temperature-based Penman-Monteith (PMt) method has proven to be a more accurate and reliable alternative to the reference method in data-limited conditions, while the Hargreaves method can be used with caution due to its slightly lower accuracy.

Keywords: *Evapotranspiration, Penman-Monteith, temperature-based Penman-Monteith, Hargreaves, statistical evaluation.*

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1. INTRODUCTION

Evapotranspiration (ET) is a prominent hydrological process that represents the basis for calculations in hydrology and water resource management, particularly in the context of agricultural water use and irrigation planning. This includes evaporation from soil and transpiration from plant canopies. Estimating ET is central to sustainable water resource management, especially where water availability is limited or varies seasonally [1]. To estimate ET, several models have been developed ranging in complexity and data requirements. These contain physical based methods, empirical models and hybrid approaches.

Three reference evapotranspiration (ET_0) estimation methods were analyzed in this study: the standard FAO-56 Penman–Monteith (PM), its temperature-based variant (PMt), and the empirical Hargreaves (HARG) method. The PM method is widely accepted as a physically based standard requiring comprehensive meteorological input, including solar radiation, air temperature, humidity, and wind speed [1]. In contrast, the PMt approach excludes wind speed and simplifies radiation estimation, allowing application in data-scarce environments while maintaining acceptable accuracy under various climatic conditions demonstrated in comparative evaluations of temperature-based ET methods [2]. The HARG method relies solely on air temperature and extraterrestrial radiation, offering a computationally simple alternative that is particularly useful in regions lacking detailed weather records [3].

The Penman–Monteith (PM) method was adopted as the reference model for estimating reference evapotranspiration (ET_0), due to its physical robustness and reliance on a full set of meteorological parameters [1]. The temperature-based variant of the Penman–Monteith method (PMt) and the empirical Hargreaves method (HARG) were evaluated by comparing their results against the reference values. The following statistical indicators were used to assess model performance: Pearson correlation coefficient (r), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE), mean absolute error (MAE), standard deviation (s), index of agreement (d), relative square residual (RSR), relative error (RE), and percent bias (PBIAS) [2, 4]. These metrics enable a comprehensive evaluation of the agreement between estimated and reference values under given climatic conditions and represent standard criteria for performance assessment in hydrometeorological modeling.

2. METHODOLOGY

In this analysis, three commonly used methods for estimating the reference evapotranspiration (ET_0) were used and compared: the FAO-56 Penman-Monteith (PM) [1], the simplified temperature-based version of it (PMt), and the empirical Hargreaves (HARG) [2] approach. These methods were selected based on their distinct data requirements and appropriateness across different climates and levels of data availability. The PM approach is, traditionally, the standard reference model as it is the most physically rigorous and makes use of more comprehensive meteorological variables. The equation, as provided by FAO-56, can be expressed as follows:

$$\mathrm{ET}_0 = \frac{0.408\Delta(\mathrm{R_n}-\mathrm{G}) + \gamma\frac{900}{(\mathrm{T}+273)}\mathrm{u}_2(\mathrm{e_s}-\mathrm{e_a})}{\Delta + \gamma(1+0.34\mathrm{u}_2)} \quad (1)$$

where R_n represents 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}], and γ psychrometric constant [kPa °C^{-1}].

This model requires solar radiation, air temperature, relative humidity, and wind speed, and is suitable for regions where comprehensive meteorological data is available.

The temperature-based Penman–Monteith (PMt) equation is a simplified version of the classical Penman–Monteith (PM) equation without wind speed and using net radiation calculated in an approximate or estimated way [4]:

$$\mathrm{ET_0} = \frac{0.408\Delta \mathrm{R_n} + \gamma \frac{900}{(\mathrm{T}+273)}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma} \tag{2}$$

It is specifically established for regions without a lot of data, demonstrating adequate accuracy when some of the meteorological elements are either missing or not reliable, due to the fact that it is being derived on "missing" or "incomplete" data.

The Hargreaves (HARG) equation is an empirical equation based only on temperature and extraterrestrial radiation and is expressed as:

$$ET_0 = 0.0023 * (\mathrm{T_{mean}} + 17.8)(\mathrm{T_{max}} - \mathrm{T_{min}})^{0.5} * \mathrm{R_a} \tag{3}$$

HARG is being used more widely because there can be minimal data to work with and the simplicity associated with the use of an average temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}). R_a represents extraterrestrial radiation [MJ m^{-2} day^{-1}].

All three methods were applied to the same long-term dataset (1980–2015) for the Novi Sad region, and compared to establish the accuracy and applicability of the simplified (PMt and HARG) to the Penman-Monteith (PM) in the context of continental climate.

To evaluate the performance of the temperature-based Penman–Monteith (PMt) and Hargreaves (HARG) methods in comparison to the reference Penman–Monteith (PM) model, a set of statistical indicators was applied to numerically assess the agreement between simulated and reference evapotranspiration (ET_0) values [3]. The following metrics were used:

- Pearson correlation coefficient (r):

$$\mathrm{r} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i}-\overline{\mathrm{O}})(\mathrm{P_i}-\overline{\mathrm{P}})}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i}-\overline{\mathrm{O}})^2}\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i}-\overline{\mathrm{P}})^2}} \tag{1}$$

The Pearson correlation coefficient (r) quantifies the strength and direction of a linear relationship between observed and simulated values [3]. The coefficient ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation). Pearson coefficients near zero indicate no linear correlation.

- Coefficient of determination (R^2):

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2} \cdot \sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \right)^2 \quad (2)$$

The coefficient of determination (R^2) represents the proportion of the variance in the observed data explained by the model [3, 4, 5]. It is the square of the Pearson coefficient and ranges from 0 to 1, where higher values indicate a better fit.

- Nash-Sutcliffe efficiency (NSE):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (3)$$

Nash-Sutcliffe efficiency (NSE) indicates how good model predictions are in comparison to the observed data, when comparing the predictions to using the mean of the observed values [3] [5]. A perfect prediction would have an NSE of 1, while any less than zero implies that the model prediction is worse than predicting the mean observed value.

- Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \quad (4)$$

RMSE gives the average magnitude of the observed and simulated values, and is presented in the same unit as the variable [3, 4, 5]. Smaller RMSE values indicate a better fitting model.

- Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \quad (5)$$

MAE represents the average of the absolute differences between observed and predicted values [3, 5]. Unlike RMSE, MAE treats all errors equally, without emphasizing larger deviations.

- Standard deviation of model predictions (s):

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(P_i - \bar{P})^2} \quad (6)$$

The standard deviation of model predictions (s) quantifies the variation, or how dispersed the simulated values are in relation to their mean [3, 5, 6]. It is useful to see if the model overestimates or underestimates the variation of the data.

- Index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (7)$$

The index of agreement (d) quantifies how well the predicted values fit with the observed data regarding both magnitude and trend [3]. Values approaching one imply very decent agreement, while values approaching zero imply weak or no agreement.

- Relative square residual (RSR):

$$RSR = \frac{RMSE}{s_O} \tag{8}$$

The RSR is the normalized RMSE, computed by dividing the RMSE by the standard deviation of the data [3]. Small RSR values indicate good performance of the model.

- Relative Error (RE):

$$RE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{O_i - P_i}{O_i}\right| \cdot 100\% \tag{9}$$

Quantifies the average observed and simulated value as a fraction of the observed values [3]. RE is helpful in comparing models when observed values span fairly large ranges of magnitudes.

- Percent Bias (PBIAS):

$$PBIAS = 100 \cdot \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \tag{10}$$

PBIAS shows the average tendency of the model to either overestimate or underestimate the observed values (keeping track of the PBIAS's sign) [3]. Positive values indicate a tendency to underestimate while negative values indicate a tendency to overestimate.

These statistics enable a multidimensional evaluation and comparison of models in terms of accuracy, variability, and systematic deviations, providing a reliable analysis of the applicability of individual methods under conditions of limited meteorological data.

3. RESULTS AND DISCUSSION

The analysis was conducted in the study area of Novi Sad, which is situated in northern Serbia and features a continental climate with a significant seasonal variability, including hot summers and cold winters. Average annual maximum and minimum air temperatures during 1980–2015 were 16.5°C and 6.4°C, while relative humidity varied between 60% and 85%. The monthly mean precipitation ranged between 30 and 85 mm, with an average wind speed of about 1.9 m/s, these extreme climates are among the reasons that accurate estimation of reference evapotranspiration is essential for agricultural development and drought management in the local environment [5].

Statistical assessment of the simplified reference ET_0 methods — the temperature-based variation of Penman–Monteith (PMt) and the Hargreaves (HARG) method —was accomplished by comparing their monthly ET_0 values against the FAO-56 Penman–Monteith reference ET_0 method over a 36-year period. The evaluation consisted of ten performance measures: Pearson correlation coefficient (r), coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), index of agreement (d), root mean square error (RMSE), mean absolute error (MAE), relative square residual (RSR), relative error (RE), percent bias (PBIAS), and standard deviation (Table 1).

Table 1. Statistical evaluation of PMt and HARG methods compared to PM reference.

Metric	PMt	HARG
r	0.995	0.989
R^2	0.99	0.978
NSE	0.982	0.927
d	0.995	0.982
RMSE	0.24	0.41
MAE	0.17	0.32
RSR	0.15	0.26
RE (%)	2.34	3.45
PBIAS	-0.86	-1.72
Standard Deviation	0.29	0.35

Both PMt and HARG showed linear correlation with the reference method ($r > 0.989$) which demonstrates the methods are capable of tracking seasonal trends. However, PMt was superior to HARG across all error type metrics. For example, PMt had a lower RMSE (0.24 vs. 0.41), MAE (0.17 vs. 0.32) and RSR (0.15 vs. 0.26) and had a better NSE (0.98 vs. 0.93). Both PMt and HARG had PBIAS near zero suggesting both methods are unbiased; however, PMt had slightly better agreement.

It was concluded that both methods could be used in climatological ET_0 estimation, but the PMt model would be considerably closer to the reference, especially when availability of radiation data is limited. While the HARG method is pragmatic under data-scarcity, it demonstrates increased uncertainty, especially during periods of extreme temperature or solar input. Thus, when wind or humidity data are not available, a PMt could be a more reliable alternative to PM in continental climates such as Novi Sad.

4. CONCLUSION

The results of this study indicated that the temperature-based Penman–Monteith (PMt) and Hargreaves (HARG) methods are valid alternatives to the standard FAO-56 Penman–Monteith (PM) model to estimate reference evapotranspiration (ET_0) in regions with limited meteorological data, but that PMt outperformed HARG in all statistical indicators and was in higher agreement with PM and had lower errors than HARG. Despite the aforementioned, PMt is a more valid substitute to the reference model in continental climates such as Novi Sad, on a physical basis and on the basis that PMt only uses the variables of precipitation and temperature, but when wind and humidity data are not available. HARG is a simpler method, but it did have a slightly lower accuracy and should be used with care under extreme climatic conditions. Overall, the findings of this study endorse simplified methods to be used in support of hydrological planning and agricultural water management, in data-scarce regions.

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Research paper

HEATING A RESIDENTIAL BUILDING USING THERMALLY ACTIVATED BUILDING SYSTEMS (TABS) AND PARTIAL EARTH-BURIAL: A CASE STUDY

Jelena Jović[1], Dušan Ranđelović[2], Vladan Jovanović[3], Jelena Stevanović[4]

Abstract

The most significant amount of electrical energy is obtained by burning fossil fuels, which release substantial amounts of harmful gases, that contribute to environmental degradation. Because the most crucial part of the energy produced is used during the construction and operation of buildings, it is necessary to build buildings that can provide the energy needed for heating and cooling through renewable energy sources. Geothermal energy is the clean energy source with the most significant potential for solving this problem. However, the thermal capacity of energy forms and exploitation systems have not yet been sufficiently researched, significantly limiting their application. This paper presents two geothermal energy systems for heating buildings: the passive system, which is burying objects, and the active system, which is the thermally activated building system (TABS). The work aims to highlight the significance and potential of geothermal energy, which can achieve energy independence for the facility. Through a case study of a residential building, based on software simulations conducted in the EnergyPlus program, it has been determined that the total consumption of thermal energy needed for heating is 26,43 kWh/m2. The findings demonstrate that applying the passive and active geothermal strategies can achieve significant energy savings required for heating buildings, thereby mitigating environmental impact. The obtained results will allow for the assessment of the expected impacts of climate change on building energy performance and the adaptation of both passive and active strategies, such as TABS systems and geothermal regulation, to future conditions.

Key words: *Geothermal Energy, Thermally Activated Building Systems, Energy Efficiency, Building Performance Simulation*

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1. INTRODUCTION

In recent decades, most scientific research in architecture and civil engineering has focused on the problems of global warming, air pollution, and the depletion of fossil fuel reserves, as well as potential solutions to these issues. Many researchers emphasize the importance of renewable energy sources and propose various methods for their utilization to reduce energy consumption and, consequently, environmental pollution. Since the largest share of harmful gas emissions in the construction sector is caused by heating buildings through the combustion of fossil fuels, the main objective is to find an alternative energy source that can ensure thermal comfort without negatively impacting the environment. A review of the available literature [1, 2] indicates that, among all renewable energy sources, geothermal energy offers the most significant potential for a long-term solution to this problem. However, this form of energy remains the least explored and underutilized, both globally and in Serbia.

Numerous studies and existing examples worldwide highlight the significant potential of geothermal energy and the substantial energy savings that can be achieved through the implementation of appropriate systems. The most commonly used are active systems, which involve the use of geothermal heat pumps or the direct exploitation of hydrogeothermal energy. By applying these technologies, some countries have enabled the heating of entire cities, significantly reducing both energy consumption and harmful gas emissions, for example, in Reykjavik [3]. Passive use of geothermal energy – such as the burial of buildings into the ground – has also been thoroughly researched. This construction method utilizes the earth's thermal insulation properties, which reduce heat losses from indoor spaces [4, 5]. Given that geothermal systems still require a certain amount of energy to maintain indoor thermal comfort, engineers are developing new technologies and heating systems to reduce the heating demands of buildings further. A review of the literature [6] has shown that the innovative system of Thermally Activated Building Structures (TABS) can significantly reduce energy consumption. According to a study by J. Lind and F. Otterman [7], TABS offers better energy performance compared to traditional heating systems, which is why its application is becoming increasingly widespread worldwide.

This raises the question of the applicability of these systems for heating buildings during the winter season in Serbia. From this, the main objective of the research emerges – to highlight the importance of the underutilized potential of geothermal energy through the application of the TABS system and the construction of earth-burial buildings. The selected location for this study is Vranjska Banja, a settlement renowned for its geothermal springs, which have temperatures exceeding 80°C. The potentials of the TABS system and the passive use of geothermal energy were analyzed in the context of a single-family residential building. The building was modeled using Google SketchUp with the OpenStudio plug-in. To determine the energy savings provided by these systems, heating energy demand and total energy consumption were simulated for three different scenarios. The first scenario represents a standard building without any of the systems applied. The second includes a building equipped with the TABS system, while the third scenario involves a semi-buried building with an integrated TABS system. A comparison of the results, obtained using EnergyPlus software, showed that the most significant energy savings were achieved in the third case.

2. METHODOLOGY

2.1. Heating of buildings using the TABS system

The Thermally Activated Building System (TABS) is a system that utilizes the structural elements of a building to transfer and accumulate thermal energy. In these installations, indoor space heating is achieved by activating the building's thermal mass, which is done by embedding a thermally active barrier into the opaque part of the building envelope. This typically involves pipes carrying warm water embedded within the concrete structure. By integrating the pipes into the structural elements, the temperature difference between the heated indoor space and the structural element is reduced [6]. In this way, the TABS system significantly lowers the building's heat losses. As the temperature difference is reduced – by controlling the fluid temperature within the pipes – the system's heat losses also decrease. This means that heat loss through the building envelope becomes negligible if the water temperature in the TABS system is around 20°C, which corresponds to the standard indoor heating temperature during the winter season [8]. However, maintaining a constant indoor temperature and reducing energy consumption also depend on the type of materials used, as well as, the number and thickness of the layers within the structural elements [9]. Additionally, the thermal performance of a building equipped with a TABS system may be influenced by factors such as pipe positioning, the type of working fluid, and the system's operational method.

The pipes of a TABS system can be embedded in the wall, floor, or ceiling structures of a building. According to scientific studies [9,10], the most effective configurations for space heating are those with floor or wall heating, while ceiling heating provides the least energy savings. However, all of these structural elements provide large heat exchange surfaces, allowing for efficient space heating using low-temperature fluids (up to 30°C). Since lower operating temperatures typically characterize renewable energy sources, this system is ideal for their application.

Higher temperatures of the building's exterior structural elements, although they reduce heat losses from the heated interior toward the building envelope, result in twice as much heat loss to the external environment compared to a building without embedded pipes [8]. This outward radiation of energy from the TABS system can have a negative environmental impact if the thermal energy is produced by burning fossil fuels. However, this issue can be addressed by combining the TABS system with renewable energy sources, as clean energy significantly reduces both the building's energy demand and the emission of harmful gases.

2.2. The impact of building earth-burial on thermal energy savings

Energy savings for building heating, in addition to utilizing renewable energy sources through active systems, can also be achieved by maximizing the use of the site's natural conditions through proper building orientation. Good building orientation can maximize solar gains during the winter period, which positively contributes to reducing energy consumption. However, the most significant energy savings can be achieved by burying buildings into the terrain, which enables the use of the soil's favorable thermal properties. Since this construction approach requires a steeper slope, its potential application is significantly limited.

How does soil, through its thermal properties, enable energy savings required for heating buildings? At specific depths, the earth's temperature remains constant (10–15°C), regardless of the season or time of day [3]. Therefore, by burying a building into the ground, the temperature difference between the interior and exterior is reduced, resulting in decreased heat loss through the building envelope. In addition to providing thermal insulation, the soil also increases the thermal mass of the building's structural elements, thereby helping to maintain a stable indoor temperature. To achieve optimal indoor conditions (20–25°C) in such buildings, it is only necessary to supply additional heating to compensate for the temperature difference (5–15°C), which requires less energy compared to a freestanding building. The reduction of heat loss in earth-sheltered buildings largely depends on the degree of burial, orientation, and the number of exposed facades. According to studies [4, 5], the most significant energy savings are achieved in buildings with openings oriented toward the south and a fully buried north facade, which protects from cold northern winds. In contrast, the lowest energy efficiency is observed in buildings positioned on north-facing slopes, where the southern facade must be buried.

2.3. Model settings

The location selected for this research is in Vranjska Banja, Serbia. The site's most significant advantages are its steep south-facing slope (37%) and the presence of hot water springs (80°C). The conceptual building is positioned so that the northern facade is fully embedded into the terrain, while the lateral sides are partially buried. The southern facade is the only exposed side, allowing for natural ventilation and daylighting of the interior. The building is a single-story structure, with a floor area of 139.57 m² and a ceiling height of 2.60 m. For heating purposes, a TABS (Thermally Activated Building System) was implemented, utilizing the local hydrogeothermal energy as its energy source. TABS requires the installation of pipes within the opaque structural elements of the building. Since heated air rises from the lower to the upper parts of rooms, pipes are installed in the building's floor structure and exterior walls. The windows are double-glazed. The building envelope consists of:

- Green roof: finishing plaster (1.5 cm), reinforced concrete (RC) slab (20 cm), low-grade concrete (5 cm), vapor barrier, EPS insulation (25 cm), SikaPlan membrane, geotextile, barrier layer, drainage layer, filter layer, substrate (10 cm), vegetation
- Ground floor slab: gravel (10 cm), PVC foil, low-grade concrete (10 cm), waterproofing layer, reinforced concrete (RC) slab (40 cm), EPS insulation (10 cm), PVC foil, cement screed for underfloor heating (8 cm), hardwood flooring (2.2 cm)
- External wall 1: reinforced concrete wall (15 cm), waterproofing, EPS insulation (12 cm), cement screed for wall heating (5 cm), reinforced concrete wall (25 cm), finishing plaster (1.5 cm)
- External wall 2: reinforced concrete wall (15 cm), waterproofing, reinforced concrete wall (25 cm), finishing plaster (1.5 cm)
- External wall 3: finishing plaster (1.5 cm), EPS insulation (12 cm), cement screed for wall heating (5 cm), reinforced concrete wall (25 cm), finishing plaster (1.5 cm).

To determine the impact of building earth-embedding and the TABS system on energy savings required for space heating, simulations of the building's heating energy demand were conducted for three scenarios:

- First case – a standard free-standing building without any implemented systems
- Second case – a free-standing building equipped with a TABS system
- The third case – a semi-embedded building fitted with a TABS system.

The modeling of the building with integrated systems was carried out using Google SketchUp along with the OpenStudio plug-in. Simulations were performed in EnergyPlus software based on the following input parameters: indoor design temperature of 23°C, TABS system supply temperature of 45°C, outdoor temperatures were taken from the weather file for Vranje.

The data used in this study covers the period from 2009 to 2023 and represents the most recent available values. Since complete meteorological records for Vranjska Banja are not available, data from the city of Vranje – the closest relevant meteorological station located in the immediate vicinity of the study site – was used. The data were obtained from official meteorological sources and processed to generate a Typical Meteorological Year (TMY). This method uses several years of actual measured data to construct a representative year that accurately reflects average climatic conditions. This approach ensures a consistent and repeatable basis for conducting simulations in software tools such as EnergyPlus.

3. RESULTS AND DISCUSSION

Based on the conducted simulations, the building's energy consumption was determined on a monthly basis for the period from November to March for all three cases. The comparison of energy consumption for buildings with different heating systems is presented in Figure 1. The monthly consumption diagram shows that the application of the TABS system and geothermal energy (second case) results in twice lower energy consumption during the coldest months (December and January) compared to a building with a traditional heating system, while in the remaining months of the heating season, energy consumption is reduced by more than 50%. A comparison between the second and third cases reveals that embedding the building into the ground provides additional energy savings, although significantly lower than those achieved by the TABS system alone.

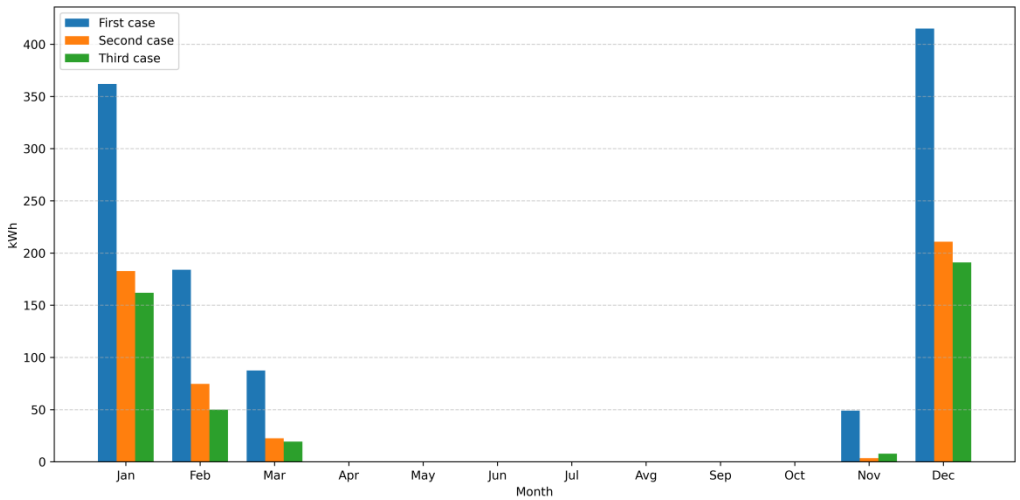

Figure 1. Graphic representation of monthly heating energy consumption, author

The obtained research results show that the highest energy demand was recorded for the building without any applied systems (first case), amounting to 1160.55 kWh. With the application of the TABS system (second case), energy consumption was reduced to 492.23 kWh. In the third case, which included both the TABS system and the earth-embedding approach, the lowest consumption was achieved at 429.97 kWh. Based on these findings, it can be concluded that the application of the TABS system allows for energy savings of 59%, while the combination of the TABS system and building burial reduces energy consumption by 67.5%.

Figure 2 presents a diagram of daily energy consumption during the heating season, illustrating how the application of the TABS system and the principle of earth-sheltering affect the energy required for heating buildings. The ground and the TABS system significantly reduce heat losses from the heated space to the external environment, helping to maintain a constant indoor temperature. By implementing these systems, the cooling of the interior is slowed down, which in turn reduces the need for heating and shortens the heating period. Based on the diagram, it can be concluded that the first case has the most extended heating period and the highest energy demand. The second and third cases are characterized by lower daily energy consumption and a reduced number of days requiring space heating. According to the diagram, in buildings equipped with the TABS system and partially earth-sheltered construction, heating is almost unnecessary during March and November, indicating that the heating period in these cases is significantly shorter.

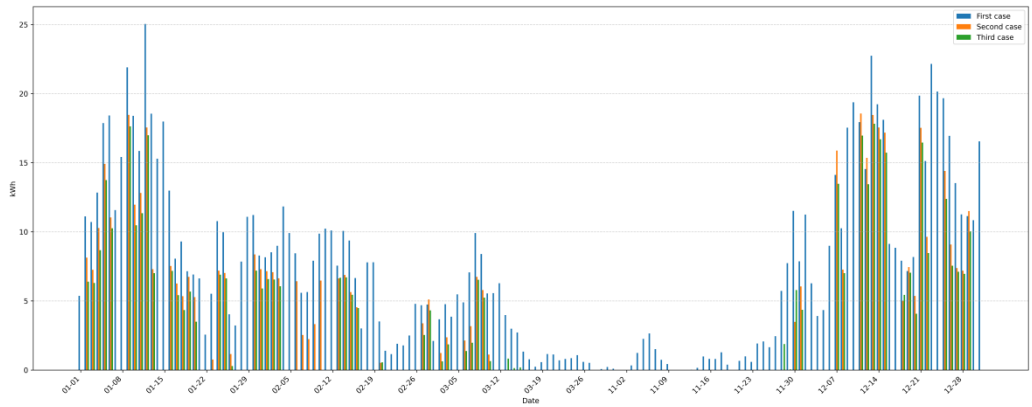

Figure 2. Graphic representation of daily heating energy consumption, author

The simulations conducted in this study were based on a TABS system operating at a heating fluid temperature of 45°C, resulting in a 59% reduction in energy consumption. Although it achieves significant energy savings, a TABS system with a temperature nearly twice that of the indoor air temperature causes greater heat radiation to the external environment compared to low-temperature TABS systems. Numerous scientific studies have shown that the temperature of the fluid in a TABS system has a substantial impact on reducing the energy required for space heating. For example, according to the research by B. Stojanović [8], a TABS system operating at a temperature half that of the indoor temperature achieves considerably lower energy savings than a system with a fluid temperature close to room temperature. He notes that energy consumption for heating can be reduced by up to 75% if a TABS system operating at 18°C is used to maintain an indoor temperature of 20°C. Based on this, it can be concluded that reducing the temperature difference between the TABS system and the heated space can significantly improve the

building's energy performance. Although the most significant savings are achieved through the application of the TABS system combined with geothermal energy, the principle of building burial also makes a substantial contribution to reducing energy consumption.

Further development of the research will focus on the study of predictive climate scenarios, including the generation of EPW files for future years (e.g., 2030, 2050) using data from the CMIP6 climate model. This will allow for the assessment of the expected impacts of climate change on building energy performance and the adaptation of both passive and active strategies, such as TABS systems and geothermal regulation, to future conditions.

4. CONCLUSION

Based on the obtained results and discussion, it can be concluded that the application of the TABS system, geothermal energy, and earth-sheltering of buildings leads to significant energy savings for space heating. Although the TABS system has a much greater impact on energy efficiency, the earth-sheltering principle can also considerably reduce energy consumption. By embedding the building into the terrain, the geothermal potential of sloped sites can be fully utilized. The combination of these systems not only reduces energy consumption but also lowers greenhouse gas emissions, which positively impacts the environment. However, the construction of such buildings is limited by high initial investment costs. Therefore, it is essential to emphasize the relatively short payback period and to raise awareness of the importance of applying such systems. Considering that these systems can also be utilized for cooling and combined with other renewable energy sources, the conclusion is that constructing such buildings is justified, as it contributes to sustainable architecture. And this, if done globally, significantly contributes to the reduction of green house gasses, as mentioned in the introduction.

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Research paper

ORGANIZATION AND SPATIAL QUALITY OF MULTI-STOREY APARTMENTS – CASE OF NIŠ, SERBIA

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Abstract

This paper explores the spatial organization and quality of multi-storey apartments in the city of Niš, Serbia, with a focus on their potential to bridge the gap between single-family housing and traditional multi-family apartments. Through a typological and regulatory overview, the study highlights duplex and mezzanine units as architectural strategies for enhancing the residential experience within multi-family buildings.

Three recent examples from Niš are analysed, examining spatial characteristics such as total area, room dimensions, ceiling height variations, and the availability of private outdoor spaces. The findings suggest that while these units offer design flexibility and the potential for improved ambiance, particularly through increased floor-to-ceiling heights, they do not significantly surpass single-level apartments in terms of spatial comfort. Challenges related to regulatory ambiguities, insufficient private outdoor areas, and variable approaches to area calculation are identified.

Key words: *Apartment units*, *Duplex apartments, Mezzanine apartments, Multi-family housing, Multi-storey apartments*

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1. INTRODUCTION

The challenges of contemporary housing in urban areas present complex dilemmas when selecting residential spaces. The individual family house in peaceful area, long regarded as the ideal living solution, now faces competition from apartments, which require less maintenance and are situated in well-developed, service-rich locations where numerous amenities are "within reach". This results in high demand for apartments in centrally developed urban areas, which is also visible at the local level through the aggressive redevelopments of plots that were originally occupied by single-family houses, but are also suitable for the construction of multi-family buildings. These circumstances suggest that contemporary housing needs and desires are positioned between the family house and an apartment located near the city centre.

A primary advantage of individual, single-family housing is the allocation of a dwelling to a distinct, independent parcel of land. Residency in a detached home provides a significant level of privacy and individuality for its occupants. Also, this type of housing typically offers a high level of comfort, as the size and spatial organization of single-family homes are usually designed to accommodate a wide range of residential needs. However, despite its desirability, this form of housing represents an inefficient model for contemporary urban areas. The implementation of the single-family housing results in lower residential densities, inefficient land use, and unnecessary urban sprawl. Consequently, due to the spatial expansion of urban areas, this model leads to economic inefficiency, reflected in increased investments in infrastructure. Lastly, and perhaps most importantly, this housing model contributes to negative ecological and environmental impacts on the urban ecosystem.

The consequences mentioned above have led to the increasing perception of single family housing in urban areas as an unsustainable model, with greater emphasis being placed on the development of multi-family housing. More efficient use of land and available spatial capacities, better infrastructure and service provision in residential areas, coupled with higher housing density, make multi-family housing a more economical and rational choice for development of urban areas. However, as the advantages of multi-family housing are generally developed at the expense of spatial comfort, privacy, and individuality, many residents continue to favor the comfort provided by single-family homes.

In order to address the shortcomings of apartment living, contemporary models aim to find transitional solutions that reconcile the extremes of these two housing types and provide an adequate alternative. One of the key advantages of single-family homes is the ownership of a private piece of land – in the form of a garden [1,2]. Additionally, the organization of residential space on two, or more levels is often cited as one of the main benefits of living in a house [1-3]. Therefore, the private outdoor space that could serve as the living are on the open and internal circulation within the dwelling unit can be considered one of key benefits of single-family houses [1,2].

2. MULTI-STOREY APARTMENTS

Traditional multi-family residential buildings are characterized by the development of residential units on a single level. While it is undeniable that this spatial organization has its advantages – such as the fact that single-level apartments lack physical barriers and can be equally functional at all stages of individual and family development – differentiation of space along the vertical axis allows for greater variability in spatial organization and individualization of apartments within buildings [1]. Contemporary practice encourages the development of new spatial configurations that would provide a more adequate living environment and better, more stimulating living conditions. The modern architectural approach to improving multi-family housing involves the three-dimensional development of apartment space.

In contemporary housing practice, it is not uncommon that apartment units are developed on multiple planes. The concept of the three-dimensional spatial organization of an apartment involves planning the living space at different levels, not being restricted to standard ceiling heights, and allowing for the spatial overlap of parts of the apartment [1,2, 4-6]. This approach contrasts with the uniformity that often characterizes multi-family housing.

2.1. Multi-storey apartment types

Multi-storey apartments encompass a variety of residential unit types that span across multiple levels. The most common among these are duplex, maisonette, and mezzanine apartments.

A **duplex apartment** is defined as a single dwelling unit distributed over two floors, connected by an internal staircase. These units are typically accessed via shared entrances and common interior areas. While duplexes can be situated on any level of a building, they are most commonly found on the upper floors, often accompanied by adjoining rooftop terraces.

The **maisonette**, derived from the French term meaning “little house,” like duplex apartment most commonly has the living space split over two floors. However, maisonettes are distinguished by their location on the ground floor, with a private, street-level entrance, separate from the building’s main access. Owing to their ground-level position, maisonettes may include a small garden or outdoor area, making them resemble terraced or individual houses.

In both duplexes and maisonettes, the ground level usually functions as the primary living area, while bedrooms and private spaces are generally located on the upper floor. Nevertheless, alternative spatial configurations can be found depending on design considerations. Because each level often serves a different function, ceiling heights may vary to optimize spatial efficiency and cost-effectiveness. A minimum ceiling height of 2.6 meters is recommended for floors that are design for daily activities, while a reduced height of 2.4 meters may be acceptable for floors with secondary functions, if these area do not exceed 50% of the apartment’s total area.

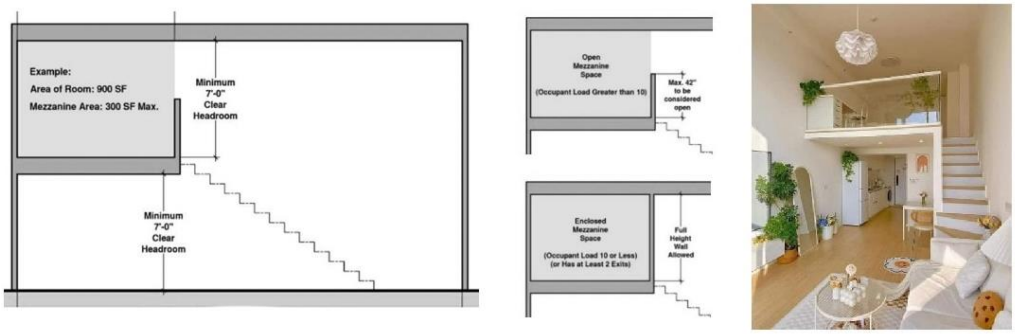


Figure 1. Mezzanine apartment type
(Source: https://buildingcodetrainer.com/mezzanine-code-requirements/)

The **mezzanine apartment** represents a different category. It is not a conventional multi-storey unit but rather features an intermediate level, called a mezzanine, inserted between the main floor and the ceiling (Figure 1). This mezzanine level is considered part of the storey below and is not typically classified as a separate floor. Mezzanines are valued for their ability to provide additional usable space without increasing the official number of storeys. Typically,

a mezzanine will occupy 30–50% of the floor area of the unit. The minimum recommended ceiling height is 2.40 meters, both below and above the mezzanine platform, although exceptions may apply in areas not requiring full clearance [7,8]. Depending on the design, mezzanines may be either open to the floor below or enclosed for privacy.

3. MULTI-STOREY APARTMENTS IN CONTEMOPRARY RESIDENTIAL PRACTICE IN THE CITY OF NIS

In Niš, multi-storey apartments that are part of the existing housing stock were predominantly constructed during the socialist period. Their design was inspired by Le Corbusier's residential concepts, which were widely implemented across Europe during that period. These apartment types were characterized by their narrow width, typically just 4.2 meters, and by their spatial organization across split levels. However, such configurations did not gain lasting popularity either in Niš or more broadly within Serbia.

A study conducted by B. Stoiljković [1], which focused on identifying the needs and preferences of residents in Niš concerning the individualization of multi-family housing, wich in some part included housing units developed across multiple levels, revealed some striking findings. The study, which examined residential buildings completed up to the year 2015, showed that 54.54% of respondents residing in multi-storey apartments perceived the multi-level layout as a drawback, while only 27.27% considered it an advantage. As the author concluded, this reflects a divergence in perception between residents and architects: while professionals may view the level-based organization as a design quality reminiscent of single-family housing, users more often experience it as an architectural constraint.

It is important to note that the study's sample likely included only multi-storey apartments developed according to the Le Corbusier model, suggesting that this specific spatial layout may not have aligned well with the preferences of domestic users.

Only in recent years has the local real estate market witnessed a resurgence of multi-story apartment development. Unlike earlier examples, these new duplex units vary significantly in width and layout, offering a wide range of spatial configurations. They are most commonly located on the top floors of residential buildings. In some cases, these units serve as a means of integrating previously underutilized attic space into the apartment below. In flat-roof buildings, duplex apartments are often complemented by large private outdoor areas in the form of rooftop terraces.

Residential construction in Serbia is regulated by the Rulebook on Conditions and Standards for the Design of Residential Buildings and Apartments *(Pravilnik o uslovima i normativima za projektovanje stambenih zgrada i stanova, "Sl. glasnik RS", br. 82/2015)*, which does not recognize multi-storey apartments as a distinct typological category. Apartment sizes are determined based on unit's structural layout, with minimum dimensions defined for each individual room (Table 1). Regardless of room purpose, the minimum floor-to-ceiling height for residential spaces is set at 2.6 meters, except in attic areas.

The possibility of developing multi-level residential units is introduced in the Local General Regulation Plan for the territory of the Medijana Municipality in the city of Nis *(Plan generalne regulacije područja gradske opštine Medijana, "Sl. list grada Niša")*. This document envisions the potential for designing ground floors with increased floor-to-ceiling height and the incorporation of mezzanine level. The area of the mezzanine level may not exceed 50% of the net floor area of the ground floor, excluding vertical circulation elements. The construction

of duplex apartments is planned on the top floors, where the upper level of the duplex utilizes attic space. The minimum clear height of the attic level must be at least 2.60 meters across a minimum of two-thirds of the floor area.

Table 1. Minimum apartment and room areas according to Rulebook

Minimum room area according to their function		**Minimum apartment area according to apartment type [4]**	
Living room	16,00 m²	Studio	26,00 m²
Double bedroom	11,00 m²	One-room apartment	30,00 m²
Single bedroom	7,00 m²	One-and-a-half-room apartment	40,00 m²;
Dining area	4,00 m²	Two-room apartment	48,00 m²
Kitchen	4,00 m²	Two-and-a-half-room apartment	56,00 m²
Storage	0,50 m²	Three-room apartment	64,00 m²
Bathroom	3,00 m²	Three-and-a-half-room apartment	77,00 m²
Toilet	1,30 m²	Four-room apartment	86,00 m²
		Four-and-a-half-room apartment	97,00 m²

For the purposes of this study, three examples of newly constructed multi-level residential units were analysed. The first example pertains to a building planned in Sestre Baković Street, the second is located on Bulevar Nemanjića, and the third in Pana Đukića Street (Figure 2). In the first case, the residential unit is situated on the ground floor and includes a mezzanine space. The second and third cases involve duplex apartments located on the top floors of their respective buildings.

To assess the quality of these residential units, the analysis focused on spatial characteristics that influence the quality of multi-level dwellings, specifically: total apartment area, individual room area, spatial zoning, availability of larger private open spaces, and living rooms with increased floor-to-ceiling height.

Case 1 – Building in Sestre Baković Street

The multi-level residential units in this building are located on the ground floor. Access to the apartments is provided through a shared corridor. The analysed apartment is a one-and-a-half-room unit with a total area of 46.72 m². The living room and dining area are integrated within a single open-plan space measuring 19.86 m². This area extends through two floor heights. The kitchen is positioned in a separate enclosed space with an area of 4.10 m². There is no sanitary facility on the ground floor. The mezzanine level, which occupies half the footprint of the ground floor, accommodates the sleeping area – comprising a bedroom and a bathroom. A notable drawback is that the bedroom, in terms of area, corresponds to the size of a single bedroom. The apartment does not include a private outdoor space.

Case 2 – Building on Bulevar Nemanjića

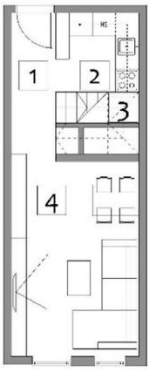
The duplex apartments in this building are situated on the top floors and are accessed via a shared central corridor. The analysed apartment is a two-and-a-half-room unit with a total area of 64.75 m². The living room and dining area are integrated within a single space measuring 21.65 m². The kitchen is spatially positioned within the open-plan living area but is physically separated by partitions.

[4] In local regulation residential units are classified according to the number of rooms, including the living room. For example, a two-room apartment is an apartment with living room and one bedroom with minimum area of 11 m². A half-room is a bedroom with reduced area, range from 7 to 11 m², intended for one person.

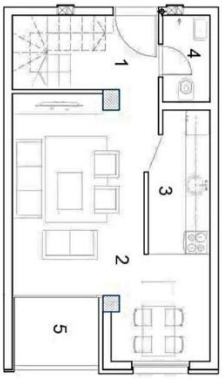
Case 1
Building in
Sestre Baković Street

Case 2
Building on
Bulevar Nemanjića

Case 3
Building in
Pana Đukića Street



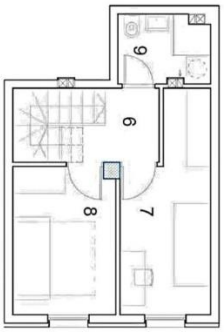
Ground floor



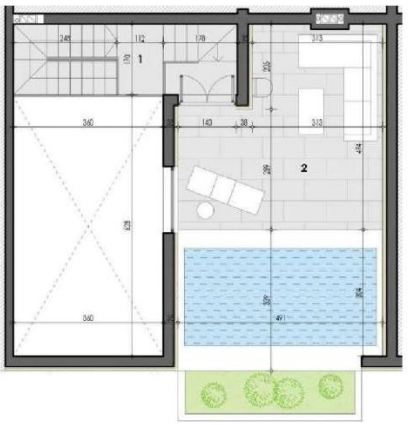
Lower floor

Lower floor

Mezzanine level



Upper floor



Upper floor – rooftop level

Ground floor		**Lower floor**		**Lower floor**	
1.Entrance area	4,00	1.Entrance and staircase	6,40	1.Entrance area	5,66
2.Kitchen	4,10	2.Living room	21,65	2.BAthroom	4,42
3.Staircase	1,67	3.Kitchen	4,88	3.Bedroom	10,97
4.Living room	19,86	4.toilet	2,42	4.Bedroom	10,35
		5. Balcony	3,36	5.Living room	25.88
				6.Balcony	7.29
total	**29,62**	**total**	**38,71**	**total**	**62.85**

Mezzanine level		**Upper floor**		**Upper floor**	
1.Staircase	1,67	6.Hodnik	3,40	1.Staircase	8.89
2.Walkway	3,40	7.Bedroom	10,11	2.Rooftop terrace	35.42
3.Bathroom	3,40	8.Bedroom	8,91		
4.Bedroom	8,63	9.Bathroom	3,62		
total	**17,10**	**total**	**26,04**	**total**	**44.04**
TOTAL NET AREA	**46,72**	**TOTAL NET AREA**	**64,75**	**TOTAL NET AREA**	**106.89**

Figure 1. Case study – examples of multilevel apartments in Niš

A loggia of 3.36 m² is directly connected to the living area. On the upper level of the duplex, two bedrooms and a bathroom are located. The larger bedroom has an area of less than 11 m², which is below the minimum defined area for a double bedroom.

Case 3 – Building in Pana Đukića Street

The top floor of this building accommodates "penthouse" apartments. Although designed as two-level units, the residential space is primarily organized on the entry level. The analysed apartment is a three-room unit with a total area of 106.89 m². The open-plan living room covers 24.96 m² and features increased floor-to-ceiling height. The night zone, located on the same level, includes two bedrooms and a bathroom. All residential rooms are open onto a spacious loggia with an area of 12.75 m². The apartment also includes access to a rooftop terrace located above the unit. This space is reached via an internal double-flight staircase. The associated rooftop terrace is designed as a seating area and includes a private swimming pool.

4. DISCUSSION AND CONCLUSION

The analysis of three contemporary examples of multi-storey residential units in Niš demonstrates the ongoing evolution of spatial organization in multi-family housing. Although previous multi-level configurations inspired by Le Corbusier were largely perceived negatively by residents, the recent resurgence of duplex and mezzanine apartments suggests a growing market interest and diversification in housing preferences.

Each case study highlights different aspects of multi-level living. The apartment in Sestre Baković Street demonstrates the potential for effective space utilization on the ground floor, though it lacks adequate room sizes and outdoor space. The unit in Bulevar Nemanjića offers a more balanced configuration, though it does not fully meet all regulatory standards. The example from Pana Đukića Street illustrates the most advanced application of spatial zoning, luxury amenities, and comfort, demonstrating how multi-level living can successfully emulate the qualities of single-family homes.

If the specific spatial elements of multi-storey apartments is considered, through analysis of unit layout, overall area, and individual room areas, it can be concluded that it does not significantly differ from that of single-level apartments of similar structure. The shortcomings commonly seen in domestic housing construction, particularly regarding the minimal area of individual rooms (often at or below regulatory minimums), are also observed in this type of apartment. Thus, we can conclude that the analysed apartments do not offer a notable improvement in spatial comfort. Additionally, differences in the treatment of staircases were observed. Specifically, in Cases 2 and 3, the staircase area is included in the total area calculation for only one of the levels. In Serbian housing practice, this issue is regulated by the national standard SRPS U.C2.100:2002 – Calculation of Building Areas in the Field of High-Rise Construction *(Izračunavanje površina obejakata u oblasti visokogradnje)*, which states that the area beneath stairs should only be included in the total area calculation if the ceiling height exceeds 1.50 meters. As this standard is not mandatory in domestic practice, it leaves possibility for varying methods of area calculation, and thus, potential manipulation when defining the apartment's structure.

A trend commonly associated with contemporary multi-storey apartments, the development of larger private open spaces, is not evident in domestic practice, except for Case 3. This may be attributed to an insufficiently clear treatment of rooftop terraces and

ground-level yards in local planning regulations. For instance, in Case 1, the unit lacks an associated outdoor space, despite having direct access to the terrain and backyard.

What is noticeable, however, is the use of multi-storey apartments' potential to enhance residential quality in terms of ambiance and visual experience. In Cases 1 and 3, the opportunity to create living rooms with increased ceiling heights has been utilized, which certainly improves the overall residential comfort.

In conclusion, multi-storey housing, offers significant design potential, but only when implemented with a balanced approach that combines creativity with regulatory and ergonomic rigor. Future residential developments should prioritize not only the formal attributes of space but also its livability, adaptability, and compliance with minimum standards to ensure both functional and experiential quality.

ACKNOWLEDGMENTS

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Research paper

EXPLORING MANAGEMENT MODELS OF PUBLIC OPEN SPACE IN RESIDENTIAL NEIGHBOURHOODS: IMPLICATIONS FOR SERBIA'S REGULATORY FRAMEWORK

Milica Ljubenović[1], Jelena Đekić[2], Milena Dinić Branković[3], Milica Igić[4]

Abstract

Public open spaces (POS) in residential areas are vital components of urban environments, contributing to quality of life, environmental sustainability, and social inclusion. Effective management models are crucial for ensuring POS are well-maintained, accessible, and responsive to community needs. This paper examines three prominent organisational models for POS management – state-centred, market-centred, and community-centred. While the state-centred approach has traditionally dominated, emerging market and community-led strategies offer enhanced flexibility, cost efficiency, and stakeholder engagement. The research provides a comprehensive review of these models' strengths and limitations in coordinating, regulating, maintaining, and investing in POS. Drawing upon this review, the paper explores the possibilities and challenges of their application within the Serbian legal and policy framework. Contributing to the understanding of diverse approaches to POS management in residential areas, this paper concludes with policy recommendations aimed at integrating these management models into Serbia's existing regulatory framework, emphasizing inclusiveness, transparency, and long-term commitment as crucial for successful POS management.

Key words: *public open space, management, residential neighbourhoods, Serbia*

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1. INTRODUCTION

Enhancing the management of public open space (POS) is gaining increasing importance in contemporary urban development. However, POS management has not been sufficiently addressed in both practice and academic debate [1], even though it is seen as an approach that can secure long-term provision of POS and its benefits [2]. POS management is defined as a strategic, inclusive, and long-sighted process of planning, re-design, construction, maintenance and place-keeping activities aimed at securing its social, environmental, and economic quality [3-5].

Considering the significance of POS for the quality of urban life, and the threats posed by intensive urbanization, developing innovative organizational and management models for residential POS has become a key concern in contemporary urban planning and design. These emerging models reshape how POSs are funded, governed, and maintained, with the tendency to form public-private-people partnerships, promoting community involvement in decision-making, design, and upkeep. Achieving such an inclusive approach requires collaboration among all stakeholders to address shared challenges.

In Serbian cities, POS management in residential areas faces twofold issues. On one hand, POS within inherited large housing estates (LHEs) as the dominant housing form from socialism generally suffer from chronic mismanagement and neglect. On the other hand, new multi-family residential developments are marked by the near disappearance of POS due to market-driven restructuring and limited public investment in the housing sector. The issue of POS management in inherited LHEs is particularly complex and stems from changes in housing ownership, lack of regulations, neglect of community significance, and contemporary urban planning practices [6, 7]. As a result, these spaces are often exposed to degradation, fragmentation, insufficient maintenance, and appropriation for private purposes.

This study aims to synthesize different management solutions for reclaiming POS in residential areas. Based on an analysis of current knowledge and Serbia's legal and institutional framework governing residential POS, the paper investigates the potential pathways to apply these models the Serbia.

The methodological framework is conceptualized on the description, analysis and synthesis of findings. By reviewing up-to-date academic research, the benefits and shortcomings of existing POS management practices are identified. Subsequently, Serbian legal documents and current POS management practices are examined. The synthesis of findings is then used to discuss the challenges and opportunities in POS management, as well as pathways towards sustainable POS management models in Serbia.

2. POS MANAGEMENT ORGANISATIONAL MODELS

In many Western countries, POS became a public service during the twentieth century, managed by local governments and funded through local taxation [5]. Recent trends in the management of POS have emerged from the process of replacing government with governance and reshaping institutional arrangements, where new stakeholders and organisations have gained a role in management. In addition, new demands have been set to POS use, planning and management due to transformed societal needs related to global megatrends such as loss of biodiversity, socioeconomic and environmental issues and lack of space as a result of urbanization, globalization and climate change [3]. Public sector and

local government reforms, along with introduction of New Public Management (NPM) in the 1980s and early 1990s have created new roles for public sector, market and users [2, 5] This led to multiplication of agencies performing the delivery of public services. However, there are differences between the countries, and outsourcing is not spread everywhere to the same extent and it depends on countries' tax system and budgetary constraints [8]. POS management has thus become a market issue with contractors and private enterprises as central actors, but also the significance of involving urban residents on the community level has been emphasized as a way of encouraging democracy and transparency of management [2].

Carmona et al. [5] identify three organisational models of public space management, that is three models of addressing the issues of coordination, regulation, maintenance and investment that are also relevant for residential POS management:

1. State-centred
2. Market-centred
3. Community-centred or user-centred

State-centred model was the dominant form of POS management in most countries during the twentieth century, and it is still the dominant management model throughout the world. In this model planning and delivery of POS management services is provided by public-sector institutions, with minimum use of external input from private contractors or the voluntary sector. It includes hierarchical structures of planning and delivery with clear separation between service and use. The main disadvantages of state-centred model include potential cost increasement due to a lack of market competition, rigid bureaucratic procedures, lack of flexibility and responsiveness to evolving community needs [9].

The other two devolved models include transfer of responsibilities for provision and management of POS from the public sector towards other social agents. However, it should be noted that this does not include necessarily the transfer of ownership of public space.

The market-centred model includes transfer management responsibilities over POS, whether publicly or privately owned, to private entities [5]. This involves the transfer of rights and obligations for POS management, and in some cases the power to define management objectives. This can be done through straightforward service delivery contracts, or as part of a development agreement in private property development. For the public sector, these contracts represent a way to fund public services by means other than public budget. The collaboration interest for private sector is profit seeking, either directly from a management/maintenance contract, or indirectly from the performance of the whole development of which the POS is a part. The main purpose of market-centred model is to reduce operational costs, but also to bring new skills and expertise [9]. However, transactional cost may occur and due to different contracts for different operations or areas operations there is a risk of fragmentation of operation. Contracting-out to the lowest bidder can also negative impacts on POS management and it is suggested that this approach should not be considered as cost-cutting, but as outcome-based [8]. Private management of POS is more established in the US, but it is rapidly being established in other countries, especially in Europe [5].

Public-private partnerships (PPPs) are increasingly widespread in POS management, however, there are also critiques, mainly related to the interest of stakeholders and the duration of the partnership [8].

The community-centred model also includes the devolution of responsibilities for provision and management of POS but to community organisation, which can be associations of POS users, POS interest groups and others [5]. This model is the least developed and the main difference from the market-centred model is that the organisations to which management is devolved are not market and profit based and their interest is directly concerned with the quality of POS.

Community-centred approach can be related and explained by the trend towards co-production of public services with their users. User engagement in the provision of public services has been seen as the most effective way to respond to diverse and complex demands of modern society. This is clearly evident in the trend of the transferring of social housing estate management to housing associations. In the context of the UK, user-centre approach is connected with a strong policy shift towards giving local and community organizations a greater role in local decision-making [10].

Contracts of POS management in this model can be well defined with voluntary organisation, for example the transfer of management of social housing estates and its POSs to housing association [5]. Arrangement can be also less formal and depend more on government funding, including agreements with ad-hoc residents' groups such as the neighbourhood management schemes, funded by government neighbourhood renewal initiatives, in which communities in deprived areas are encouraged to manage their own public spaces. In Sweden, large public housing companies often played a key role in the initiation and establishment of tenant involvement process, which has proved efficient in revitalizing declining communities [11]. Levels of control in tenant involvement process range from the lowest, when tenants are *invited to get involved* with tasks already defined by the proprietor to autonomous work of tenants, without proprietor's interaction. More organised forms of resident involvement fall under self-management.

The comparative overview of these three models are given in Table 1. In practice, these three organisation models are usually combined. State-centred model often includes outsourcing of some parts of the maintenance operations while also engaging with local community users in some areas [9]. The importance of actively involving people in PPPs scheme is increasingly recognized [12]. The process framework incorporates bottom-up participatory strategies at every stage of the PPP process.

It is claimed that partnership approach to POS management can bring many benefits, since it can give access to additional resources such as funding, skills, knowledge, land or ideas. However, involving many partners can be difficult for coordination, and partnership implies long-term commitment form partners and can be resource intensive [13].

Table 1. Comparative overview of POS management models

Model	Core Mechanism	Key Advantages	Main Constraints
State	Centralised public sector management	Equity, clear governance	Budget cuts, bureaucratic rigidity, inflexible responsiveness
Market	Private/PPP service contracts	Expertise, efficiency	Fragmented operations, low-bid risks
Community	User-led stewardship and co-governance	Local buy-in, flexibility	Capacity and financial limits, informal procedures

3. POS MANAGEMENT IN SERBIA

The large portion of multi-family housing in Serbian cities was built in the socialist period. These LHEs with generously dimensioned POS were built on state owned land. During the 1990s, public housing was massively privatized, which was not followed by clear regulations about management and maintenance. Unclear responsibilities regarding POS, lack of finance due to economic problems since the 1990s and decreasing willingness of residents have made these spaces obsolete and underused [6]. On the other hand, underutilization and maintenance issues were the main arguments for city authorities to justify the selling of "undeveloped" urban land for new construction [7]. In new development, due to the reduction of minimal standards and private developers' interest, POSs have been reduced to a mandatory minimum, and often remain unprovided.

3.1. Legal and institutional context

The management of POS in multi-family residential areas in Serbia is conditioned by its ownership, although in some cases responsibilities are unclearly defined. The Law on Communal Activities mandates local self-governments (LSGs) to provide communal activities, including the maintenance of publicly owned POS (*public green spaces*), funded through municipal budgets or communal fees [14]. The LSG may decide to entrust communal activities to external entities, in form of public-private partnerships and concession. LSGs adopt their decisions on communal order that typically distinguish the arrangement of POS as areas around buildings, areas of public use (publicly owned areas), and areas in public use.

The maintenance of area around the building, as the remaining part of the building plot, is the responsibilities of the owners or the users of the building. Planning documents define areas of public use for POS, and their maintenance is assigned to legal entities or individuals by special city regulations. Areas in public use, not designated by the planning document but available to many citizens, such as green areas within or between blocks of buildings, are maintained by their owners or users.

Based on the Law on Housing and Building Maintenance, owners must maintain spaces outside the building that belong to the land for regular building use [15]. Previous legislation, however, did not specify owners' or tenants' obligations to care for the land around multi-family buildings, leading to widespread lack of interest and neglect [16].

By acquiring ownership rights of a specific part of the building, one also acquires co-ownership rights to the underlying land in proportion to the special part's size. In practice, though, very few cases in Serbia register all building part's owners as co-owners of the land on which their building is located [16].

Reflecting on all this, the responsibility for maintenance is clear if the land rights and ownership are clear, whether public or private. In contrast, mixed rights and mixed ownership make difficult to define responsibilities. This is especially the case for POS in inherited LHEs, where the building-plot and the surrounding land lie on the separate cadastral plots under the different ownership.

3.2. POS management in practice

In practice, the management of POS within inherited residential areas from socialist past, which can be in different forms of ownership, is based on state-centred model, where

planning and delivery of POS management services is provided by public-sector institutions. LSGs entrust their maintenance to public utility companies. Yet, limited budgets of LSGs pose persistent financial challenges in performing communal activities, while their duties grow in proportion to population increases [16]. This financial strain often prevents LSGs from investing in new initiatives or even meeting current obligations. Outdated equipment and staff shortages further exacerbate maintenance problems. All these factors contribute to the absence of a reliable funding source for state-cantered POS management.

Despite these issues, outsourcing of POS maintenance operations is not implementing in Serbia. Although the Law on Communal Activities enables PPP for POS maintenance, it was carried out in only one city in Serbia (Bečej) so far. The development of PPP at the local level in Serbia has shown several shortcomings, including a lack of contract transparency, failure to fulfil obligations, and inadequate protection against corruption [17]. These issues complicate the implementation of market-centred management model.

The poor condition of POS in inherited LHEs have triggered spontaneous initiatives of local communities and placemaking, activating some previously neglected places in certain blocks, across different cities in Serbia. Some initiatives include small spatial interventions [18, 19], cleaning actions, cooperation with public institutions to encourage the participation of citizens in the planning of open spaces [20, 21], but also organizing protests in order to defend POSs from new construction [22, 23], as well as planting trees and crowdfunding as a local civic financing mechanism for collecting financial resources [24]. All these initiatives are usually implemented by means of citizen association, which often act as a mediator between residents and public institution. After the establishment of legal framework for the development of civil society, since 2010, there was an expansion in the number of established citizens' associations, some of which focus on social, environmental, economic and other issues of importance to their local community [25]. Citizens' initiatives can trigger a chain effect between residents and other local stakeholders, willing to contribute to the overall quality of POS. However, the absence of formal channels leaves these initiatives sporadic.

Figure 1. a – Cleaning action in Block 70 and 70a, Belgrade, source https://www.zdruzeno.org/zajednicka-akcija-blok-70-i-70a/;
b - Sport filed for "foot-tennis", Delijski Vis, Niš, source https://jugmedia.rs/clanovi-radne-akcije-napravili-teren-za-nogotenis-na-delijskom-visu/

4. CONCLUSION

Effective management of POS in multi-family residential neighbourhoods is crucial for urban quality of life, yet presents significant challenges, particularly within the Serbian context.

The analysis reveals that while the state-centred model remains dominant in Serbia, it faces substantial financial and operational limitations. The legacy of socialist housing development, coupled with unclear ownership structures resulting from mass privatization and ambiguous regulations, exacerbates these challenges, often leading to neglect and degradation of valuable POS. The Serbian regulatory framework currently lacks clarity in defining ownership and responsibility, particularly in the context of inherited LHEs. Market-centred approaches, such as PPPs, though legally possible, have seen minimal implementation, hindered by issues of transparency and trust.

Emerging community-centred initiatives in POS governance and management, demonstrate the potential for community-led management solutions. However, these bottom-up actions often lack formal recognition, resources, and institutional support, limiting their sustainability and impact.

Relying solely on the traditional state-centred model appears insufficient for addressing Serbia's complex POS management needs. A transition towards more hybrid approaches, integrating elements of market and community models is necessary. This could involve developing transparent and well-regulated PPP frameworks, potentially exploring and institutionalizing Public-Private-People Partnerships (4P) to enhance inclusiveness, transparency and interactiveness. Crucially, fostering community-centred management requires establishing clear regulations and providing appropriate support (financial, technical, and administrative) for citizen associations and local initiatives. Before that, it is necessary to address the fundamental issues of unclear land ownership and management responsibilities, especially in inherited LHEs, through regulatory reform. Finally, achieving sustainable and well-maintained POS in Serbian residential areas requires a shift towards more inclusive, transparent, and collaborative governance frameworks, supported by a long-term commitment from all stakeholders – public authorities, private actors, and local communities.

ACKNOWLEDGMENTS

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Research paper

COMPARATIVE ANALYSIS OF ASTM C1202 AND SRPS EN 12390-18 TESTING METHODS FOR ASSESSING CHLORIDE ION PENETRATION IN CONCRETE SUPPLEMENTED WITH RECYCLED CRT GLASS AS CEMENTITIOUS MATERIAL

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Abstract

Durability is crucial for reinforced concrete, directly influencing the service life of structures. The presence of aggressive agents, especially chloride ions, significantly impacts durability. This study investigates the differences between ASTM C1202 and SRPS EN 12390-18 standards in concrete supplemented with recycled CRT glass as cementitious material. The percentage of replacement of cement with glass is: 10% and 20%, by mass. In addition to fresh state testing, the following mechanical tests were also performed: compressive strength and splitting tensile strength. The aim of this research was to determine how the addition of finely ground cathode glass affects the resistance of concrete to chloride penetration, as well as to compare the results of chloride penetration after conducting two standardized but completely different test procedures. A review of the literature revealed very few comparative tests of chloride penetration according to the mentioned standards.

Key words: *CRT glass, comparative analysis, chloride ion penetration, mechanical characteristics*

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1. INTRODUCTION

Cathode ray tube (CRT) glass contains significant amounts of heavy metals, such as lead, making it hazardous if not disposed of properly. Consequently, advancements in safe processing and decontamination technologies enable recycling facilities to handle CRT glass with minimal environmental impact. Increasing environmental awareness also influences public behavior, further encouraging collection efforts—meaning that even if the total amount of waste declines, the systematically collected material can grow as a larger portion of available older electronic waste is properly recovered.

The use of supplementary cementitious materials (SCMs) in concrete brings environmental and practical benefits, such as reducing industrial waste and promoting sustainable production. However, their effectiveness must be proven through key performance factors, like pozzolanic reactivity, strength improvement, and long-term durability. One crucial test in this process is assessing chloride ion penetration, which helps determine how well concrete can withstand corrosion—particularly in harsh conditions like marine environments or areas exposed to de-icing salts, where embedded steel reinforcement faces significant risks.

The most widely used methods for testing chloride penetration include the standardized approach established by the American Society for Testing and Materials (ASTM) C1202 [1] and the method developed in Finland - NT Build 492 [2]. When it comes to domestic regulations in this area, the first standard SRPS EN 12390-18 [3] was published in 2021. The latest standard currently in force in our country carries the designation SRPS EN 12390-18:2024 [4].

Roz-Ud-Din Nassar and colleagues [5] from the University of Michigan researched the strength and durability of concrete made with recycled concrete aggregate and cement partially replaced with milled waste glass. The waste glass used in the experiment came from collected glass packaging of various colors and was ground to an average fineness of 19 μm. Five concrete mixtures were prepared with a water-to-binder ratio of 0.38. The authors found that the inclusion of milled waste glass resulted in a 54% reduction in the number of coulombs passed through concrete specimens containing 100% recycled aggregate compared to corresponding specimens without milled waste glass. Concrete containing milled waste glass as a partial cement replacement demonstrated improved resistance to chloride ion penetration, with slightly over 2000 coulombs passed in testing. This enhanced durability is attributed to the pozzolanic reactions of milled waste glass, which refine pores, block pathways, and fill voids, thereby reducing the conductivity of pore fluid and limiting ion movement. Due to this increased resistance, such concrete is well-suited for infrastructure like bridge decks, pavements, and parking lots that regularly face chloride-induced damage from deicing salts [5].

Ahmed Omran and colleagues [6] investigated the long-term effects of incorporating recycled glass as a partial cement replacement on the properties of concrete used in various structural elements in Canada. The replacement percentage ranged from 10% to 30% by mass. During in-situ construction, one element was made with concrete containing glass, while another was made with conventional concrete. Additionally, two concrete mixtures were prepared in a laboratory to examine properties at 28 and 91 days, comparing modified concrete with a reference mix without glass. Between 2013 and 2016—2.1 to 6.7 years after concrete placement—core samples were extracted for various tests, including chloride penetration resistance assessments. The results from real-world conditions were then

compared with laboratory findings. The study found that concrete mixes containing glass powder (GP) exhibited better resistance to chloride ion penetration compared to conventional concrete mixes. Reference mixtures without GP had higher permeability, with values of 4815 C and 3815 C, indicating susceptibility to chloride attack. In contrast, GP-modified mixes demonstrated significantly lower permeability, with values of 360 C, 660 C, and 280 C, falling below 1000 C according to ASTM C1202. This improvement is attributed to the pozzolanic reactions of GP, which generate additional hydration products and densify the concrete's microstructure over time, enhancing its durability against chloride-induced deterioration [6].

Ablam Zidol and colleagues [7] also examined the resistance of concrete to chloride exposure when part of the cement was replaced with different supplementary cementitious materials (SCMs), including finely ground glass packaging (GP), fly ash (FFA), and ground granulated blast furnace slag (GGBS). Multiple series of mixes were prepared with varying water-to-binder ratios ranging from 0.35 to 0.65. The average particle size of cement was 14.9 µm, while the glass, fly ash, and slag had average particle sizes of 10.9 µm, 9.2 µm, and 8.4 µm, respectively. The study found that concrete with 30% supplementary cementitious materials (SCMs) has significantly lower permeability—ranging from 2 to 6 times less than conventional concrete—depending on the water-to-binder ratio following ASTM 1202 standards. This reduction is attributed to various reaction mechanisms, including the filler effect, pozzolanic reactions, and the ability of mineral additives to bind chloride ions. While different SCMs led to similar permeability improvements, the concrete incorporating 30% glass powder exhibited the lowest permeability values, highlighting its superior performance in reducing chloride ion penetration.

A review of the literature revealed that there was lack of the studies in which the testing of chloride penetration on concretes with the addition of waste glass was conducted according to the provisions of the EN standard. A notable gap in research is the lack of comparative studies examining chloride penetration resistance according to both EN and ASTM standards. This study investigates the differences between ASTM C1202 and SRPS EN 12390-18 standards in concrete supplemented with recycled CRT glass as cementitious material. The percentage of replacement of cement with glass is: 10% and 20%, by mass.

2. PROCEDURE OF CHLORIDE ION PENETRATION TESTING ACCORDING TO EN 12390-18 AND ASTM C1202

According to the EN 12390-18, migration cells are positioned relative to the sample as shown in Figure 1. The reservoir of the migration cell is filled with a 5% NaCl solution and connected to the anode (negative charge), while the other cell is filled with either NaOH or KOH solution and connected to the cathode (positive charge). The duration of the test depends on the electrical resistance of the sample. Since the chloride migration coefficient (Mnss) is unknown at the start, the initial voltage should be 30 ± 0.2 V. Depending on the measured current strength at 30 V, this voltage can be maintained throughout the test. After the electric current has been applied for the specified duration, the samples are split in half parallel to the chloride penetration direction. Both halves are sprayed with a silver nitrate ($AgNO_3$) aqueous solution, causing the portion of the concrete affected by chloride penetration to change color. The chloride penetration depth is measured at nine points, with an accuracy of 1 mm (xd1, xd2, ... hd9) using a caliper gauge. When measuring, the edges of the sample within 10 mm from its sides should not be considered.

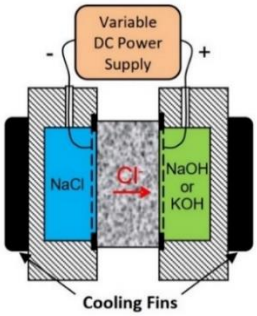

Figure 1. Schematic appearance of the chloride penetration test through a concrete sample

The chloride migration coefficient is calculated according to the equation from standard EN 12390-18. According to the SRPS U.M1.206 standard, section 5.3.2, concrete can be classified into one of three resistance classes, provided that the calculated individual values and the average migration coefficient meet the criteria specified in Table 1.

Table 1. Criteria for assessing the resistance of concrete to chloride penetration are defined based on the chloride migration coefficient [8]

Exposure class	Resistance class	Criterion	
		Value	Chloride migration coefficient
XD1	CL-1	Average	$\leq 15.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 18.0 \cdot 10^{-12}$ m^2/s
XD2	CL-2	Average	$\leq 10.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 12.0 \cdot 10^{-12}$ m^2/s
XD3	CL-3	Average	$\leq 7.0 \cdot 10^{-12}$ m^2/s
		Single	$\leq 9.0 \cdot 10^{-12}$ m^2/s

The ASTM C1202 test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This test method is applicable to types of concrete where correlations have been established between this test procedure and longterm chloride ponding procedures such as those described in AASHTO T 259. The concrete sample is cut into cylindrical discs with a diameter of 100 mm and a thickness of 50 mm. The sides of the sample are coated with an epoxy layer to prevent lateral ion penetration and ensure controlled migration through the specimen. The sample is placed in a vacuum chamber for 3 hours to remove air from the concrete pores. Afterward, it is submerged in deionized water for 18 hours to achieve full pore saturation. This sample conditioning process is almost identical to the conditioning specified by the European standard SRPS U.M1.206. This method consists of monitoring the amount of electrical current passed through 50-mm thick slices of 100-mm nominal diameter cores or cylinders during a 6 hours period. A potential difference of 60 V direct current is maintained across the ends of the specimen, one of which is immersed in a 3% NaCl solution (30 g NaCl in 970 g

of water), the other in a 0.3 N NaOH solution (12 g NaOH in 1 liter of distilled or deionized water). The total charge passed, in coulombs, has been found to be related to the resistance of the specimen to chloride ion penetration. According to appendix of the standard C1202 qualitative indications of the chloride ion penetrability based on the measured values from this test method are provided in Table 2. These values were developed from data on slices of cores taken from laboratory slabs prepared from various types of concretes.

Table 2. Chloride ion penetrability based on charge passed [1]

Charge Passed (coulombs)	Chloride Ion Penetration
> 4000	High
2000 – 4000	Moderate
1000 - 2000	Low
100 – 1000	Very Low
<100	Negligible

From the previously described chloride penetration testing procedures according to European and American standards, it can be observed that the preparation and conditioning of test specimens itself are practically identical. The key difference lies in the applied voltage and the duration of the test. Additionally, in the European standard, calculating the migration coefficient requires measuring both the average and maximum chloride ion penetration. In contrast, the American standard does not involve splitting the specimen; instead, the assessment of concrete resistance to chloride ingress is based on the charge passed (in coulombs) during a six-hour examination.

3. MATERIALS AND METHODS

3.1. USED MATERIALS

For the production of the experimental concrete series, pure Portland cement CEM I 52.5R from Moravacem Novi Popovac was used, meeting all quality requirements outlined in EN 196-1, EN 196-3, EN 196-6, and EN 197-1 standards. The first fraction of river aggregate (0/4 mm) was sourced from the Trans DN Kop separation in Čapljinac, while two fractions of crushed aggregate (4/8 mm and 8/16 mm) were obtained from Bisina, Raška. The granulometric composition of the aggregate mixture is presented in Figure 2.

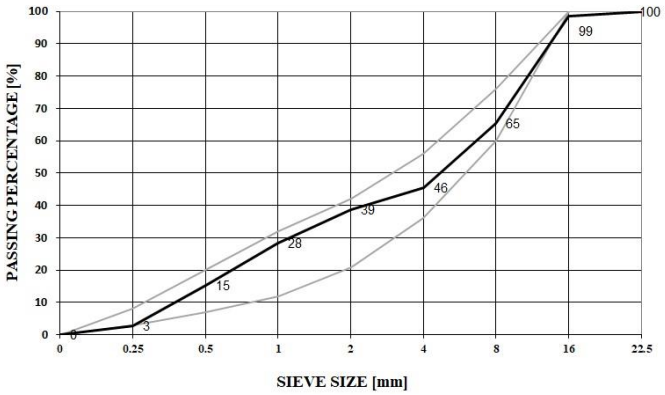

Figure 2. Granulometric composition of aggregate mixture

The CRT glass used in the concrete mixture was supplied by the recycling center Jugo - Impex E.E.R. d.o.o. from Niš. The cathode glass was finely ground using a laboratory ball mill to ensure complete passage through a 0.063 mm sieve. The chemical composition of finely ground CRT glass and cement is presented in Table 3. To enhance the workability of the concrete, a superplasticizer commercially known as MC-PowerFlow Evo 580 was incorporated into the mixture. This latest-generation MC superplasticizer is designed for high rheological demands in transport concrete and has a specific mass of 1.05 g/cm³. Finally, water from the municipal supply was used in the preparation process.

Table 3. Chemical composition of cathode ray tube glass and cement CEM I 52.5R

Binder	Chemical Compound							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3
CRT glass	60.61	2.88	0.58	1.31	0.53	6.45	7.61	0.09
Cement	19.30	4.28	2.87	62.8	2.22	0.91	0.21	3.05

3.2. Plan and program of testing

The following tests were conducted on fresh concrete:

- Slump test (EN 12350-2 [9])
- Density (EN 12350-6 [10])
- Air content - Pressure methods (EN 12350-7 [11]).

The following tests were conducted on hardened concrete:

- Compressive strength (EN 12390 – 3 [12])
- Chloride ion penetration (EN 12390-18 [4] and ASTM 1202 [1]).

Special attention was given to the blending of cement and the appropriate amount of finely ground cathode glass before preparing each concrete batch. For this purpose, a container of suitable volume with a lid, a mixer, and a specialized attachment (Figure 3) were used. The mixing process lasted for 5 minutes, with the specialized attachment operating at 850 revolutions per minute.

Figure 3. The container and special attachment for mixing cement and glass

3.3. Concrete mixture composition

Three experimental concrete mixtures were prepared (Table 4). In addition to the reference mixture, which was made using only PC 52.5 R, two additional mixtures were produced where a partial replacement of cement with finely ground glass was implemented.

The percentage of cement replacement with CRT crushed glass was 10% and 20%, based on the mass of the cement. The series labels with the glass addition were formed by combining the abbreviation for cathode ray tube glass (CRT) and the percentage of cement replacement with the glass. The target slump class for all concrete mixtures was S4 (minimum slump 160 mm), achieved by applying a chemical additive from the superplasticizer group.

Table 4. Composition of experimental concrete mixtures

Concrete	Aggregate			Cement	CRT	Water	w/b	Additive
	0/4 mm	4/8 mm	8/16 mm	CEM I 52.5 R	<0.063 mm	City Wat. Supply	-	Super-plasticizer
	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	-	kg/m³
Reference (R)	840	375	655	360	-	175.0	0.486	2.52
CRT10	840	375	655	324	36	175.0	0.486	2.52
CRT20	840	375	655	288	72	175.0	0.486	2.52

4. EXPERIMENTAL RESULTS AND DISCUSSION

The slump test results are in the range from 160 mm to 170 mm, class S4, which was the goal when designing concrete mixtures. The results of fresh concrete density and air content testing are shown in Figure 4. The density of fresh reference concrete was 2386 kg/m³, while the concrete with 10% cement replacement by glass exhibited a slight increase of approximately 1%, reaching 2408 kg/m³. The air content in both the reference mix and CRT10 was 3.5%, exceeding the typical value of 2%. Given that no air-entraining additives were used, it can be inferred that the superplasticizer itself contributes to increased air entrainment in the mix.

More pronounced changes in these properties were observed when 20% of the cement was replaced with glass. Specifically, the CRT20 series exhibited a significantly lower density of 2321 kg/m³, directly linked to increased air content in the concrete mixture. The average air content in CRT20 reached 6.5%, which is considerably higher than the expected range.

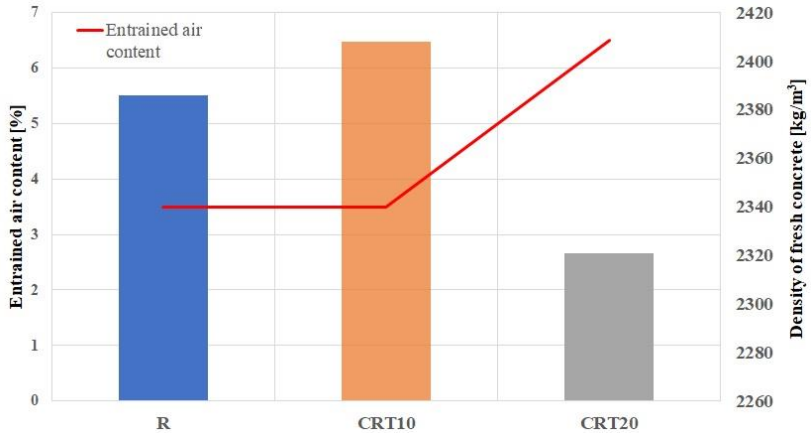

Figure 4. Density and air content of fresh concrete

These notable variations in fresh concrete properties due to CRT powder addition do not align with previous findings from the authors' earlier research [13]. In study [13], where cement replacement by glass reached 35%, only a slight decrease in bulk density (-1%) was observed compared to the reference mix, while changes in air content remained within the resolution limit of the porosimeter device. Further testing is necessary to provide a clearer explanation for the significant air entrainment observed in the CRT20 concrete mix.

For the compressive strength tests, digital, hydraulic press "UTEST UTC - 5740" measuring range 0 - 3000 kN and accuracy class 0.5% is used. Test are conducted at the concrete age of 7 and 28 days. Figure 5 provides the graphic presentation of achieved compressive strengths of concrete mixtures in time.

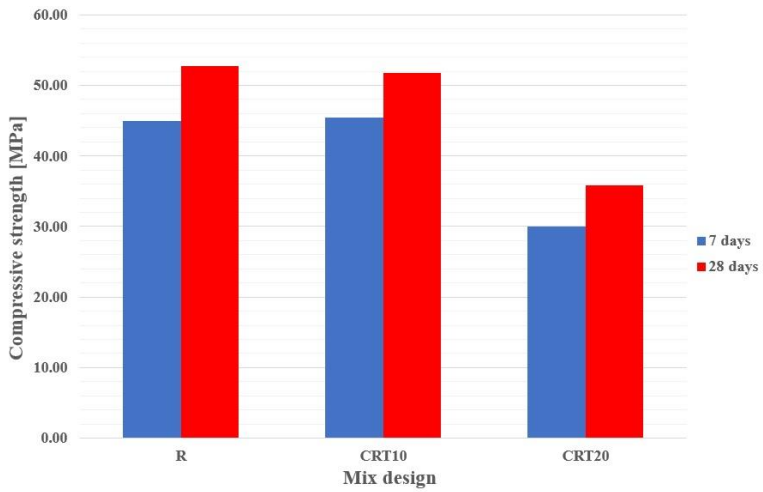

Figure 5. Graphic presentation of achieved compressive strengths of concrete series in time

Replacing 10% of cement with recycled glass did not significantly reduce the compressive strength of concrete during testing at 7 and 28 days compared to the reference mix. However, the CRT20 series exhibited a notable decrease in compressive strength, with reductions of 33% and 38%, respectively, at these ages. This drastic strength loss is primarily attributed to the high amount of entrained air in the concrete mixture. Based on the authors' previous research, it is anticipated that the difference in compressive strength between CRT20 and the reference mix will be somewhat less pronounced at 90 days. This is due to the pozzolanic reaction, which occurs later than the cement hydration process and becomes most intense after 28 days. The obtained results align with the findings of Aliabdo et al. [14], who concluded that replacing up to 10% of cement with glass does not negatively impact compressive strength at later concrete ages.

The results of the chloride migration coefficient M and charge quantity Q at a concrete age of 28 days are presented in Table 5. Based on the test results, it can be concluded that with the increase in the level of cement replacement with CRT glass, there is an increase in the depth of chloride ion penetration, which is directly related to the increase in the migration coefficient value. Based on the individual and average values of the migration coefficient and criteria from Table 1, referent concrete series and CRT10 can be classified to resistance class CL-2. Furthermore, CRT20 belongs to lowest resistance class CL-1. Unfortunately, the obtained results are not consistent with the research results [15-17].

Table 5. Results of chloride penetration testing according to EN 12390-18 and ASTM C1202

Mix design	Sample Designation	Chloride migration coefficient M_{nss} [m^2/s]	Average chloride migration coefficient $M_{nss,\ average}$ [m^2/s]	Charge passed Q [C]	Average charge passed $Q_{,average}$ [C]
R	R1	$9.2 \cdot 10^{-12}$	$8.9 \cdot 10^{-12}$	2149	2131
	R2	$8.3 \cdot 10^{-12}$		2298	
	R3	$9.1 \cdot 10^{-12}$		1945	
CRT10	CRT10/1	$9.0 \cdot 10^{-12}$	$9.7 \cdot 10^{-12}$	2245	2258
	CRT10/2	$9.6 \cdot 10^{-12}$		2362	
	CRT10/3	$10.5 \cdot 10^{-12}$		2168	
CRT20	CRT20/1	$11.4 \cdot 10^{-12}$	$11.4 \cdot 10^{-12}$	2265	2205
	CRT20/2	$10.0 \cdot 10^{-12}$		2181	
	CRT20/3	$12.9 \cdot 10^{-12}$		2170	

When it comes to the charge passed results, we can see that the results for all three concrete mixtures are fairly uniform. According to the criteria in Table 2, the chloride penetration can be descriptively classified as 'moderate' for all mixtures. There is no direct correlation that connects the chloride ion migration coefficient with the charge quantity. Both parameters are influenced by numerous factors, the most significant of which are: water-cementitious materials ratio, type and quantity of supplementary cementitious materials in the concrete mixture, the presence of polymeric admixtures, ionic solutions of admixtures like calcium nitrite, specimen age, air-void system, aggregate type, degree of consolidation, and type of curing. For the specific composition of the concrete mixture and the levels of cement replacement with cathode glass of 63 µm fineness (Table 4), as well as for the obtained chloride penetration results according to EN and ASTM standards (Table 5), a dedicated curve was established to represent the dependency between the migration coefficient and total charge quantity, as shown in Figure 6. This is a logarithmic function with a correlation coefficient of $R^2 = 0.82$. To determine a more precise dependency, a comparative study on a larger number of samples needs to be conducted. A sufficient number of concrete samples were set aside for chloride penetration testing at 90 days, aiming to assess whether the pozzolanic reaction of the glass by that stage enhances the concrete's resistance to chloride ingress.

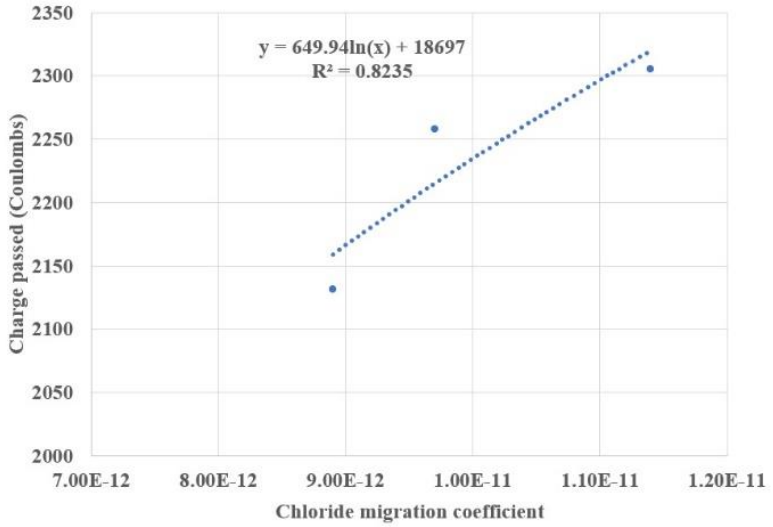

Figure 6. Logaritham function between chloride migration coefficient and charge passed

5. CONCLUSIONS

Based on the obtained experimental results, a number of conclusions can be drawn:

- The replacement of cement with ground CRT glass up to a level of 10% insignificantly affects the fresh concrete's volume density, as well as the percentage of entrained air. The CRT20 concrete mixture had a low volume density value of only 2321 kg/m³ and an entrained air content of as much as 6.5%.
- Replacing 10% of the cement with recycled glass slightly reduced the compressive strength of the concrete when tested at 7 and 28 days compared to the reference concrete. The CRT20 series, at the aforementioned ages, had 33% and 38% lower strength compared to the reference series.
- Based on the determined resistance classes of the experimental concrete series, it can be concluded that the reference concrete and the CRT10 mixture satisfy the XD2 exposure class, while the CRT20 series satisfies the XD1 exposure class.
- The charge passed value is uniform for all three concrete mixtures according to ASTM C 1202, while the level of chloride penetration can be characterized as "moderate" according to the annex of the mentioned standard.
- The logarithmic relationship has been established between the migration coefficient and charge passed, with a correlation coefficient of 0.82.
- A sufficient number of concrete samples were set aside for chloride penetration testing at 90 days, aiming to assess whether the pozzolanic reaction of the glass by that stage enhances the concrete's resistance to chloride ingress.

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Review paper

DESIGN AND ENVIRONMENTAL IMPACT ASSESSMENT OF A RECYCLE CENTER FOR RECYCLE CONSTRUCTION AND DEMOLITION WASTE

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Abstract

Recycling of construction and demolition waste (C&DW) provides new raw materials, reducing the use of natural resources and the amount of waste for disposal. This work aims to increase the recycling rate of C&DW by building a recycling yard with a mobile plant, with minimal negative environmental impacts. Primary separation at source, including removing hazardous waste, is key to increasing the recycling rate. If this is impossible, the waste is transported to recycling yards for secondary separation. When selecting a location for recycling yards, environmental impact, energy requirements, transportation, distance from settlements, and natural factors are taken into account. Recycling yards have control points for measuring the mass of waste and storage. Construction waste is recycled using the best available technologies, and the resulting materials are reused in construction. Waste that is not suitable for recycling is disposed of in landfills, while the excavated soil is used for site rehabilitation. The impact of the recycling technological process on the environment was assessed using the Leopold matrix. Based on the assessed negative environmental impacts, measures were given for their elimination or reduction to an acceptable level, emission limits into the environment were determined, and environmental monitoring was carried out.

Key words: *Technology project, Recycling, Mobile plant, Environmental impact assessment.*

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1. INTRODUCTION

Urbanization encourages increased generation of construction and demolition waste (CDW), which requires effective management practices as it is one of the largest sources of waste globally, and has a major impact on environmental degradation [1, 2].

Construction waste and demolition waste make up about 40% of the total municipal waste generated as a result of large-scale construction activities [3, 4, 5].

According to the Law on Waste Management ("Official Gazette of RS", No. 36/2009, etc.), waste is any discarded substance or object and is divided into communal, commercial, and industrial, while according to its properties, it is classified as inert, non-hazardous, or hazardous. Construction and demolition waste (CDW) are generated during construction, demolition, reconstruction, maintenance, and excavation, and can be non-hazardous (eg, recyclable) or hazardous, and is subject to special regulations [6]. This waste can be defined as a mixture of different materials produced by the construction, maintenance, demolition, and deconstruction of buildings and construction works [7, 8].

Hazardous waste from construction materials used for insulation and roofing poses health risks during demolition or reconstruction [9]. Waste is classified by origin and composition in the Waste Catalog, aligned with the EU system. In Serbia, classification and handling rules are defined by the Rulebook on waste categories. Each waste type has a unique six-digit code; an asterisk indicates hazardous waste [10].

Developers are responsible for managing waste during demolition and reconstruction, and waste owners must arrange collection via authorized companies. Special regulations apply to this waste stream. Asbestos waste removal is overseen by labor inspectors under safety laws. Although banned in the EU since 2005, asbestos still appears in construction waste. It must be separated at source, properly packaged, and disposed of at authorized landfills. Its recycling or reuse is strictly prohibited [11, 12, 13].

Management according to the global hierarchy of waste management (rule 5R) can be proposed as a possibility to reduce landfilled CDW. Hierarchy of waste management (5R):

- Prevention of waste generation and reduction of resources,
- Product reuse,
- Recycling for the production of raw materials,
- Utilization for energy production i
- Environmentally responsible disposal.

Utilization procedures are marked with R and disposal procedures with D. Preferred options in the construction waste management hierarchy are waste utilization activities such as energy recovery (R1), metal recycling (R4), and recycling of other inorganic materials (R5). The disposal of construction waste is challenging because of hazardous materials such as asbestos, heavy metals, and volatile organic compounds that affect human health and the environment. The growing amount of construction waste globally has become an urgent environmental and economic problem, which requires effective waste management practices to mitigate its effects [14].

For proper waste management, it is necessary to accurately determine the index number based on the activity of origin, composition, and presence of hazardous substances. Documentation must follow the waste through the entire chain of handling to ensure safety and compliance with legal regulations [10].

Construction waste is classified in the Waste Catalog as group 17. Non-hazardous waste includes concrete, soil, brick, glass, metal, plastic, wood, and ceramics, while hazardous

waste contains asbestos, PCBs, mercury, and other harmful substances. Effective recycling depends on waste separation at the source, as mixed waste complicates recycling and increases pollution [11]. Concrete is the main component of construction waste [15].

CDW is categorized by origin:

- waste from full or partial demolition,
- waste from new construction,
- waste from road construction and maintenance,
- removal of soil, stones, and vegetation during site preparation.

Common materials include concrete, brick, plaster, soil, gravel, asphalt, metals, wood, and plastic. Demolition waste is more voluminous, while construction waste is often more reusable. Excavated material used on-site is not considered waste but a mineral raw material.

The EU Construction and Demolition Waste Management Protocol aims to build trust in the CDW management process and the quality of recycled materials through better identification, separation, logistics, processing, quality management, and policies [16]. Sustainable construction and a circular economy rely on the continued reuse of construction materials, supported by both the public and international authorities [8, 16].Proper waste treatment and recycling play a key role in preserving the environment and promoting sustainable development. In order to increase the percentage of CDW recycling, it is necessary to build recycling centers with mobile facilities. Recycling centers specialized in CDW allow reducing the load on landfills, preserving natural resources, and reducing greenhouse gas emissions. However, the design process of these facilities requires careful analysis of potential environmental impacts [17].

This paper aims to present the key aspects of the design of a CDW recycling center and the environmental impact of the project (EIA).

2. METHODOLOGY

This study includes an analysis of literature and legal frameworks for the design of a CDW recycling center and the environmental impact of the project using Leopold's matrix. The Leopold matrix is named after the American environmentalist Aldo Leopold. It helps in identifying, quantifying, and evaluating the environmental effects of different project activities on different aspects of the environment.

2.1. Designing a recycling center

Recycling includes all reuse operations (R2–R10, R12) that process waste into products, materials, or substances, excluding energy recovery and conversion into fuel or landfill material [6]. It enables the recovery of useful materials and energy, reduces landfilled waste, lowers treatment costs, and prepares waste for storage. Recycling can also generate funds for further treatment phases, with main goals being waste reduction and conservation of mineral resources.

Construction waste recycling involves technical solutions ranging from mobile crushers to complex recycling centers. Technology selection depends on site-specific conditions, and off-site sorting facilities may also be used. Reliable data on waste origin, composition, and quantity is essential for selecting sustainable technologies and sizing facilities.

Designing a recycling center involves:

• Location (proximity to waste source, road access, minimal environmental impact);

• Infrastructure (reception area, storage, administration buildings, emission treatment systems);

• Technology (crushers, vibrating and magnetic separators, dust control systems).

Site selection must consider environmental impact, energy and utility needs, supply of construction and demolition waste, post-recycling material use, distance from residential areas, wind patterns, and flood risk. The center should include checkpoints for weighing incoming waste and designated storage areas. Recycling uses best available techniques, with products reused in construction and other markets. Non-recyclable mixed waste is sent to licensed landfills, while excavated soil can be used for site rehabilitation [1, 18].

The study by Ding et al. (2018) covered the design and construction phases to assess construction waste reduction. A two-level model was developed in Vensim software, covering waste generation, management, disposal, and environmental benefits assessment. The model supports measures such as prefabricated components, minor design changes, sorting, and reuse. It highlights the growing importance of waste prevention already in the design phase, in addition to construction [1].

2.1.1 CDW recycling procedures

The CDW recycling process at the recycling center consists of the following steps:

1. Reception of waste - visual inspection;
2. Selection - classification according to the waste catalog;
3. Crushing - use of primary and secondary crushers to reduce particle size;
4. Separation - metal parts are separated using magnets; light materials (plastic, wood) are separated by air separators;
5. Classification by granulation - sieve systems classify materials by grain size;
6. Storage - recycled materials are separated and stored according to type (concrete aggregate, metal, wood, etc.);
7. Resale or reuse - materials are used for new construction projects or sales [19].

At the location of the waste generator, the construction waste is selected - useful, useless, dangerous, and other materials are separated and are ready for treatment.

The waste generated from the demolition of the existing stadium is listed in Table 1, by the Rulebook on categories, testing, and classification of waste ("Official Gazette of RS," no. 56/2010, 93/2019, and 39/2021) [10].

Table 1: List of generated waste and total amount after demolition [10]

Index number	**CDW**
17 01	Concrete, bricks, tiles, and ceramics
17 01 01	Concrete
17 01 02	Brick
17 01 03	Ceramics, tiles
17 02	Wood, glass, and plastic
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 03	Bituminous mixtures, tar, and tar products
17 03 02	Bituminous mixtures other than those specified in 17 03 01

Index number	CDW
17 04	Metals (including their alloys) 17 04
17 04 02	Aluminum
17 04 05	Iron and steel
17 05	Earth (including earth excavated from contaminated sites), rock, and excavation
17 05 04	Earth and stone other than those mentioned in 17 05 03
17 06	Insulation materials and building materials containing asbestos
17 06 04	Insulating materials other than those mentioned in 17 06 01 and 17 06 03
17 08	Construction material based on gypsum
17 08 02	Gypsum-based building materials other than those specified in 17 08 01
17 09	Other construction and demolition waste

After the final selection, the waste was placed in bags or containers, which prevented spillage. As the owner of the waste, the producer sorted it according to regulations. The waste was stored until it was handed over to authorized collectors, transporters, or storage facilities with a contract and a valid permit from the Ministry of Environmental Protection. There is supporting documentation for waste transport, but it was unavailable when writing [20].

Bricks, roof tiles, ceramic materials, asphalt, concrete, and reinforced concrete elements, bulky waste, stone, and the like are crushed and classified on the mobile plant. Treatment of construction waste includes mechanical crushing and screening. Crushing is done with a mobile crusher, and sieving and classification with a mobile sieve. The material is loaded with an excavator into the infill vibro-basket of the crusher, from which it falls by gravity into the jaw crusher. The tailings ("soil") are separated on the vibro-grid (first sieve). The crushed material then falls on the conveyor, which, via the magnetic separator, transports it to the mobile sieve, where it is sifted and classified into three fractions: 0–15 mm, 15–45 mm, and 45–160 mm. All fractions are temporarily stored at the waste generator location. The obtained aggregates are recyclable and are used as raw material in construction. Metal waste (iron and steel) is separated on the magnetic separator, which is also stored on site and can be sold as secondary raw material. The main equipment of the mobile plant for the treatment of non-hazardous construction waste is a mobile crusher and a mobile sieve. The crusher crushes all types of stone and solid materials, including crushed concrete, old asphalt, and brick. The auxiliary belt separates small impurities (eg, soil, clay) to obtain clean recycled material.

The plant moves independently as needed. The maximum diameter of the input material is 550 mm, and the crushed material is obtained in fractions of 0–15 mm and 15–45 mm, depending on the need. The capacity of the crusher depends on the type and granulation of the input material, as well as the required size of the output aggregate, and includes the amount of separated material on the magnetic separator. The amount of waste depends on the amount generated amounts of the specific waste generator. Since the already selected material is treated, except for tailings from the vibro-grid, no additional residues are produced [19].

The following figure shows a block diagram of the treatment of non-hazardous construction and demolition waste.

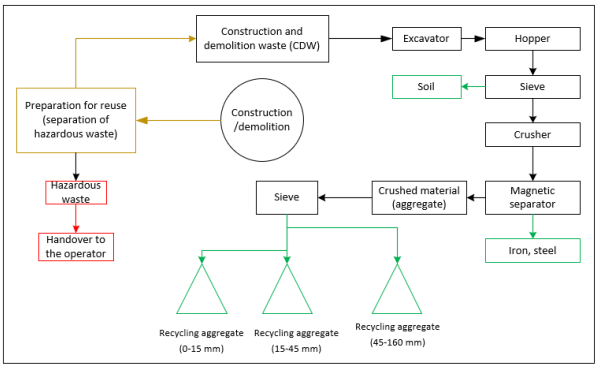

Figure 1. Block scheme for the treatment of non-hazardous construction and demolition waste

Recycled aggregates from construction waste can be classified as concrete, masonry, mixed, and those originating from mixed construction waste with a higher degree of contamination. Their composition depends on the origin and method of processing, which affects the physical properties and quality. The presence of materials such as asphalt, plaster, plastic, or wood can negatively affect the strength of concrete. The research analyzed the properties of recycled aggregates and proposed a classification based on performance. The importance of selective demolition, examination of composition and physical properties before use, as well as proper processing and categorization to ensure reliability in construction application, was emphasized [21].

A large part of the generated construction waste is not returned to the supply chain but is still disposed of in landfills [2]. The problem of construction waste has reached a critical point in many countries. The following negative impacts caused by construction waste can be explained by the following: land occupation, energy consumption, raw material consumption, environmental pollution, and greenhouse gas emissions, all of which threaten ecological sustainability [8].

2.2 Environmental Impact Assessment (EIA)

Urban development requires a project, and all projects aimed at increasing the well-being of urban settlements are associated with numerous environmental and social effects, resulting in positive and negative effects [22].

Environmental impact assessment is the process of identifying and evaluating the possible consequences of projects, plans, or laws on the natural and social aspects of the environment. Its main purpose is to enable decision-making that respects environmental aspects and promotes sustainable development. It includes analyzing impacts, proposing measures to reduce them, and considering alternative solutions. This procedure was introduced in response to the bad consequences of earlier projects that did not take environmental factors into account. Although it has met with resistance in some quarters, especially in developing countries, it helps in better planning and environmental protection. The process includes several stages, including identification of relevant issues, impact analysis, proposing mitigation measures, and involving the public in decision-making [23].

Impact assessment is part of a systemic process that predicts and evaluates the Project's impacts on the physical, biological, socio-economic, and cultural environment, with the

identification of measures to avoid, reduce, and mitigate negative impacts and increase positive impacts. EIA includes the following stages:

• Identification of potential impacts: air emissions, noise, water and soil pollution, impact on biodiversity.

• Analysis and assessment: Using standard procedures and models to predict pollution levels.

• Proposal of mitigation measures: technical, technological, and organizational measures to minimize negative effects [24].

Environmental impact assessment is a systematic process that assesses how human activities affect the ecosystem. It includes data collection, prediction of pollution levels, and analysis of project sustainability. Based on that information, a decision is made whether the project is acceptable from an environmental point of view [23].

The environmental impact assessment study includes data on the project holder and location, a description of the project and its alternatives, the state of the environment, possible impacts (including adverse situations), protective measures, a monitoring plan, a summary for the public, and information on possible technical limitations [25].

2.2.1 Identification of potential impacts

To identify the impact, a modified Leopold matrix is used, which links project activities with the impact on society and the environment. It consists of a two-dimensional table in which the rows represent project activities and the columns represent environmental aspects. At the intersection of each activity and aspect, it is assessed whether there is an impact, and if there is, its importance and intensity are assessed. A modified version of the matrix may include additional factors, such as time duration, reversibility, or likelihood of impact, as well as specific local conditions. Based on the characteristics of the location, project documentation, and identification of sensitive receptors, possible significant impacts during the construction, operation, and closure of the Project are analyzed (Table 1).

Table 1: Possible significant impacts of the project on the environment

Receptor	**Activities**				
	Project Construction	Project Operation	Waste Management	Emergency/Accident Project	Closure
Air quality	√	√		√	√
Surface water				√	
Underground water				√	
Land	√	√	√	√	√
Flora and fauna	√	√	√	√	√
Noise and vibration	√	√			√
Population		√		√	

Gas emissions are caused by the combustion of diesel fuel in engines and are present only during the duration of the work. The technological process does not use water, so there is no wastewater or risk of pollution. Working fluids are stored in tanks, and any leaks are taken care of in metal barrels and handed over to authorized operators. Since the process is dry and without the use of water, no wastewater treatment system is required. During plant

operation and material transportation, there may be a temporary increase in noise (90–100 dB(A)). Greater vibrations are not expected.

2.2.2 Impact analysis and assessment

A sensitivity and strength assessment are used to define the significance of the impact, which ranges from negligible to large (Table 2).

Table 2: Significance of the project's impact on the environment

		Sensitivity		
Influence		Low	Medium	High
	0 No significant impact	Negligible	Negligible	Negligible
	1 Weak	Negligible	Small	Moderate
	2 Moderate	Mali	Moderate	Large
	3 Strong	Moderate	Large	Large

An impact is negligible if any of the receptors (including humans) will essentially not be affected in any way by the particular activity, or the predicted effect is considered "invisible" or indistinguishable from natural variation.

The impact is low if there is a noticeable effect on the resource/receptor, but the magnitude of the impact is small enough, and/or the resource/receptor is of low sensitivity/vulnerability/importance. In any case, the size should be according to the applicable standards.

The impact is moderate if the magnitude of the impact is within the applicable standards, but is in the range from the threshold below which the impact is smaller, to the level where legal limit values may be exceeded. The emphasis on moderate impacts is therefore on demonstrating that the impact is reduced to as low as reasonably practicable.

The impact is significant when a limit value or standard may be exceeded, or large effects occur on highly valued / sensitive resources/receptors. The impact assessment aims to arrive at a position where the project has no significant residual impacts, especially not those that will last in the long term or extend over a large area.

2.2.3 Assessment procedure

The operation of any process plant, regardless of all the technical and technological characteristics of the process itself and the equipment used, can, in certain situations, represent a source of environmental pollution. The impacts that occur during the arrangement of the location itself and which are by nature temporary in nature are the result of the presence of people and machines, as well as the technology and organization of the preparatory works for the construction of the building.

Aspects of the environment that may be affected by the Project, as required by regulations, namely:

The project may have local and temporary environmental impacts, primarily on air quality due to emissions of exhaust gases and dust during construction and, later, from transportation and mechanical waste treatment during operation. There is no impact on surface water quality, as wastewater and rainwater are treated through separators. Short-

term effects on soil and groundwater may occur from material storage and potential spills, but proper waste handling prevents long-term contamination. Noise levels from machinery reach 70–85 dB(A) but are limited to the construction site. There is no expected negative impact on public health due to the project's distance from populated areas and controlled emissions. The project does not affect protected natural or cultural assets, and a green buffer zone offers additional protection. There is no influence on population dynamics or residential zones. Communal infrastructure is unaffected since no water is used in the technological process. Visual impact on the landscape during construction is temporary and will be mitigated with vegetation and architectural solutions. Land use is in accordance with spatial plans, and areas will be restored to their original or improved condition after project completion.

A simplified example of Leopold's matrix was used to assess the impact of the construction and operation of a recycling center for construction waste.

The table shows key project activities (rows) and environmental components (columns), with an impact assessment:

0 = No significant impact; 1 = Weak; 2 = Moderate; 3 = Strong.

Table 3: Leopold's matrix for environmental impact assessment

Activity/ Aspect	Air quality	Noise	Soil	Surface and groundwater	Population	Flora and fauna	Use of resources
1. Reception of waste	1	1	0	0	1	0	1
2. Crushing	3	3	2	0	2	1	2
3. Separation	1	1	1	0	1	1	0
4. Storage	0	0	1	0	0	0	1

Table 4. Type and characteristics of impacts during construction, operation, and closure of the Project

Environmental factor	Significance of impact
Construction and closure of the project	
Air	Moderate
Surface water and municipal infrastructure	Small
Soil and groundwater	Small
Noise and vibration	Moderate
Public health	Small
Flora and fauna	Small
Resource use	Small
Project work	
Air	Moderate
Surface water and municipal infrastructure	Small
Soil and groundwater	Small
Noise and vibration	Moderate
Public health	Small
Flora and fauna	Small
Resource use	Small

3. RESULTS

The key results based on the assessment of the project's impact on the environment, using the Leopold matrix methodology, are:

• The greatest negative impacts are expected in the crushing phase (on air, noise, and population);

• Overall impacts are mostly local in nature and temporary in duration;

• There are positive impacts in terms of employment and the re-use of resources.

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• The greatest negative impacts are expected in the crushing phase (on air, noise and population);

• Overall impacts are mostly local in nature and temporary in duration;

• There are positive impacts in terms of employment and re-use of resources.

4. DISCUSSION

The obtained results show that the design of the recycling center according to the principles of sustainable development has multiple benefits, including the protection of natural resources, reduction of pollution, and economic benefits through the sale of recycled materials. The application of Leopold's matrix enabled the systematic analysis of all relevant impacts and the prioritization of mitigation measures.

Environmental protection measures can be classified into the following categories:

• Legally prescribed measures and standards;

• Protection measures in the event of an accident;

• Technical and planning solutions for protection;

• Measures during the cessation of work or removal of the facility;

• Other relevant measures.

When designing, you should choose a location that is at least 500 m away from residential areas and watercourses in order to minimize the impact of noise and water pollution.

It is necessary to comply with regulations on air protection, use technical solutions to prevent emissions, regularly maintain equipment, and carry out monitoring with reporting to competent authorities. The application of a water spraying system and closed crushers reduces dust emissions.

It is forbidden to dispose of dangerous substances that threaten the soil. Waste must be managed according to the law - it must be properly classified, stored, handed over to authorized persons, and the flow of waste must be monitored.

It is necessary to comply with regulations on noise, apply technical measures to reduce it, perform measurements, and react if the permitted values are exceeded. The installation of sound barriers can reduce the noise level by 15-20 dB.

It is necessary to apply safety procedures, train employees, use protective equipment, and regularly control safety at work.

5. CONCLUSION

Designing a recycling center for construction waste, with an adequate environmental impact assessment, contributes to sustainable waste management. The Leopold matrix is an effective tool for impact assessment and helps in the design of environmentally friendly plants. The main challenges are dust and noise emissions, which require measures such as sprinkler systems and sound barriers. Mitigation of these impacts is key to the acceptance of the plant by the local community.

Success depends on the correct choice of location, modern technologies, legal regulations, investor motivation, and citizens' awareness. Further activities should be directed towards education and encouragement of the private sector.

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Review paper

OVERVIEW OF ARTIFICIAL NEURAL NETWORKS APPLICATION IN DAMAGE DETECTION OF MASONRY STRUCTURES

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Abstract

In order to ensure the durability of masonry structures, prevent their deterioration and serious damage, it is necessary to carry out regular inspections of the condition of building elements. Determining the condition of masonry structures is most often done manually, by visual inspection, which is a time-consuming process, the quality of which largely depends on subjective feeling. As there is an increasing need for automated data processing and work processes today, in recent years there has been an increasing application of artificial intelligence in the process of segmentation and damage detection in masonry structures using Artificial Neural Networks (ANNs). The aim of this paper is to carry out a detailed analysis of the application of artificial intelligence in the segmentation of masonry elements and the detection of damage to masonry structures through a review and analysis of papers published in the literature.

Key words: *Masonry Structures, Artificial Neural Networks, Damage Detection*

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1. INTRODUCTION

Masonry structures represent the largest part of building structures in the world, of which there are a large number of historical buildings that are part of the cultural heritage, and in addition, masonry structures are still widely used today for the construction of modern structures [1,2]. The materials used for the construction of masonry structures are among the oldest used for the construction of buildings, from stone masonry elements to those made of clay, as well as modern construction materials. Structural elements in masonry structures are formed from masonry elements (bricks, blocks, irregular stone, etc.) that are joined together with or without mortar [3]. Structural and non-structural elements formed by masonry are one of the main components in both modern and historical buildings around the world.

Cultural heritage is of great importance for the preservation of the nation's history and the transmission of the precious knowledge and skills of the ancestors. Due to the aging process, activities due to use, as well as unpredictable natural disasters, historical buildings deteriorate over time. The existence of a large number of old masonry structures shows that their lifespan can be significantly extended. In order to ensure the structural integrity of masonry buildings, regular inspection and maintenance are required [4].

As a result of the process of gradual deterioration, different forms of damage will be visible on the structures, which mainly leads to a decrease in load capacity, stiffness and integrity. Damage is always reflected on the surface of structures in the form of cracks, efflorescence, peeling. Cracks in masonry walls are a common problem that can have significant structural and aesthetic implications, so it is considered that cracks are the main concern for the durability and safety of masonry structures, so it is of great importance to identify and localize surface damage quickly and efficiently [5]. The key task for ensuring the safety and longevity of masonry structures is the timely detection of damage. The goal of damage detection is to identify and locate cracks, that is, the separation of masonry elements, which needs to be detected at the earliest stage in order to avoid unwanted situations, such as damage or collapse of the structure due to large cracks, and this is one of the key steps in analyzing the stability and load-bearing capacity of masonry structures.

In the process of inspection of masonry structures, detection and definition of damage pathology (cracks, breakage, etc.), traditional techniques are used mainly in the form of visual and manual inspection [2]. Manual inspection is the most common in practice due to its simplicity during the identification and assessment of surface damage of masonry structures. This approach is expensive and sometimes difficult to implement, because there are parts of objects with limited access and difficult to reach. To detect surface damage in real practice, a visual inspection performed by trained inspectors is used to detect various defects in historical structures in situ supplemented by professional equipment. Applying this method in the crack detection process has significant operational advantages, but requires an extremely high level of professional experience and is expensive, while operators must be able to fully understand the properties of the inspected cracks and determine whether repairs are needed. Manual and visual inspection can achieve an effective performance in most scenarios, however sometimes this approach is unreliable as serious damage may not be detected [5,6]. One of the methods for damage detection is based on sensor systems that are integrated and installed in historical structures, which also requires a professional workforce to operate them. In recent years, advances in laser scanning and photogrammetry have begun to change the construction industry as such techniques are able to rapidly and remotely capture objects and features in image and point format using drones [2,4]. However,

in this approach, it is difficult to create appropriate datasets as the images become more complex, their complexity increases and it is difficult to distinguish the target and background region, i.e. the detection performance decreases, because the wall surface is complex.

Research in this area is increasingly focused on the development of new and innovative methods for fast, accurate and non-destructive damage detection. As the process of damage detection can be considered multidisciplinary, in recent years there has been an attempt to apply artificial intelligence in this area, i.e. in image processing for the quantification of deformations and damage detection on the wall. Image-based analysis can be considered a key step in stability analysis, condition assessment and damage detection of objects, i.e. in the detection and delineation of their structural components, which is a key and initial step in the process of documenting the state of a masonry structure. As a brick wall is a heterogeneous material that contains individual masonry elements (bricks, blocks, hewn and irregular stones and others) and bonding agents (mortar, clay, chalk, etc.) between the main elements, which connect them, it is often necessary to determine the original arrangement of brick and mortar parts of masonry components that are damaged, or obscured by various objects such as ornaments or vegetation [7,8]. In recent years, deep learning techniques have been applied to the analysis of masonry wall images, where large amounts of annotated data need to be provided to achieve high accuracy, which can be difficult. The aim of this work is to present the possibility of applying artificial intelligence in the segmentation of masonry walls and damage detection through the presentation and analysis of works available so far in the literature.

2. ARTIFICIAL NEURAL NETWORKS

Artificial Neural Networks (ANN) represent a special category of machine learning models inspired by the human brain. A specialized subtype of ANN is convolutional neural networks (CNN). CNN was created in response to the need for more efficient image analysis, because classical ANN networks were not adequate for processing data with a large number of dimensions (eg images with millions of pixels). CNN uses the basic principles of ANN, but adds specialized layers: Convolutional layers - extract features from images through filters, Pooling layers - reduce data dimensionality without losing key information, and Fully Connected layers (FCN) - perform classic ANN processing for decision-making at the end of the network. According to these possibilities, this type of network has also found application in many areas of construction, where an image can be used as an input data in the network. This era of application is being significantly refined and applied after the first applications of ANN in structural modeling [9], when Ghabousi et al. first showed possible applications in this area.

Over the last decade, ANNs have been applied in many areas of civil engineering, including soil behavior, flow, pile bearing capacity, support structure and slope stability, site characterization, tunnel design, and structure identification [10,11]. The application of ANN is especially pronounced in construction problems where, until now, it was not possible to define numerical dependencies.

During the creation, training and testing of a neural network, it can be taught to perform a specific task on a specific example, that is, a set of specific data that is used for training the network, just as humans process information and learn on a specific example. That is why

the correct definition of input data, their segmentation, classification, normalization and preparation is a key process for the quality operation of the network itself.

Finding the best network model for a particular case is a difficult task that generally requires repeated testing and evaluation of results. The process of solving problems using ANN is reduced to learning or training and continues until the error between the response of the neural network and the desired output (called the goal) is minimized for the entire set of pairs: given input - known output. Such research has shown that CNNs are very suitable for solving problems that can be applied in construction. CNNs have made significant progress in the digital analysis of construction objects, and especially in the segmentation and detection of damage to masonry structures. The first significant CNN architecture, LeNet, was developed at AT&T Bell Laboratories during the period 1988-1998, laying the foundation for later developments. A large number of researchers improved this model, which resulted in the emergence of standard datasets for machine learning research and training. One of the representative ones is CIFAR-10 as well as ImageNet as a large visual database designed for use in visual object recognition software research. Since 2010, the annual Large Scale Visual Recognition Challenge (LSVRC) has been held, featuring AlekNet in 2012, which achieved an error rate of 15.3%, thanks to the development of parallel graphics processors, and ZFNet in 2013, which achieved an error of 13.5%. Its structure is similar to the AlexNet network, except that it uses the ReLU function. In 2014, at the same competition, Google presents the GoogLeNet network, which achieves an operating error of 6.7%, when in the same competition they share the first place with the VGGNet network, whose error is 7.4%, which is much simpler. All these results speak in favor of the quality and potential that these networks can have, and thus they are becoming more and more common in various applications [12].

CNN models have found a particularly significant application in wall segmentation and crack detection. U-Net is one of the first architectures specialized for segmentation, while the later DeepLabV3+ and FPN models improved the accuracy of wall construction analysis [9]. FPN (Feature-Pyramid-Network) is an FCN network for object detection and has shown good results in construction applications. LinkNet is a special type of FCN networks developed for pixel-by-pixel segmentation that can be used for real-time applications [2]. In order to improve performance, achieve high accuracy, robustness and adaptability in image classification, CNN models are becoming more and more complex.

It is shown that the complexity of the model and the obtained results are extremely dependent on the availability of training data. In paper [6], the models show good results in the detection of cracks on masonry facades, however, the performance of these models largely depends on the availability of training data. In addition, it is shown that not only the input data is crucial for certain types of problems, but that many problems also depend on the experience of the one who processes them. Based on the analysis of the review papers presented in the literature so far [10,11,13,14,15], it can be concluded that artificial neural networks have found their application in almost all areas of construction engineering and that due to the greater flexibility of work, the results obtained can be much better than if some of the traditional methods for solving construction problems were applied.

3. REVIEW OF PAPERS DEALING WITH DAMAGE DETECTION USING ARTIFICIAL NEURAL NETWORKS

In this part of the paper, different approaches to the application of artificial neural networks, i.e. deep learning in the detection, segmentation and analysis of damage to masonry structures are presented.

K. Chaiyasarn et al. [4] developed an automatic system for crack detection in masonry structures using a combination of convolutional neural networks and Support Vector Machines (SVM). Data was collected using a drone and a DSLR camera at historical sites. VGG16 CNN architecture was used for feature extraction, while SVM served as a classifier. The model was evaluated using accuracy, precision, sensitivity and F1-score metrics. The CNN-SVM combination achieved 86% accuracy and an F1-score of 78%, outperforming the classic CNN model (79.35% accuracy). The results show that the combination of CNN and SVM enables more accurate crack detection compared to the stand-alone CNN model.

In further research, K. Chaiyasarn et al. [16] deal with the application of CNN in crack detection, where they compared the performance of different classifiers: Softmax, Support Vector Machines and Random Forest (RF). The models were evaluated based on the accuracy, precision, sensitivity and F1-score metrics on the validation and test sets. The CNN+SVM model achieved the best performance with an accuracy of 86% on the validation set and 74% on the test set, with an accuracy of 89% and an F1-score of 87%. The CNN+RF model had an accuracy of 82% on the validation set, while the CNN+Softmax had the worst performance due to unbalanced classes. The results show that the combination of CNN for feature extraction and SVM for classification enables higher accuracy and robustness in crack detection compared to other classifiers.

N. Wang et al. (2018) [5] developed an automatic damage classification system on historic masonry structures using CNN. The system is trained to classify four types of damage: intact brick, crack, efflorescence and spalling. AlexNet and GoogLeNet models were used. GoogLeNet achieved 94.3% accuracy on a large dataset, while AlexNet achieved 92.1%. On a smaller dataset, GoogLeNet achieved 89.7% accuracy and AlexNet 87.4%. The conclusion of the paper is that GoogLeNet achieves better performance than AlexNet and enables higher accuracy and sensitivity in damage classification on historical masonry structures.

Luqman A. et al. [17] used Faster Region Convolutional Neural Networks (FRCNN) for damage detection and localization of masonry structures based on a set of historical wall images collected using a DJI Phantom 4 drone and a DSLR camera. The algorithm consists of a Region Proposal Network (RPN) for generating damage region proposals and Fast R-CNN for damage classification and localization. ZF-net architecture was implemented to improve efficiency. Model evaluation was performed using Mean Average Precision (mAP), with the model achieving 96.50% mAP. The paper shows that Faster R-CNN enables high accuracy and speed in automatic detection and localization of damage to masonry structures.

Yahya I. et al. [7] developed a technique for automatic brick segmentation on brick walls using a U-Net convolutional neural network for marker detection and the Watershed algorithm for precise brick segmentation. The experiment was conducted on a dataset of 162 images of walls from archaeological sites and modern buildings. The U-Net architecture uses ReLU activation and Max Pooling layers in the encoder, while the decoder uses up-convolution layers for image reconstruction. The Adam optimizer was used to train the network with a binary cross-entropy loss function. The performance of the model was defined based on the F1-score, which ranged from 76% to 97%, depending on the type of wall. The

Watershed algorithm showed better performance compared to Connected Component Analysis (CCA), especially on walls with complex brick-mortar structures.

D. Brackenbury et al. [18] developed an automated system for detecting defects (cracks, landslides, mortar loss, vegetation) on masonry arch bridges using the GoogleNet Inception v3 architecture, trained by transfer learning. Nine multi-story arched bridges were photographed, which generated around 24,500 images. The best results were achieved when mortar and brick were completely separated, with an accuracy of 94.7%, a response of 95.3% and an F1-score of 95.0%. Mortar and brick separation significantly increased classification accuracy and reduced performance variation between different masonry images. The strategy without mortar separation achieved the lowest accuracy, with an F1-score of 83.6%, due to confusion between cracks and mortar lines. The paper shows that the complete separation of mortar and bricks enables greater accuracy and reliability in the detection of defects on masonry arched bridges.

N. Wang et al. [19] developed an automated damage detection system on historic masonry buildings using Faster R-CNN with ResNet101 architecture. The model achieves high precision (AP 0.999 for flowering, 0.900 for collapse, mAP 0.950) and enables accurate detection, localization and classification of damage even in real conditions. They also implemented a mobile system for real-time inspection using IP cameras and smartphones.

A. Rózsás et al. [20] developed an automated method to quantify the similarity of cracks in masonry structures using deep neural networks. Using an 8-layer CNN model, they generated numerical crack similarities for objective damage assessment. Due to the lack of data, they created synthetic crack images using the Markov-walk algorithm. The model achieved an accuracy above 99% in crack classification, proving the high precision and reliability of the approach.

Yahya I. et al. [8] developed a fully automatic algorithm for the detection, segmentation and reconstruction of brick walls using the U-Net network and GAN models. Wall segmentation includes three classes: bricks, mortar and damaged regions, while GAN models enable virtual reconstruction of hidden parts of the wall. The Watershed algorithm precisely extracts the contours of the bricks, and the style transfer enables the transfer of color and texture. The model achieves an F1-score of up to 97.58%, proving the high precision of segmentation and reconstruction.

M. Sakamoto et al. [21] developed an improved method for the automatic extraction of stone blocks from the walls of historical buildings by combining multiscale image segmentation and a three-phase Stacked Conditional GAN (cGAN) network. Multiscale segmentation generates block polygons, while cGAN improves edge detection and fuzzy contour reconstruction. The method significantly increases segmentation accuracy, allowing better separation of stone blocks and reducing the need for manual parameter setting.

D. Dais et al. [1] focused on improving crack detection accuracy by testing different pre-trained CNN architectures. MobileNet proved to be the most accurate model, achieving 95.3% accuracy in patch classification and 79.6% F1-score for pixel-level segmentation. Kaiwen C. et al. they further investigated this problem by using drones for facade inspection. Their system, a combination of a CNN for patch-level classification and a U-Net model for pixel-level segmentation, achieved an F1-score of 96%, outperforming traditional crack detection methods.

In the paper Kaiwen C. et al. [22] developed an automated system for crack segmentation on building facades using UAV imagery and deep learning. Patch-level classification is

performed by the CNN model, while U-Net performs crack segmentation at the pixel level. The CNN model achieves an accuracy and F1-score of 94%, while U-Net achieves 96%. The two-stage CNN+U-Net model outperforms Canny Edge Detector and stand-alone U-Net, providing higher detection accuracy. The study shows that the combination of patch-level classification and pixel-level segmentation enables accurate and robust detection of cracks on UAV images of facades.

In the continuation of the research, Yahya I. et al. [23] developed an end-to-end blind inpainting algorithm for the detection and reconstruction of damaged parts of brick walls. They used U-Net for segmentation and two GAN models for automatic damage detection and filling. The first GAN recovers the structure of the wall, while the second predicts the pixel color. The efficiency of the algorithm is confirmed by PSNR and SSIM metrics. The evaluation shows that the combination of U-Net segmentation and two GAN models enables high precision in the generation and realistic filling of the hidden parts of the walls.

The paper of D. Loverdos and V. Sarhosis [2] deals with the automation of brick segmentation and crack detection on brick walls using image processing and machine learning. Various deep neural network architectures, including U-Net, DeepLabV3+, LinkNet, and FPN, have been used for pixel-level segmentation. Watershed algorithm was applied for precise segmentation of bricks, while Inverted Distance Transform (IDT) and H-minima transform improved the accuracy of marker generation. U-Net achieved the best results, with an F1-score of 97.58% on bricks and 94.19% on pixels for fine cut stone and 79.93% for slate. The combination of CNN and Watershed algorithm enables precise and robust segmentation even in complex conditions.

The paper of L. Minh Dang et al. [24] focuses on automatic segmentation and length measurement of cracks in brick walls using deep learning. An extensive database of manually annotated cracks was created, and three neural network architectures were tested: U-Net, DeepLabV3+, and Feature Pyramid Network (FPN). The DeepLabV3+ model with ResNet-50 as the base model achieved the best result (IoU = 0.97) and was chosen for the final implementation. The Mask-RCNN model was used to detect bricks, allowing precise measurements of cracks in millimeters. The proposed method significantly improves the accuracy of segmentation and enables a quick assessment of damage severity, reducing the subjectivity of manual inspections.

The paper of S. Katsigiannis et al. [6] deals with the detection of cracks in brick walls using deep and transfer learning. The dataset consists of 700 images of facades with different types of cracks and complex backgrounds. Pre-trained CNN models, including MobileNetV2, InceptionResNetV2 and Xception, were tested with two training strategies: end-to-end and fine-tuning back layers. MobileNetV2 achieved 100% accuracy and F1-score with end-to-end training with data augmentation, while the fine-tuning strategy led to a decrease in accuracy (F1-score 92.99%). The results show that end-to-end training is a superior strategy for adapting models to masonry structures, while MobileNetV2, due to its high accuracy and small model size, enables the application of mobile devices and drones.

In the paper of Sheetal Sharma [25], an automatic system for damage detection and segmentation on historical masonry buildings was developed using Mask R-CNN model based on DenseNet architecture. The model uses Region Proposal Network (RPN) for damage identification and RoI Align for precise pixel-level localization. The dataset contains images of walls with efflorescence and spalling, manually annotated with bounding boxes and binary masks. The model achieves an accuracy of 99.9% and an F1-score of 98.5% for

efflorescence, while for spalling the accuracy is 90% and an F1-score of 87.5%. Mask R-CNN on the DenseNet framework showed superior performance compared to Faster R-CNN and U-Net models, enabling high accuracy segmentation and damage classification of masonry objects.

Qinghua L. et al. [26] propose a new DeepCrackAT architecture for brick wall crack segmentation, aiming to improve accuracy in scenarios with different crack widths and complex backgrounds. The model uses a combination of Hybrid Dilated Convolution (HDC) to increase the receptive field and Tokenized Multi-Layer Perceptron (Tok-MLP) for optimized projection of high-dimensional features into a more compact space, thereby reducing the number of parameters and improving noise immunity. The model achieves an F1-score of 76.67% and an IoU of 64.44% on the Masonry dataset, while the results on the Rissbilder dataset are somewhat weaker. Experiments have shown that DeepCrackAT outperforms Unet, SegNet, DeepLabV3+ and UneXt models, especially in the segmentation of cracks.

D. Marín-García et al. [27] developed a deep learning model for efflorescence detection and classification on brick facades using YOLOv5. The model discriminates bricks that only require cleaning from those that need to be repaired, achieving an mAP of 0.894 after 100 training epochs. The classification accuracy was 85% for "clean" and 82% for "repair". The results show that YOLOv5 enables fast and accurate detection of efflorescence, even in real-time conditions.

Yahya I. et al. [28] developed an end-to-end deep learning-based system for the analysis, reconstruction, and stylization of brick walls. The U-Net network segments the wall into bricks, mortar and damaged regions, while two GAN models restore the structure and color of the obscured parts. Style transfer allows you to move textures and colors between walls. The model achieves an F1 segmentation score of 83.6% and a realistic wall reconstruction, proving the high precision and applicability of the method.

A. Iannuzzo et al. [29] deal with the identification of the causes of cracks in masonry structures using artificial neural networks. The research combined the piecewise-rigid displacement (PRD) method to quickly generate data on possible foundation settlement scenarios with neural network models that analyze crack patterns. Testing has shown that the model achieves an accuracy of 98.3% for vertical settlement and 97.1% for horizontal settlement, enabling automatic and precise analysis of the causes of cracks in masonry structures.

4. ANALYSIS OF THE PRESENTED PAPERS

As damages to masonry structures, especially those of historical importance, are frequent, and their knowledge is essential for the stability and durability of the building, it is sometimes necessary to determine the cause of their occurrence in the shortest possible period. The process of damage detection used to be laborious and time-consuming, so the use of modern means to detect them has been increasing in recent years. As part of this paper, papers were analyzed in which artificial intelligence was used, especially deep neural networks, in the area of damage detection and analysis of masonry structures. A total of twenty-one papers published in the period from 2018 to 2024 were analyzed, which mainly dealt with historical buildings at specific archaeological sites, brick bridges and facades of older buildings where cracks were detected and degradation of building materials was performed. The largest number of papers was published in 2023, which may indicate the

increased application of deep learning in the analysis of masonry structures and the improvement of segmentation and damage detection methods. Most of the papers deal with the detection of cracks, classification and analysis of damage, segmentation and reconstruction of walls as well as detection and segmentation of wall elements when performing the following activities:

- Classification – categorization of damage (eg cracks, collapse, efflorescence).
- Segmentation – precise marking of damage areas at the pixel level.
- Detection – finding damage in the image using bounding boxes.
- Reconstruction - filling in damaged parts of the wall.

Certain areas in which the analyzed papers deal with are also noted.

Table 1. Areas of application in the analyzed works

Areas of application	Papers
Crack detection	[1],[4],[6],[16],[22],[24], [26]
Damage classification and analysis	[5], [19], [20], [25], [27], [29]
Segmentation and reconstruction of walls	[8], [21], [23], [28]
Brick/mortar detection and segmentation	[2], [7], [17], [18]

Analysis of the available papers in the literature shows that they have been used:

- Convolutional Neural Networks (CNN) for feature extraction.
- Transfer learning to improve model performance.
- Generative adversarial networks (GAN) for wall reconstruction and stylization.
- Region Proposal Network (RPN) and Mask R-CNN for damage detection.
- Watershed algorithm for precise brick segmentation.
- Piecewise Rigid Displacement (PRD) + ANN for crack cause analysis.
- DeepLabV3+, U-Net, YOLOv5 and other segmentation architectures.

The following neural networks were used:

- CNN architectures: VGG16, AlexNet, GoogLeNet, Inception v3, ResNet34, ResNet50, MobileNetV2, DenseNet, Xception.
- Specialized architectures: Faster R-CNN, Mask R-CNN, U-Net, DeepLabV3+, Feature Pyramid Network (FPN).
- GAN models: Conditional GAN (cGAN), Style transfer GAN.
- Multilayer Perceptron (MLP) in ANN models for crack analysis.

The most frequently used methods of validation and achieved values for the evaluation of applied models have been carried out:

- Accuracy: from 79% to 100% depending on the model.
- Precision, Recall, F1-score: values between 76% and 99.9%.
- Mean Average Precision (mAP) for damage detection and localization.
- Intersection over Union (IoU) up to 0.97 for precise segmentation.
- PSNR and SSIM for evaluating the quality of wall reconstruction.

As in the process of forming a network for the accuracy of the achieved results, a significant number of data in the analyzed papers was:

- Less than 1,000 images with 76-94% accuracy achieved
- 1,000 - 10,000 images with 85-97% accuracy achieved
- More than 10,000 images with 92-100% accuracy achieved

5. CONCLUSION

The largest number of papers focuses on historical buildings and archaeological sites, which shows the researchers' interest in preserving cultural heritage, while a smaller number of papers is focused on modern construction objects. Most of the papers deal with segmentation, because the precise detection of damage and boundaries of the masonry element is crucial for the analysis of the stability and durability of masonry structures. Larger datasets generally lead to better results, but some models successfully use transfer learning to compensate for the lack of data. Deep learning outperforms traditional methods in most cases, so it can be assumed that in the future classical image processing methods will be used as auxiliary techniques. The application of neural networks in damage detection can reduce the need for skilled labor, speed up inspection processes and enable more objective damage assessment. In this way, it can help civil engineers and archaeologists when studying the condition and stability of masonry structures during maintenance, documenting or assessing the required level of protection, especially for buildings of historical importance.

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Research paper

AI SUPPORTED PYTHON PROGRAMMING IN ARCHITECTURAL FORM-FINDING PROCESSES

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Abstract

In recent years, artificial intelligence (AI) has become widely accessible, with powerful AI tools integrated into common ICT services and new AI-based applications emerging almost daily, often freely available. The Architecture, Engineering, Construction, and Operation (AECO) sector is no exception, as numerous studies highlight AI-enhanced applications supporting various aspects of the industry. While many focus on visualization, AI is also increasingly contributing to design and construction processes. This paper explores the process of architectural form generation using Rhino 3D, leveraging Python scripting for parametric geometric modeling. ChatGPT-3 was utilized to generate Python scripts compatible with the Rhino 3D Python Editor, benefiting from its ability to integrate mathematical concepts with programming logic and respond to textual programming prompts. Through this approach, a series of complex geometric forms was modeled, visually examined, and selectively 3D printed. Following an introduction to the relevant mathematical concepts and digital tools (ChatGPT, Python, and Rhino 3D), the paper details the methodology for guiding AI through parametric modeling. Since achieving the desired results is not always straightforward, specific strategies for controlled, purpose-driven interaction with ChatGPT are outlined. The study is illustrated with characteristic examples, and the generated architectural forms are analyzed, discussing the advantages and limitations of the approach. The paper concludes by examining the evolving technological skillset required for contemporary architectural design in the AI era.

Key words: *AI, Python, Architecture, Geometry, Form-finding*

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1. INTRODUCTION

Artificial intelligence and its wide usage is a phenomenon that could be examined in almost every aspect of the human activity in the digitalized world. It is present, sometimes invisible, in services ranging from simple email correspondence, to complex managing of urban life. The appearance of freely available, user oriented chat bots in recent years, additionally challenges fields like education, medicine, marketing, music creation, language assistance, data analysis, content writing and many others.

In this study, one professionally-controlled usage of AI is demonstrated. It relates mostly to an assistance to Python coding for the Rhino 3D software. The main framework of the study is geometric form-finding as a part of architectural design. The experimental work was completed in the summer 2023 and 3D printing was realized in spring 2024.

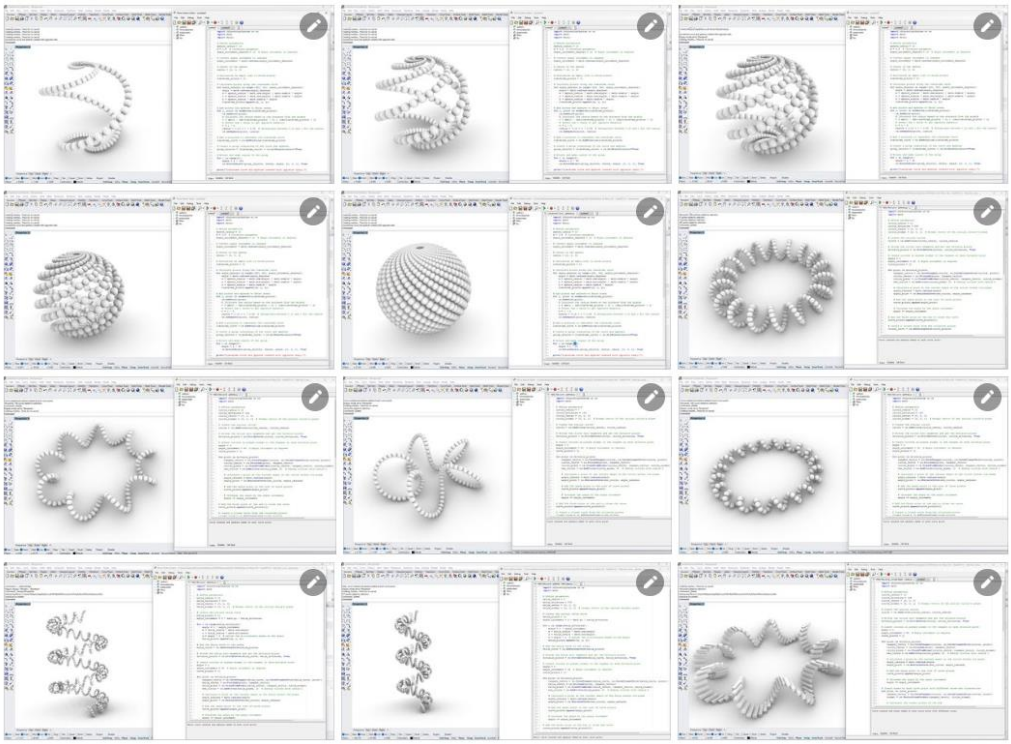


Figure 1 A set of geometric forms created by combining mathematics, AI, Python and Rhino 3D

In the study, a series of geometric forms have been created (Figure 1) and several different knowledge aspects were mutually used:

- Mathematical/geometry-wise (regarding parametrization of spatial curves and surfaces),
- AI-wise,
- Python-wise (regarding programming),
- Rhino 3D–wise (regarding modelling and visualization), and
- 3D printing-wise

Each of the knowledge aspects is analysed in the following sections.

In this research it is assumed that spatial curves play a crucial role in forming a tectonics of architectural form, defining often its structural elements, shell geometries and decorative parts.

Relying on mathematical knowledge with which architects are equipped, in this study, well known, parametrically defined curves have been examined, relying on their potential to contribute to architectural form-finding by their relatively unexpected appearance.

It is important to stress that the examination process relies on significant previous experiences of the authors in both fields of architectural 3D modelling and various aspects of coding.

2. MATHEMATICAL / GEOMETRY-WISE ASPECT

Differential geometry, serving as a mathematical discipline dedicated to the study of smooth shapes and spaces, empowers architects with the capacity to craft sleek, refined forms through its foundational principles. By employing differential equations, architects can precisely manipulate the geometry of structures and surfaces within digital environments, enhancing both the accuracy and efficiency of design iterations, ultimately leading to the creation of more refined and optimized architectural solutions.

In this study, a key focus lies in exploring the parametric representation of curves and surfaces, a method widely applied in computer graphics, CAD, and mathematical modelling, for describing shapes in three-dimensional space. This method expresses points on a curve or surface as functions of one or two parameters, respectively. To be more precise, a space curve can be described by a vector function of a single parameter t: $r(t) = (x(t), y(t), z(t))$, where t varies over some interval, while $x(t), y(t)$ and $z(t)$ are functions that define the coordinates of points on the curve. A helix is a common example of a space curve whose equations can be given as: $x(t) = a\cos t$, $y(t) = a\sin t$ and $z(t) = bt$, where a is the radius of the helix, b is the pitch, and t is the parameter.

This mathematical concept is quite basic but sufficient for the subject of this study, and we certainly assume that architects are proficient in this knowledge, as well as knowing the realm and the aesthetics of space curves and surfaces [1], especially the ones widely used in architecture [2]. For a deeper understanding and exploration of more complex mathematical concepts that can also be applied in generating architectural form, we recommend a [3] and [4].

However, the essence of this work lies not in the application of complex mathematical theory, nor in deep familiarity with the next two tools discussed in the following sections, but rather in the synergy of understanding fundamental concepts from all three fields, enabling architects to optimally leverage their expertise in shape generation without the intervention of mathematicians and programmers, exploring, programming, and creating seemingly independently.

3. AI-WISE ASPECT

In this study, AI is used to assist in the process of Python coding for Rhino 3D. The AI chatbot was ChatGPT, version 3, which is freely available on the Internet.

A chatbot is defined as a software application or web interface that is designed to mimic human conversation through text or voice interactions [5] ChatGPT is one of the most well-known chatbots, developed by OpenAI Company. It appeared in the late 2022 and was dramatically quickly widespread [6].

The interaction with ChatGPT was called here “conversation” [7]. The conversations were conducted in English language.

The conversation with ChatGPT normally started with a mathematical/geometry introduction. This step was very important in terms of focus the chatbot on the desired area. Here are the examples of the introductory questions asked:

- “Could we talk this time about space curves?”
- “Could you, please, list the well-known space curves with their parametric representations?”
- “Could you give an example of space curve, represented parametrically (X, Y, Z)”
- ….

It is possible to say that, in this area, ChatGPT deals with a considerable body of reliable knowledge. Here’s an example of conducted a simple (helix-related) conversation (Figure 2):

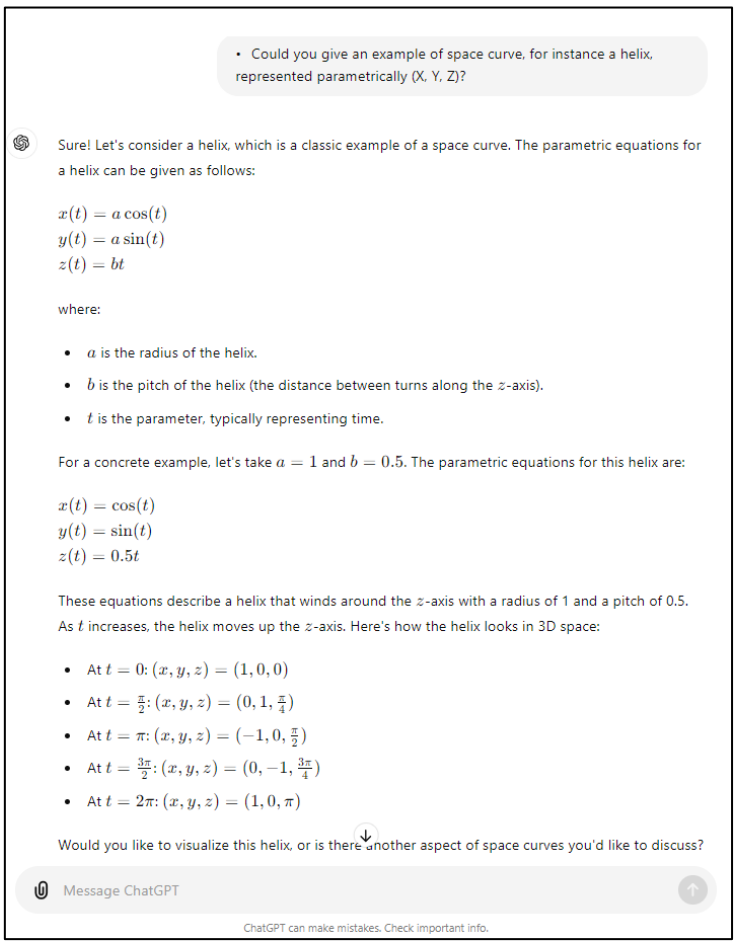
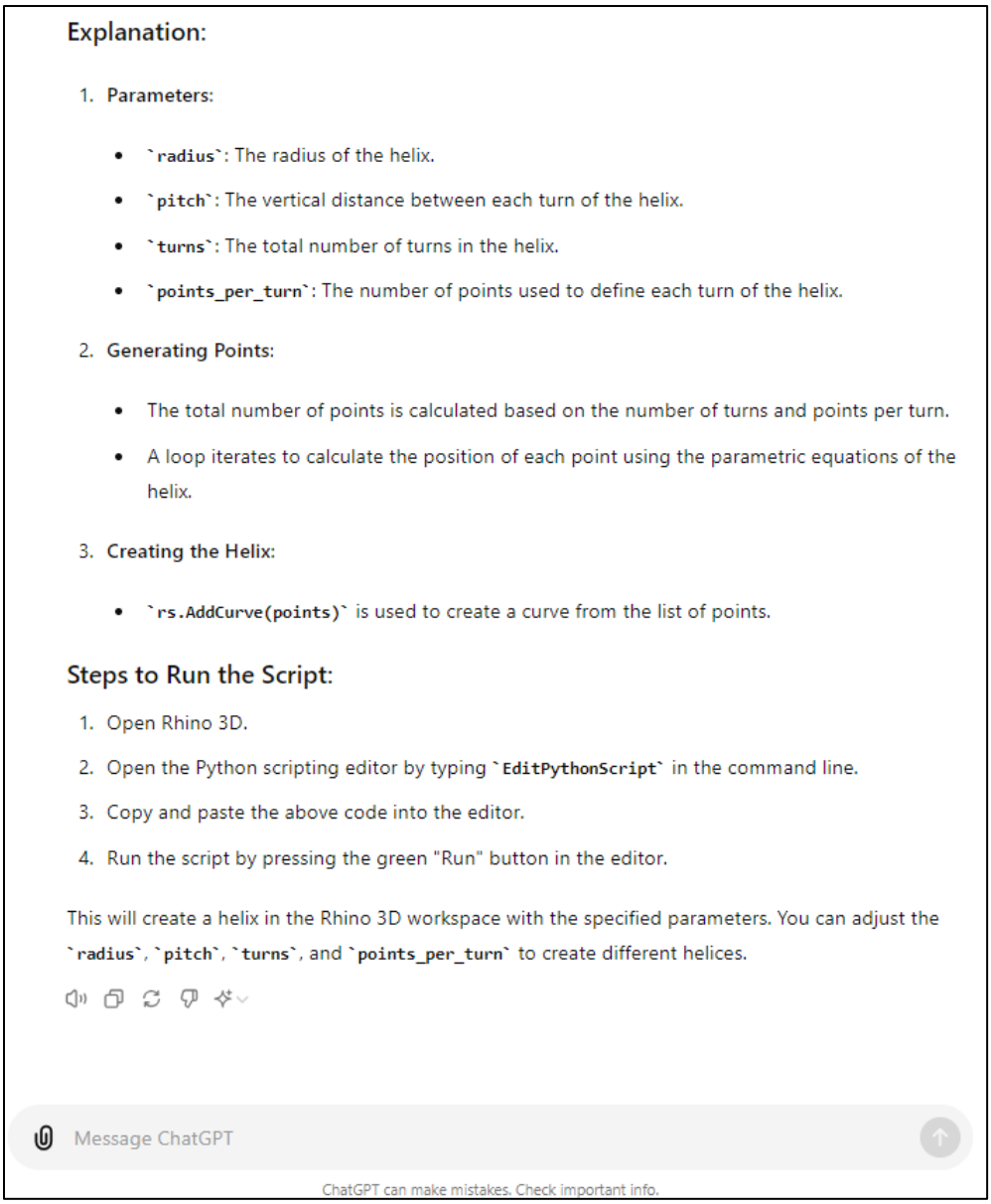


Figure 2 An example of a conversation with ChatGPT about a helix space curve, represented parametrically

After such a simple introduction and double checking the validity of the information provided, the conversation continued towards the Python for Rhino3D coding (Figure 3).

Figure 3 An example of a code created by ChatGPT that could be executed within Rhino 3D to generate a helix

In addition, ChatGPT gave an explanation of the created code (Figure 4). This helped very much to understand the structure and elements of the proposed code.



Explanation:

1. **Parameters:**
   - `radius`: The radius of the helix.
   - `pitch`: The vertical distance between each turn of the helix.
   - `turns`: The total number of turns in the helix.
   - `points_per_turn`: The number of points used to define each turn of the helix.
2. **Generating Points:**
   - The total number of points is calculated based on the number of turns and points per turn.
   - A loop iterates to calculate the position of each point using the parametric equations of the helix.
3. **Creating the Helix:**
   - `rs.AddCurve(points)` is used to create a curve from the list of points.

Steps to Run the Script:

1. Open Rhino 3D.
2. Open the Python scripting editor by typing `EditPythonScript` in the command line.
3. Copy and paste the above code into the editor.
4. Run the script by pressing the green "Run" button in the editor.

This will create a helix in the Rhino 3D workspace with the specified parameters. You can adjust the `radius`, `pitch`, `turns`, and `points_per_turn` to create different helices.

Message ChatGPT

ChatGPT can make mistakes. Check important info.

Figure 4 An explanation of the created code used to model a helix in Rhino 3D

The coding process, however, is not always and necessarily easy and successful [8]. It needs to be pre-controlled, validated within the Rhino 3D software and if it works properly, a recommendation is to get ChatGPT back informed about the fact that the coding was satisfied (Figure 5). This step is very important, since, within one conversation, ChatGPT memorizes and learns from its own mistakes.

In some cases, the created script simply does not work properly. Then, ChatGPT should be informed about the error, in order it to refine the script in the next steps.

On the other hand, a script can be edited in the Rhino 3D Python Editor manually, and copied back to ChatGPT. In such situation, ChatGPT analyses the given script and returns

comments. These are two equal ways to teach or train the ChatGPT within the extended and repetitive conversation.

Finally, there are cases when ChatGPT persistently makes mistakes creating scripts that don't work. Such problems can be overcame by:

- Editing the script manually, according to available Python coding skills
- Starting the scripting process from the very beginning, redefining textual instructions
- Applying alternative parametric definitions

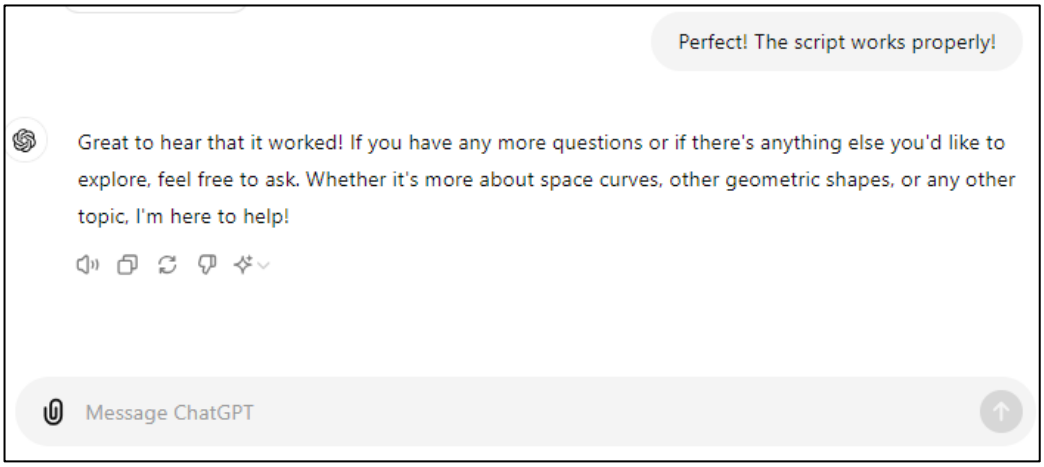


Figure 5 A part of the conversation with ChatGPT in which it was informed about the code that worked properly

4. PYTHON-WISE ASPECT

Python is a versatile and widely-used programming language known for its simplicity and readability. Its syntax is designed to be readable and straightforward, making it an excellent choice for beginners and experienced developers alike. It is an interpreted language which means code is typically executed line-by-line. This allow for quick testing and debugging [9].

Python is extensively used in many CAD applications, including Rhino 3D, a popular 3D computer graphics software. Python scripting in Rhino provides powerful tools for automating tasks, manipulating geometry, and creating custom functionality. RhinoScriptSyntax is a Python library that mirrors the functionality of RhinoScript, making it easier for users familiar with RhinoScript to transition to Python. It provides a straightforward API to access and manipulate Rhino objects and properties [10].

Here's an example of the Python script written with the assistance of ChattGPT that creates a multi-loxodrome form:

```
import rhinoscriptsyntax as rs
import math
import Rhino

# Define parameters
sphere_radius = 100
k = 0.5  # Curvature parameter
angle_increment_degrees = 5  # Angle increment in degrees
```

```
# Convert angle increment to radians
angle_increment = math.radians(angle_increment_degrees)

# Center of the sphere
center = [0, 0, 0]

# Initialize an empty list to store points
loxodrome_points = []

# Calculate points along the loxodrome curve
for angle_degrees in range(-600, 600, angle_increment_degrees):
    angle = math.radians(angle_degrees)
    x = sphere_radius * math.cos(angle) / math.cosh(k * angle)
    y = sphere_radius * math.sin(angle) / math.cosh(k * angle)
    z = sphere_radius * math.tanh(k * angle)
    loxodrome_points.append([x, y, z])

# Add points and spheres to Rhino scene
for i, point in enumerate(loxodrome_points):
    #rs.AddPoint(point)
    # Calculate the radius based on the distance from the middle
    t = abs(i - len(loxodrome_points) / 2) / (len(loxodrome_points) / 2)
    # Invert the t value to get opposite behavior
    t = 1 - t
    radius = 1 + t * 10  # Interpolate between 0.15 and 1 for the radius
    #rs.AddSphere(point, radius)

# Add a polyline to represent the loxodrome curve
loxodrome_curve = rs.AddPolyline(loxodrome_points)

# Create a group consisting of the curve and spheres
group_objects = [loxodrome_curve] + rs.AllObjects(select=True)

# Rotate and make copies of the group
for i in range(6):
    angle = i * 60
    rs.RotateObject(group_objects, center, angle, [0, 0, 1], True)

print("Loxodrome curve and spheres created with opposite radii.")
```

This script, executed in the Rhino 3D Python Editor, created the form shown in Figure 6.

Once created and executed, such script could be easily alternated in terms of changing characteristics parameters (in this case angle of rotation, number of rotated items, radii of spheres, etc.). For being able to manipulate geometric form that way, it is recommendable to well understand the structure and elements of the script [11].

Despite possible imperfections and errors in the Python coding for Rhino 3D, it is important to stress that AI represented here by ChatGPT, serves as an efficient programming assistant that returns considerable scripting results if it is professionally human-guided. It nevertheless saves enormous coding time and helps users that are not programmers to benefit from the Python functionalities [12].

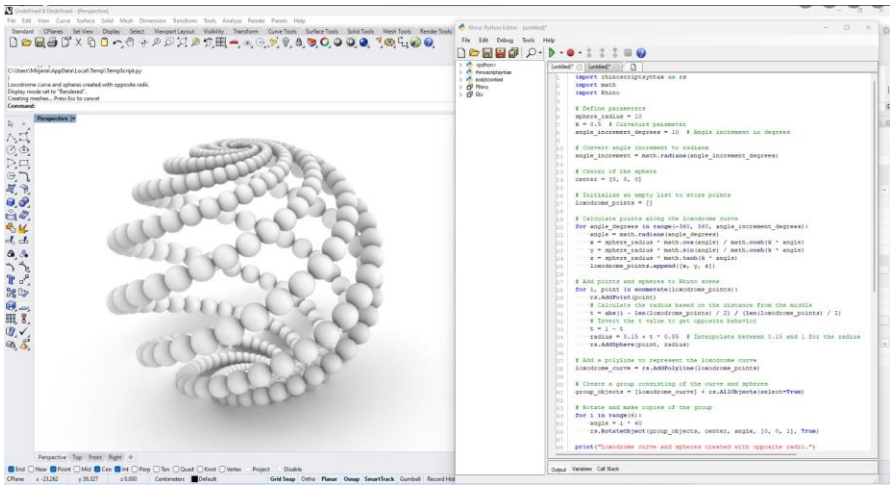


Figure 6 A multi-loxodrome form created from the script executed in the Rhyno 3D Python Editor

5. RHINO 3D MODELLING, VISUALIZATION AND 3D PRINTING

To reach the aim of this investigation successfully, possession of Rhino 3D modelling skills is needed. Although the process of modelling is automated and entirely performed by the Python Editor component, it is necessary to carefully control the display, to choose appropriate viewpoints, etc. It is also desirable to well understand the process of Rhino3D modelling performed by the Python script, when some details ought to be alternated manually.

In this study the process of visualization entirely relied on the software`s defaults (regarding scene material, light, ambient shadow…). The results obtained in that way, were satisfactory and affirming obtained geometric forms.

Figure 7 The 3D printed multi-loxodrome form

A rigid control of the model preceded the printing process, including the checking of its consistency, minimal dimensions, global dimension, etc. Once the digital model was fine-tuned and finalized, it was considered for 3D printing. As an example, only several models was exported in the .stl format and 3D printed. 3D prints were produced within the 3D IMPULS (Serbian National Laboratory for 3D printing) at the Faculty of Mechanical Engineering in Kraljevo [13].

6. CONCLUSIONS

This study demonstrates the potential of synergy between mathematics, AI, Python programming, Rhino3D, and 3D printing in the domain of complex geometric forms creation. This interdisciplinary approach not only enhances our ability to design intricate shapes, but also opens new horizons in various fields such as architecture, engineering, and digital art. The study indicates and goes parallel with other studies [14], that programming and usage of AI might be a set of very useful, even necessary skills for the architects in the near future.

The further research might be directed towards the question in what sense could this methodology be used to develop a generative system of emergent forms, in which the result is unknown but intended to be discovered.

The integration of mathematics, AI, Python, Rhino3D, and 3D printing signifies a transformative shift in the design and fabrication of complex geometric forms. This approach fosters innovation and efficiency, enabling the creation of structures that are both aesthetically pleasing and functionally robust.

The research presented is foreseen as part of incorporating the coding methods in architectural 3D modelling in both academic education and professional activity. It also tends to enrich the basic digital literacy of modern-day architects.

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Review paper

ENVIRONMENTAL AND ARCHITECTURAL ASPECTS OF TIMBER CONSTRUCTION IN LONG-SPAN STRUCTURES: A REVIEW OF SELECTED EVALUATION CRITERIA

Agnieszka Starzyk[1], Vuk Milošević[2]

Abstract

The article presents an interdisciplinary view of long-span timber structures, combining architectural and environmental approaches. The authors, working in the field of architectural design, analyze wood not only as a structural material, but also as a means of spatial, aesthetic and cultural expression. Particular attention was paid to such aspects as expression of form, quality of detail, user comfort and integration of the structure with function and environment. In parallel, an environmental analysis was conducted, including material life cycle (LCA), carbon footprint, energy efficiency, and the potential of wood for reuse and recycling in the context of a circular economy. The results of the 2021-2025 literature review indicate that engineered wood (CLT, glulam, LVL) allows combining sustainability goals with high quality architectural space. The article emphasizes the importance of integrating environmental and design criteria in the creative process and the need for further research into the sustainability, adaptability and regulatory aspects of wood construction. Wood appears as a material of the future, both in terms of aesthetics and climate responsibility.

Key words: *Timber Architecture, Long-span Timber Structures, CLT Buildings, Sustainability, LCA, Carbon Footprint, Circular Timber, Architectural Expression*

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1. INTRODUCTION

Contemporary long-span wooden structures represent one of the most dynamic fields of architectural and environmental exploration. Their significance goes beyond the engineering understanding of structure; they are also a manifestation of new design values: sustainability, material expression, user comfort and integration into the local spatial context. In this context, engineered wood [CLT (Cross-Laminated Timber) – multilayer wooden panels in which each layer of boards is glued crosswise, providing high strength in two directions; Glulam (Glued Laminated Timber) – structural beams or components made from thin layers of wood glued parallel to the grain, used to carry heavy loads; LVL (Laminated Veneer Lumber) – an engineered wood product made from thin wood veneers glued together lengthwise, known for its high strength and uniform properties] becomes not only a structural material, but also a carrier of architectural identity and ideas [1, 2].

The purpose of this review is to identify and organize the key criteria for evaluating long-span timber structures, with an emphasis on their architectural and environmental dimensions. The authors, working in the field of architecture and design, focus on those issues that allow us to understand the role of the material in shaping public space, the aesthetics of the structure and the quality of the indoor environment, while also analyzing its impact on climate and resources [3, 4].

In order to organize the review, a two-part division of criteria was proposed: (i) environmental criteria and (ii) architectural criteria.

Environmental criteria – refer to the environmental impact of wood structures over the full life cycle of a building. They include both quantitative indicators, such as greenhouse gas emissions (carbon footprint), primary energy consumption or the results of LCA analyses, as well as qualitative considerations related to the comfort of the indoor environment [5, 6, 7, 8, 9]. A special place in the analysis is given to the potential of wood material in the context of a circular economy: the possibility of disassembly, reuse of components, recyclability of structural components and locality of supply chains [10, 11]. As a material that is separable and recyclable with relatively low energy input, wood fits into the GOZ concept, which in recent years has become a key paradigm in sustainable design [3, 12].

Architectural criteria – describe how wood influences the form of a space, the expression of a structure, the quality of a detail and the user experience. Issues such as wood's ability to create spanning spatial structures, the visibility of the structure as an aesthetic element, the integration of the structural system into the building's functional program, as well as the acoustic, thermal and visual qualities of the material in the indoor environment are included [13, 14].

Structuring the review in this way makes it possible not only to organize existing knowledge, but also to identify areas of data deficiency and research that can be the subject of further exploration, especially within interdisciplinary teams combining architecture, environment and materials engineering.

2. METHODOLOGY AND MATERIALS

The purpose of this paper was to conduct a review of the scientific literature on the environmental and architectural aspects of wood construction in long-span structures, from the perspective of architecture as a design and cultural discipline. A qualitative approach was

adopted, focusing on the identification and classification of key evaluation criteria that appear both in the scientific literature and in design practice.

A full systematic model was abandoned in favor of a problem-thematic analysis, typical of architectural research. This method allows not only the compilation of quantitative indicators, but also the interpretation of qualitative spatial, aesthetic and functional phenomena.

2.1. Assumptions and objectives of the review

The purpose of the analysis was to identify (i) key directions for environmental and architectural research on large-scale wood buildings, (ii) the most frequently addressed research problems and gaps in the literature, (iii) examples of best practices and innovative design solutions.

2.2. Literature selection criteria and data sources

Only publications meeting the following criteria were included in the analysis: peer-reviewed articles published in scientific journals indexed in the Scopus or Web of Science database; published between 2020 and 2025; bearing a DOI number and available in full text. Topics - environmental issues (e.g., carbon footprint, energy efficiency, LCA) and architectural issues (e.g., aesthetics, user comfort, structural form). The following databases were used for the literature search: Scopus (Elsevier), Web of Science Core Collection (Clarivate), supplementary: ScienceDirect, MDPI, SpringerLink and Taylor & Francis - provided that articles were simultaneously indexed in Scopus. Searches were supported by manual selection by reviewing references from papers with high citation counts. The search process was conducted in English and Polish using a combination of keywords, such as timber architecture, long-span timber structures, CLT buildings, sustainability, LCA, carbon footprint, circular timber, architectural expression. In addition, a back-reference analysis was performed on publications considered key to identify complementary and contextual works.

2.3. Analysis process

The analysis was conducted in three stages: (i) Categorization - division of articles into two main thematic groups: environmental and architectural, (ii) Comparative analysis - review of research approaches, types of construction, materials and case studies, (iii) Synthesis and classification of research problems - identification of challenges, recurring methodological limitations and niche topics. Ultimately, the results of the analysis allowed the formulation of research problems and cognitive gaps, which are discussed in the following sections of the article in the context of both engineering practice and further scientific research.

3. ANALYSIS OF ENVIRONMENTAL AND ARCHITECTURAL ASPECTS

An analysis of selected publications reveals a clear diversity of research approaches to timber construction in long-span structures, with environmental and architectural aspects being particularly emphasized. While many studies to date have focused on structural-engineering aspects, one can now see an intensification of research covering a broader spatial, aesthetic and environmental context.

The following section provides a detailed overview of environmental (3.1) and architectural (3.2) approaches, taking into account both research-developed areas and those in need of further exploration. A key goal is to identify current trends and cognitive gaps that can provide a starting point for further research and design work in the area.

3.1. Environmental aspects

In the environmental stream, special attention is paid to the analysis of the life cycle of wood materials, their carbon storage capacity, as well as the potential environmental advantages of wood over conventional building materials in terms of emissions, energy efficiency and reusability. Importantly, not only quantitative data are considered, but also geographic, climatic and socioeconomic conditions affecting the environmental performance of wood technology [9, 15].

In recent years, there has been growing interest in the use of engineered wood in long-span structures due to its potential in reducing greenhouse gas emissions and its ability to sequester carbon. Life cycle analyses (LCA) show that wood, as a renewable material, can significantly reduce the carbon footprint of buildings compared to traditional materials such as steel or concrete [16].

Comparative studies indicate that structures made of cross-laminated timber (CLT) have a lower environmental impact throughout the building life cycle. Analyses show that CLT-based buildings have a smaller carbon footprint than their concrete or steel counterparts, especially in the context of long-span structures [1, 5, 17, 18].

Additionally, engineered wood exhibits favorable thermal properties, resulting in better energy efficiency of buildings. Thanks to the natural insulating properties of wood, these structures can provide better thermal comfort with lower energy consumption for heating or cooling. Studies confirm that solid wood buildings have lower energy consumption compared to traditional structures [19, 20, 21].

It is also worth noting that the use of wood in construction contributes to reducing the consumption of non-renewable resources and emissions associated with the production of building materials. As a natural material, wood requires less energy to process compared to steel or concrete, further reducing the overall environmental impact of a building.

In summary, the use of engineered wood in long-span structures offers significant environmental benefits, including reduced greenhouse gas emissions, improved energy efficiency and reduced consumption of non-renewable resources. These properties make wood an attractive material in the context of sustainable construction and the fight against climate change.

3.2. Architectural aspects

The architectural approach, on the other hand, considers wood not only as a structural material, but as a carrier of spatial, aesthetic and cultural values. In the literature analyzed, there is a strong tendency to combine structural expression with functional and symbolic requirements, which is particularly important in the design of large-scale public buildings. Some studies also point to the importance of wood for improving the quality of the indoor environment, including thermal, acoustic and visual comfort of users. The growing role of digital design tools that enable generative shaping of wood forms and their integration with prefabrication is also not without significance.

As a structural material, wood offers architects a wide range of possibilities for shaping the form and aesthetics of long-span buildings. Its natural texture, warmth of color and ability to create complex geometries make it a frequent choice for projects requiring both functionality and distinctive visual character [22]. An example is the use of glulam in long-span roof structures, where the material allows for the creation of lightweight yet strong structures that give spaces a unique character [23].

The visibility of wood structural elements in a building's interior space not only emphasizes aesthetics, but also influences users' perception of the space. Exposing a wooden structure can reinforce a sense of security and stability, as well as introduce elements of rhythm and order into the interior design [12, 24]. In projects such as the Cochrane Transit Hub, the use of visible glulam beams not only serves a structural function, but is also a key aesthetic element, integrating the building with its surroundings and emphasizing its identity [25].

The precision of detailing in wood structures is crucial to the durability and aesthetics of a building. Modern woodworking technologies, such as CNC, make it possible to create intricate joints and details that are both functional and aesthetically refined [3]. High-quality detailing also influences the perception of users, increasing their comfort and satisfaction with the space [26].

Wood has natural acoustic and thermal properties that affect user comfort. Studies show that the presence of wood in a space can improve the acoustic quality of rooms, reducing noise and reverberation [27]. In addition, wood has good thermal insulation, which contributes to maintaining a stable temperature inside the building and increases the thermal comfort of users [28]. In addition, the presence of wood in a space can have a positive impact on the well-being of users, reducing stress and improving the overall experience of the environment [29].

The flexibility of wood as a construction material allows spaces to be easily adapted to different functions. Prefabrication of wood elements allows for quick and efficient implementation of projects, which is particularly important in buildings with a variable functional program [30]. An example is the Carbon12 building, where the use of wood allowed the creation of living spaces of a high standard, while integrating a variety of functions in a single structure [31].

In light of the above reflections, it is worth highlighting several European examples that illustrate the architectural and cultural potential of long-span timber construction. In Poland, the Education and Culture Center in Kozienice demonstrates how glulam roof structures can create both functional and inviting interior spaces. In Serbia, the exhibition pavilion in Novi Sad stands out as a project where locally sourced timber forms an open, rhythmic spatial experience that resonates with the regional architectural identity.

In Germany, the Hallenbad Pforzheim sports hall uses curved glulam beams to emphasize both the rhythm and lightness of the interior. The port terminal in Bergen, Norway, shows how cross-laminated timber (CLT) can serve as both a structural and expressive element, strengthening the building’s identity while echoing the surrounding landscape and local building culture. In Austria, the Bildungscampus Seestadt Aspern exemplifies how timber construction can support the integration of learning and communal spaces while creating interiors with high acoustic and visual comfort.

These cases show that timber, when used in large-scale architecture, goes far beyond technical requirements. It enriches spaces with symbolic, emotional, and cultural meaning. Referring to realized European projects deepens the understanding of timber’s potential to

bring together function and architectural expression, helping create environments that are both coherent and inspiring for users.

4. DISCUSSION

Long-span timber construction is increasingly being presented as an alternative to concrete- and steel-based technologies, for both environmental and architectural reasons. Based on previous analyses, it can be seen that wood structures not only reduce the carbon footprint, but also offer spatial and performance values difficult to achieve with other technologies.

Environmentally, engineered wood structures, especially CLT and glulam, show significantly lower CO_2 emissions than their concrete and steel counterparts. Studies indicate that the use of wood in place of conventional materials can lead to up to a 50% reduction in emissions over the life cycle of a building [31]. Additionally, wood not only generates fewer emissions during production, but also sequesters carbon, acting as a “carbon store” [32].

In contrast, concrete and steel production involves very high primary energy consumption and emissions, mainly due to the energy-intensive nature of the clinkerization and metallurgical processes [33]. Moreover, concrete and steel do not offer comparable benefits in the context of a circular economy, unlike wood, which can be more easily dismantled, recycled and reused [34].

At the utilitarian level, wood is characterized by its natural thermal and acoustic properties, which positively affect the comfort of indoor spaces. The material exhibits low thermal conductivity and the ability to stabilize the microclimate inside buildings [28]. Moreover, wooden interiors, especially when exposed, are perceived by occupants as more welcoming, warm and less stressful than their steel or concrete counterparts [12].

In architectural terms, wood offers a unique material and structural expression. The visibility of beams and structural frames often becomes an important compositional element, while allowing for the integration of form and spatial function [15]. In many cases, wood serves a narrative function, highlighting the identity of a place and connecting the design to the local cultural context [29].

The prefabrication and digital precision of the material allow for faster construction and greater programmatic flexibility, important for public or multi-use facilities. Wood allows for subsequent changes in functional layout without disturbing the main load-bearing structure, which is more difficult to achieve in concrete structures [35].

Despite these advantages, it should be noted that wood construction is not without its limitations. The most commonly cited challenges are fire resistance, biological durability and the availability of certified raw material in adequate quantities. However, advances in engineering and materials technology are effectively mitigating these risks, including through the use of protective coatings, waterproofing, multi-layer CLT assemblies and advanced fire detection systems [36].

5. SUMMARY AND CONCLUSIONS

Long-span wood construction offers a number of significant advantages over conventional technologies in both environmental and design terms. Wood's ability to store

carbon, the high quality of its indoor environment, its expressive aesthetics, and its potential for prefabrication and space adaptation make it one of the most relevant materials for future sustainable construction. Its wider use, however, requires overcoming regulatory and logistical barriers. Nevertheless, with the current emphasis on decarbonizing construction, wood appears as a key material in the sustainable development strategies of the architectural and engineering sector.

The purpose of this article was to review the environmental and architectural aspects of wood construction in long-span structures. The analysis was based on scientific publications from 2020-2025, indexed in Scopus and Web of Science databases, oriented to modern structural and design solutions using engineered wood (CLT, Glulam, LVL). The article was prepared from the perspective of architects, and the research approach adopted made it possible to extract a set of key evaluation criteria from the field of environmental impact and architectural values.

Among the environmental criteria were carbon footprint, energy efficiency, life cycle (LCA), recycling potential and the material's ability to fit into the principles of a circular economy. The analysis showed that wood significantly reduces CO_2 emissions compared to concrete and steel, and promotes the implementation of decarbonization strategies in the construction sector.

Architectural aspects were referred to such categories as form and aesthetics, structural expression, quality of detailing, integration with the functional program, and comfort of the indoor environment - especially acoustic and thermal. In light of current research and realizations, wood appears as a material that enables the creation of coherent, aesthetic and welcoming functional environments, while at the same time fostering prefabrication, adaptability and integration of structural and spatial design.

A comparative discussion with other technologies, mainly concrete and steel, unequivocally demonstrated the advantage of wood in terms of environmental impact and potential for creating quality space. At the same time, limitations such as fire resistance or local availability of certified raw material were pointed out, which require further research and technological optimization.

Conclusions:

1. Long-span timber construction is a viable, sustainable alternative to conventional technologies, offering environmental and architectural benefits important in public, sports and mixed-use facilities.
2. An integrated design approach, combining life cycle analysis (LCA) with spatial design, should be standard in the evaluation and planning of engineered wood projects.
3. Exposure of wood structure can be not only an aesthetic expression, but also a factor supporting user comfort and place identity.
4. Further interdisciplinary research is needed, especially on durability, fire resistance and adaptation systems of wooden structures in the context of changing functional programs.
5. Increasing availability of materials data and environmental assessment tools will promote further development of responsible wooden architecture.

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Research paper

GEOTECHNICAL AND GEODETIC STRUCTURAL MONITORING FROM THE PERSPECTIVE OF THE INDUSTRY 4.0 CONCEPT AND CHALLENGES TOWARD INDUSTRY 5.0

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Abstract

Contemporary challenges in monitoring and preserving civil and infrastructure structures require the application of intelligent, digitally supported systems. This paper presents the possibilities and benefits of applying Industry 4.0 concepts in the field of geotechnical and geodetic structural monitoring, with a particular focus on sensor networks (IoT), edge computing technologies for integrating various types of data, and cloud platforms for managing and controlling the collected information. Implementation examples are presented in the context of urban construction sites. The second part of the paper analyzes the challenges and perspectives of transitioning toward Industry 5.0, which emphasizes human-centered design, sustainability, and system resilience. The need to balance automation with the human role is highlighted, along with maintaining infrastructure safety and environmental responsibility. It is concluded that the integration of these concepts transforms the way critical structures are monitored and maintained, significantly enhancing the overall safety and efficiency of the system.

Key words: *geotechnical monitoring, geodetic monitoring, IoT, edge computing, structural health monitoring, system resilience*

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1. INTRODUCTION

Structures and infrastructure systems play a significant role in improving the economic, social, and environmental welfare of nations [1]. Faced with challenges affecting both old, traditionally built infrastructure and new structures striving to be instantly constructed and technically sophisticated, humanity, perhaps more than ever before, has the need to establish control over the behavior and maintenance of its environment. The aging of structures, the progressive increase in operational demands, extreme weather events caused by climate change, as well as the pressures of social and economic factors (lack of maintenance funding, urbanization, population growth), create a complex environment in which monitoring the real behavior of structures has become essential.

The service life of structures does not progress evenly or predictably. Even during the construction phase, deviations can occur that cause behaviors different from those anticipated by design and simulations. During operation, structures are exposed to variable conditions, loads and external influences, that often exceed the predicted scenarios, both in type and intensity. The accumulation of these uncertainties throughout the entire life cycle of a structure presents a serious challenge to everyone responsible for its safety, maintenance, and reliable operation.

Although regular inspections provide a certain level of safety, they are time-limited and focused only on visible parts of the structure, while changes occurring between inspections remain undetected. Their safety, functionality, and longevity are directly linked to the ability to continuously monitor their condition and to respond in a timely manner to changes that may threaten their stability. By installing a network of sensors at key locations of the structure and continuously measuring parameters that reflect mechanical behavior and external influences, it is possible to monitor, in real time, changes in stability and structural integrity. This is why the concept of Structural Health Monitoring (SHM) was developed, with the aim of providing reliable and continuously updated information about the actual condition of a structure. Definition of SHM is given at [2], where structural health monitoring is defined as the measurement of the operating and loading environment and the critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and/or deterioration or damage indicators that may affect operation, serviceability, or safety reliability.

Although the implementation of SHM systems represents a significant advancement in infrastructure asset management, realizing their full functionality requires detailed project preparation, careful integration with existing risk assessment methodologies, and the establishment of clear protocols for data analysis, interpretation, and application. The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition, storage, transmittal hardware [3]. In line with modern requirements, there is an increasing need for the development and application of intelligent, digitally integrated monitoring systems. In this context, the concept of the Fourth Industrial Revolution (Industry 4.0) introduced a new paradigm, bringing smart sensor networks, the Internet of Things (IoT), big data processing, and artificial intelligence into the field of structural monitoring. However, as the world rapidly moves toward the principles of Industry 5.0 in which a human-centric approach, sustainability, and collaboration between humans and machines will play a key role, new questions and challenges arise: How can SHM systems be designed to ensure technical reliability and promote infrastructure resilience in response to social changes, ethical demands, and ecological imperatives? The

concept of Industry 5.0 provides a different focus and highlights the importance of research and innovation to support industry in its long-term service to humanity within planetary boundaries [4]. The aim of this research is to analyze the application of Industry 4.0 technologies in structural monitoring, with a particular focus on geodetic and geotechnical monitoring. Within the research, perspectives of the transition toward Industry 5.0 are also considered, which promises further improvements in the precision, efficiency, and automation of infrastructure monitoring processes.

2. CONTEMPORARY INDUSTRIAL CONCEPTS IN THE CONTEXT OF GEODETIC AND GEOTECHNICAL MONITORING OF STRUCTURES

Looking back over the past decades, traditional production systems and technologies have often led to serious environmental and social issues, including high resource consumption, global warming, environmental degradation, and increased pollution. These issues prevent the optimization of opportunities for sustainability enhancement, which naturally leads to the question of whether emerging technologies can be used to provide the necessary solutions [5]. These problems pose significant obstacles to sustainable development, prompting an urgent need for a shift in the approach to manufacturing and industry. This has long been a leading topic at global economic forums, United Nations general assemblies, and activist movements raising awareness about the risks present in humanity's immediate environment.

Industry 4.0 offers a potential solution to many of the ecological and societal challenges that traditional industrial practices and technologies have failed to address. Industry 4.0 addresses and solves some of the challenges facing the world today such as resource and energy efficiency, urban production and demographic change [6]. It not only integrates advanced technologies such as artificial intelligence, big data, blockchain, the Industrial Internet of Things (IIoT), and simulations, but also creates an opportunity for developing more sustainable and efficient production systems. The implementation of Industry 4.0, although complex, has represented a necessary and significant opportunity to overcome the limitations characteristic of traditional industrial practices, enabling the construction of a more sustainable future.

In the context of SHM, Industry 4.0 technologies have shown significant contribution to more efficient monitoring and maintenance of structures such as bridges, tunnels, highways, buildings, and industrial facilities. As data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by varying operational and environmental conditions [3]. Further, SHM systems rely on the integration of various technologies and sensor platforms stemming from a wide range of engineering disciplines. Geodesy, geotechnics, civil engineering, computer science, and electrical engineering are key fields contributing to the development of these systems.

In the modern approach to preserving the stability and safety of infrastructure, there is a clear recognition of the need to integrate geodetic and geotechnical monitoring into unified, comprehensive surveillance systems. Although each discipline individually provides essential information about the condition of a structure and its surroundings, their combination enables a deeper understanding of deformation mechanisms and the timely detection of potentially

critical conditions. In addition to monitoring ground deformations during the design phase, as well as the behavior of constructed objects within the monitored area, these systems also serve to evaluate implemented design solutions. They contribute to the revitalization, automation, and centralization of structural health monitoring, improving the technical surveillance system used for tracking structural behavior and conditions during operation, while simultaneously maximizing ease of use and increasing system accuracy. In the context of increasingly demanding climatic, seismic, and anthropogenic influences on infrastructure, the integration of geodetic and geotechnical monitoring is becoming a standard of good engineering practice, shown int Figure 2.

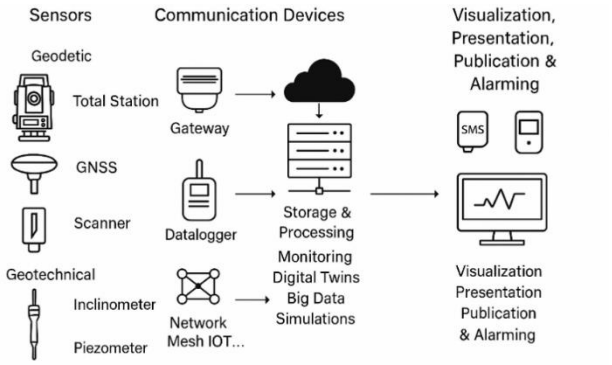

Figure 1. Geotecnical and geodetic SHM architecture

Geodetic engineering plays an irreplaceable role throughout all phases of the life cycle of infrastructure objects, from design and construction to long-term monitoring and maintenance. Geodetic engineering undoubtedly belongs to the group of engineering disciplines without which precise spatial positioning of infrastructure objects would be unimaginable [7]. Within the SHM context, geodetic methods enable quantitative tracking of changes in position, shape, and dimensions of structures with high accuracy and reliability. From the perspective of geodetic acquisition, the primary need lies in the precise measurement of point positions, displacements, and deformations of structures (e.g., bridges, buildings, slopes). These data are usually collected through GNSS systems, total stations, or terrestrial laser scanners.

The database is complemented through geotechnical approaches, which take into account soil and foundation conditions, including ground displacement, foundation pressures, groundwater level, soil saturation, vibrations, and more. Integrated geotechnical monitoring should include several independent measuring and controlled systems, which should complement each other and ensure structural safety at all stages of construction and operation of the structure [8]. Within SHM systems, geotechnical methods allow for the detection of changes in stress-strain states, stability, and safety of structures in real time. This forms the basis for monitoring the condition of foundation soil and structures that interact with it.

Since all measurements depend on the atmospheric conditions of the surrounding environment, it is important to note that the full potential of monitoring is realized when measurements from temperature, weather, and other environmental sensors are included.

One of the key challenges in managing such systems is interoperability. Different technologies and sensors often use different communication protocols, measurement frequencies, data formats, and measurement units, which can cause difficulties in data

alignment. Unstructured data has no concrete data schema for data storage, e.g., a distributed data storage using folder-based storage systems [9]. The main steps to solve that challenge are recognized as standardization, conversion, and validation processes to enable integrated and reliable analysis. Standardization involves harmonizing units, time stamps, and data formats into a unified system that allows seamless interoperability of data from various sources. Data conversion includes transforming data from various technical and physical formats into forms suitable for analysis and further processing. Data validation enables early detection of errors, inconsistencies, and anomalies that could compromise the accuracy of conclusions drawn from the measurements.

Another significant challenge is the synchronization of data in time and space. Measurements from different sensors must be precisely aligned to ensure accurate comparison and integration of data. Inconsistencies in synchronization, such as differences in time stamps or coordinate systems, can lead to incorrect interpretations of the structural condition, which can have serious consequences for infrastructure analysis and management.

System security is also a crucial component in managing complex monitoring systems. These systems must be resilient to data loss, communication interruptions, and potential cyber threats. Traditional sensor-based SHM systems, which rely on IoT-enabled wireless networks, often face cybersecurity vulnerabilities, data tampering risks, and unauthorized access [10]. Ensuring data integrity and availability is essential for maintaining trust in the system, which is critical for making accurate decisions related to infrastructure.

In the following part of this paper, we present an example of a SHM system architecture composed of leading Industry 4.0 technologies, with a proposed application in urban construction sites, and an analysis of the trends to observe in the future.

3. SHM ARCHITECTURE AND APPLICATION IN URBAN ENVIRONMENTS

A complete monitoring system in civil infrastructure is multidisciplinary and requires careful integration of hardware and software components, based on the principles of Industry 4.0, among which IoT, cyber-physical systems (CPS), artificial intelligence (AI), machine learning, digital twins, and simulations are dominant.

The role of CPS in SHM is essential for the development of modern infrastructure maintenance systems, contributing to the real-time monitoring and analysis of physical assets. CPS is defined as transformative technology for managing interconnected systems between its physical assets and computational capabilities [11]. IoT enables the interconnection of various sensors and devices, continuous communication, and data analysis. Furthermore, by analyzing the monitoring needs, defining tolerance thresholds, and enabling predictive thinking, space has been created for the application of AI and machine learning, which play a key role in analyzing data collected from sensors. By using machine learning algorithms, anomalies in structural behavior can be detected and future failures predicted. These systems are capable of learning from historical data and developing models for pattern recognition that indicate potential issues. In this way, AI and machine learning enable a proactive approach to infrastructure maintenance, which can reduce the risk of serious damage and optimize operational costs. In the context of civil engineering, no quantitative methods currently exist that can reliably determine whether buildings are safe for

reuse after a strong earthquake. SHM technology could one day enable the reduction of uncertainty associated with existing visual methods for post-earthquake damage assessment. The rapid reuse of buildings, especially those related to production, can significantly mitigate the economic losses caused by major seismic events. Currently, machine learning methods are widely adopted in SHM, yet they are still mostly black boxes. On the other hand, given the significant responsibility associated with SHM, understanding the rationale behind it is critically important [12].

As part of ongoing SHM system maintenance, cloud computing has become essential for centralized storage and processing of data from multiple sources, providing real-time access from any location, particularly valuable in situations requiring rapid response to structural changes [13]. Another important aspect in infrastructure monitoring is the use of simulations and digital twins, which represent a key technologies in structural health monitoring. Digital twins enable the creation of virtual replicas of physical objects which are used to simulate structural behavior under various conditions [14]. These simulations may include factors such as loads, vibrations, and temperature, allowing for a better understanding of the object's response to external influences. Digital twins can also be used to test different scenarios and predict potential real-world issues, significantly reducing the need for costly physical testing.

3.1 Key recommendations for SHM design

Effective design of SHM systems requires careful planning of communication protocols, measurement data validation, format standardization, and ensuring compatibility with analytical software. Based on modern experience and best practices, the following key recommendations are provided:

- Adapting communication technologies to the specific conditions of each location forms the foundation for reliable data transmission.
- For remote, hard-to-access, and energy-constrained environment, such as mountainous areas and tunnel structures, LoRaWAN is recommended.
- Technologies such as LTE-M/NB-IoT are suitable for urban environments with developed mobile infrastructure and stable network coverage.
- Wi-Fi/Ethernet is most appropriate for facilities with existing infrastructure, such as bridges, buildings, and industrial complexes.
- To preserve the integrity of measurement data and enable timely detection of potential errors, it is essential to implement redundant systems by placing at least two different types of sensors at each critical point of the structure.
- Schedule regular field inspections and compare IoT data with manually conducted reference measurements.
- Standardization is of vital importance, both for internal data use and for its use in forensic or legal contexts
- Strict adherence to internationally recognized standards (e.g., ISO, ASTM, DIN) is recommended to ensure the consistency and verifiability of the collected data.
- To enable seamless integration with advanced analytical software solutions, all data should be converted into standardized formats such as CSV, JSON, LAS, or RINEX, and prepared for processing in software tools specialized in structural monitoring.

Table 1 presents sensors, devices, validation methods, data conversion, and standardization approaches used in SHM systems with IoT connectivity for geodetic and geotechnical monitoring.

Table 1. Sensors, devices, validation and conversion, with IoT connectivity and integration in SHM systems for geodetic and geotechnical monitoring

Sensor Type	Description	IoT Prot.	Comm.Dev.	Data Validation	Data Conver
GNSS TS TLS	3D position, displacement angles, distance, 3D coordinates 3D modeling	TCP/IP MQTT, LoRaWAN Ethernet, Wi-Fi, 4G LAN	Modem, RTK base, GNSS Gateway Data logger, Cloud connector Edge device, server	RMS error, PDOP Redundant measurements, control points Point registration, ICP algorithm	NMEA, RINEX CSV, XML E57, LAS, PTS
Inclinometer Piezometer Vibration Sensor Extensometer Strain Gauge FBG Tiltmeter	Tilt angle, Pore water pressure, Vibrations and seismic waves, Ground displacements, Structural strain, Distributed strain and temperature, Structural tilt	LoRaWAN LTE-M, RS-485 NB-IoT Wi-Fi, LTE, Fiber Modbus, LoRa TCP/IP Ethernet (DAS) Zigbee	Gateway, Edge computer Data collector, IoT node Seismic station, logger RTU DAQ Optical interrogator IoT Gateway	Reference calibration, drift analysis Comparative manual readings FFT Peak Ground Acceleration Cross-validation with geodetic data Load test, bridge balancing FBG wavelength calibration Linearity test, verification	JSON, CSV SEED, miniSEED XML HDF5,

3.1.1 Proposed SHM for monitoring construction sites in urban areas

The sensor network must be dense and redundant due to the high risk associated with urban environments, with IoT connectivity enabling real-time monitoring and rapid response. Validation must be conducted regularly, at least on a weekly basis, with an *Alarm Zone* functionality implemented for critical displacement or vibration thresholds. Table 2 presents the main sensor groups along with their typical locations on an urban construction site. Table 3 provides the communication architecture of the system.

Table 2. Key sensors for urban construction site monitoring

Sensor	Function	Location
GNSS receivers (static or dynamic)	Monitoring displacement of adjacent structures and piles	On top of buildings, poles, and at the construction site
Total Station (robotic)	Monitoring relative displacement (prisms on buildings)	On adjacent buildings and monitoring pillars
Terrestrial Laser Scanner (TLS)	3D scanning of construction site deformations	Fixed points around the construction site
Inclinometers (MEMS)	Monitoring tilt of soil masses, piles, foundations	In boreholes, behind retaining walls
Piezometers	Monitoring groundwater level	Boreholes on the construction site
Extensometers	Monitoring displacement of piles and walls	In boreholes and on structures
Vibration sensors	Detecting vibrations from excavation and works	On nearby buildings
Fiber optic sensors (FBG)	Monitoring strain/structural deformations	On critical structural elements
Temperature sensors	Thermal monitoring (important for concrete works)	Embedded in the structure and surrounding environment

Table 3. Communication components for the SHM System on an urban construction site

Layer	Component	Description
Sensor Layer	GNSS, Total Station, TLS, Inclinometers, Piezometers, FBG,	Data acquisition from geodetic and geotechnical sensors
IoT Edge Devices	ComBox, Data Logger, IoT Nodes, RTUs	Initial data buffering, basic preprocessing, and transmission preparation
Communication Layer	LoRaWAN, NB-IoT, LTE-M, Wi-Fi, Ethernet	Wireless or wired transmission depending on site conditions
Gateway / Network Layer	IoT Gateway, Cellular Router, Mesh Network	Aggregation and secure routing of data to the central server
Server / Cloud Layer	Local server or cloud storage	Data storage, SHM software processing, digital twin simulation
Processing Tools	AI, ML, Digital Twins, Big Data Analytics	Real-time data analysis, anomaly detection, forecasting
Visualization Layer	SHM Dashboard, Web Access, Mobile App	Real-time visualization, alarms (SMS/email), and reporting tools

Data validation for geodetic monitoring should be performed by comparing RTK measurements with total station readings. Geotechnical monitoring should be validated through manual verification (e.g., dip meter for piezometers), while vibration data should be compared against calculated vibration standards (DIN 4150-3). Alarm thresholds must be defined based on deformation and vibration limits to enable automatic notifications (e.g., SMS/email alerts).

In SHM monitoring of particularly complex and critical structures in urban environments, it is essential to highlight the SHM architecture based on edge computing technology, apart from cloud computing. Edge computing enables data to be processed at the point of collection or in its immediate vicinity, rather than requiring that all data be sent to a central server for analysis. This approach is crucial for applications in geodetic and geotechnical monitoring, where rapid response to changes in structures or ground conditions is required. Data is processed immediately at the source, reducing latency and enabling instant reaction to potential risks or changes. By leveraging edge computing, the latency and consequently the user experience for time-sensitive applications could be improved significantly [15]. For example, if foundation displacement is detected, the system can automatically trigger an alarm or initiate preventive measures. By using edge computing, the need for constant connectivity with central servers is minimized. This is particularly beneficial in areas with poor internet connectivity or where a high level of system autonomy is required. Processing data at the source also reduces the amount of information that must be transmitted to the central system, saving network bandwidth and decreasing server load.

3.2. Case Studies on the Implementation of SHM Systems in Civil Infrastructure

3.2.1 Regent's Park Development Project, London

The Regent's Park Development project in London involved the demolition of a series of buildings, as well as the excavation and construction of new structures. The zone of influence, resulting from unloading during excavation and reloading during construction, extended within a radius of approximately 80 meters. The affected area included protected historical buildings of Grade I and II, London Underground tunnel passages, and electrical infrastructure facilities.

A specialized monitoring system was employed using a combination of optical and sensor equipment to track all changes affecting the objects within the zone of influence. The system configuration enabled continuous automatic monitoring of both aboveground and underground structures, with the objective of generating two types of reports:

- A report analyzing aboveground displacements of buildings and other technical facilities such as power supply stations, and
- A ground movement report, which included monitoring of the Jubilee line tunnel (running north–south) and the Metropolitan line tunnel passing beneath the demolition site.

Two monitoring processes operated continuously as part of the monitoring scheme, which used a combination of multiple geotechnical and optical technologies connected into a unified sensor network:

MultiStations were used for laser monitoring. MultiStations are platforms that combine the features of a total station, laser scanner, GNSS receiver, and a digital optical system for documentation and control. Although still considered high-end systems, their use is becoming increasingly common in projects requiring high reliability and time optimization, especially in the field of engineering geodesy and monitoring.

Wireless tilt sensors were used to track stable deformations, convergence, and longitudinal subsidence in London Underground tunnels.

Automatic monitoring of vibration, noise, and dust was conducted in parallel with the previously mentioned tools.

Alarm functions, based on the GeoMoS monitoring solution, allowed all project stakeholders access to the monitoring database, with different permission levels for viewing, editing reports, and receiving alarm messages. All data were integrated into the GeoMoS software, a commercially available solution that enabled users to have a centralized view of all data through a unified desktop and web interface. Leica GeoMoS is a professional software platform for automated geodetic and geotechnical monitoring of structural and ground displacements in real time. It enables continuous observation of critical infrastructures, such as bridges, tunnels, buildings, dams, and slopes, by integrating data from various sensors (e.g., total stations, GNSS receivers, tilt meters, vibration sensors), performing automated analysis, and providing real-time alerts when predefined safety thresholds are exceeded.

For the monitoring of multiple buildings in this central London project, three MS60 MultiStation devices were used, geometrically linked via common control points connected to a ComBox5 unit. ComBox is a modern ruggedized communication and power management device that allows for easy and fast setup of any monitoring sensor and can adjust power consumption. The latest ComBox devices support communication over EdgeConnect and within LAN. This configuration allows data transmission via internet connection to the GeoMoS server.

The twin-track Metropolitan line tunnel, built of brick, was monitored using an automatically controlled MS60 station that reads rail reflectors and laser scanning data. The two Jubilee line tunnels were equipped with 250 wireless tilt sensors connected via fiber optic cable, enabling data transfer to the internet and further into the GeoMoS system. GeoMoS supports connection with any monitoring sensor or software. Flexible communication options ensure seamless connectivity, sensor management, and instant data storage and analysis. Through the GeoMoS API, GeoMoS data can be integrated into a user's own system. Automated data flows use numerous open interface standards that enable simple but powerful sensor fusion. The GeoMoS Monitor application allows 24/7 measurements with scheduled sensor operation cycles, while all key data are stored in a single SQL database.

This system architecture enabled the observation and recording of building and ground displacement parameters, as well as deformation of railway tracks and segments of London underground tunnels. The centralized software tool recorded all monitoring data collected from various sensor sources, including: 3D reflector data, manual leveling measurements, values from electronic tilt sensors, data from wireless tilt sensors, and results from laser scanning.

Within the London project, the implemented monitoring system enabled the recording of displacements in three dimensions (X, Y, Z coordinates), allowing the determination of characteristics and total 3D deformation values on buildings and the ground. Based on total station measurements, in addition to absolute deformation magnitudes (longitudinal, lateral, and vertical), it was possible to calculate movement velocity and identify types of movement such as regressive, progressive, transitional, or stick-slip models.

Using the system in combination with advanced project management, data processing, and visualization software, real-time information was obtained on longitudinal displacements, lateral displacements, vertical displacements, as well as horizontal and vertical movement vectors across the entire monitored area.

Based on this data, the monitoring team could perform risk assessments and take preventive and corrective actions within the zone of influence. It was also possible to observe changes in movement intensity depending on seasonal conditions, geotechnical factors, and construction activities in the immediate environment. In addition to geometric monitoring, the system also collected data from various environmental sensors on-site, such as dust, vibration, and noise sensors, which operated within their own alarm routines but accumulated their results in a weekly data report within the GeoMoS web interface. The use of GeoMoS Now enabled an integrated data interface for the client's engineers. The software streamlines real-time data flow from thousands of sensor channels into a simple and clear report. The new algorithm automatically processes monitoring surfaces and compares them to reference epochs. Changes exceeding predefined parameters automatically trigger additional laser scan monitoring. This continuous, live communication and data exchange between the field and office—enabled by reliable equipment—eliminates delays, prevents collapses and failures, and removes the need for costly corrective measures.

3.2.2 Crossrail Paddington Station – SHM System for Complex Urban Construction

The following section analyzes a complex infrastructure project in London — *Crossrail Paddington Station* — where structural health monitoring (SHM) systems were implemented. The primary objective was to ensure safe construction and the preservation of existing infrastructure through the deployment of advanced monitoring systems.

The main goal of the *Crossrail Paddington Station* project was to construct a new underground station beneath an existing historic building, without interrupting traffic or introducing safety risks.

The technological monitoring system included 52 Leica TM30 robotic total stations as part of the automated optical system, over 1,800 monitoring prisms, functioning as smart sensors with continuous feedback, IoT architecture enabling the connection of all measuring devices and sensors via optical and wireless communication networks, three central servers for real-time data processing, and software platform Leica GeoMoS. GeoMoS Adjustment and Leica GeoOffice, enabling data processing, analysis, and visualization in real time.

Internet of Things (IoT) enabled constant connectivity between all sensors and devices, allowing the system to operate 24/7 without manual intervention. Smart sensors (robotic stations and prisms) generated large volumes of high-precision data, essential for predictive analysis. Intelligence and automated algorithms, integrated into the GeoMoS software ecosystem, identified displacement patterns, anomalies, and potentially critical deformations at early stages, enabling decision-making without human error. Edge computing architecture allowed preliminary filtering and analysis of data locally before transmission to the central system, reducing latency and improving response time. Digital infrastructure management was achieved through a centralized platform for visualization and alerting, aligned with digital twin concepts for smart cities.

Construction of the underground station directly beneath a historic building was achieved without damaging the above-ground infrastructure. The system reduced the need for manual inspections, significantly increasing operational efficiency. Data processing speed increased by up to 90%, enabling faster decision-making. Continuous real-time monitoring allowed early-stage response to potential ground movement. Precise risk control led to lower insurance costs and greater confidence among project stakeholders. Most importantly, the

system minimized safety risks for both construction workers and station users by automatically detecting potentially hazardous deformations in their early stages.

3.3 Critical Review of SHM System Implementation

The implementation of SHM systems based on Industry 4.0 principles brings promising innovations in automation, predictive analytics, and real-time infrastructure management. However, these advancements also introduce new technical, ethical, and economic challenges that require critical assessment.

SHM systems depend heavily on digital infrastructure: stable electricity supply, continuous internet access, and secure server communication. In events such as power outages, telecommunication failures, or cyberattacks, these systems may completely lose functionality.

As SHM systems connect hundreds of devices via wired and wireless networks, they become potential targets for cyber threats. Risks include data breaches, sensor manipulation, ransomware, and entry points to other critical systems.

Economic Viability Despite claims of cost-saving through preventive maintenance, SHM implementation entails, high capital and operating costs and need for skilled personnel In developing countries or deteriorating infrastructure, such investments may be hard to justify. Sustainable adoption requires scaling system complexity to real risk levels, and ROI-based decision-making and cost-benefit analysis, modular implementation at critical points, use of commercial/open-source tools and standardized protocols, public-private partnerships and alternative funding models and integration with existing asset management and BIM systems.

SHM systems using drones, 3D scanners, or cameras may capture private data (faces, license plates, property details). Even anonymized data sharing could breach GDPR or local laws. Transparency is needed on what data is collected and why, who can access it and under what conditions, how long it is stored and whether it is shared.

While enhancing public safety, SHM systems may pose surveillance risks if not governed ethically. High-resolution sensors and continuous monitoring could intrude into private life. I4.0-based SHM systems must be technically resilient, economically justified, cybersecure, and transparent and ethically aligned. This balance is central to the evolution toward Industry 5.0, where technology coexists with human-centric values, inclusivity, and sustainability.

3.4 Future trends toward the concept of Industry 5.0

Industry 5.0 represents a shift from machine-based automation (Industry 4.0) towards a deeper synergy between humans and technology, integrating advanced tools such as Artificial Intelligence (AI), the Internet of Things (IoT), robotics, and automation [16]. This approach introduces numerous challenges and opportunities, including in sectors such as geodetic and geotechnical structural monitoring.

Industry 5.0 recognizes the potential of industry to drive social transformation, moving beyond the boundaries of digital transformation towards a paradigm that also embraces human and environmental needs. This concept is complementary to the advancements already achieved through Industry 4.0, but adds a new dimension — the dimension of values.

The concepts of Society 5.0 and Industry 5.0 are closely connected, as both refer to a fundamental shift in society and economy towards a new paradigm [16].

Society 5.0 envisions a society where advanced information technologies, the Internet of Things, robots, artificial intelligence, and augmented reality are actively integrated into everyday life, industry, healthcare, and other sectors — not primarily for economic gain, but for the well-being and comfort of every citizen.

A purely profit-driven approach is becoming increasingly unsustainable. In a globalized world, a narrow focus on profit fails to adequately account for environmental and social costs and benefits. For industry to become a genuine source of prosperity, its core purpose must include social, environmental, and societal dimensions. This requires responsible innovation, not aimed solely or primarily at increasing cost efficiency or maximizing profit, but rather at enhancing prosperity for all stakeholders — including investors, workers, consumers, society, and the natural environment.

In the contemporary context of rapid technological advancement, the transition from Industry 4.0 to Industry 5.0 marks a significant shift in how the roles of technology and humans are understood—particularly in fields such as geodetic and geotechnical infrastructure monitoring. Industry 4.0 brought intensive automation, the integration of sensor networks, IoT systems, artificial intelligence, and big data analytics into the processes of monitoring infrastructure assets. These systems enabled continuous real-time data acquisition and analysis, leading to improvements in efficiency, accuracy, and response speed. In this environment, the role of engineers and technicians was largely focused on supervising and managing automated processes. Industry 5.0, however, introduces a new paradigm centered on synergy between humans and technology. The key difference lies in bringing the human back to the core of the process—not as a passive operator, but as an active creator and decision-maker. In geodetic and geotechnical monitoring, this means that advanced tools such as AI and digital twins are not only used for data processing but also to enhance engineering understanding, support complex decision-making, and develop customized solutions tailored to the unique characteristics of each infrastructure asset.

Beyond technological advancements, Industry 5.0 emphasizes ethical values, sustainability, and social responsibility. In the context of monitoring, this translates into the development of solutions that not only observe and predict the condition of structures but also contribute to long-term safety, resource conservation, and environmental impact reduction. While Industry 4.0 is characterized by standardization and mass deployment of technology, Industry 5.0 promotes flexibility, interdisciplinarity, and a high degree of personalization—an especially important feature in monitoring projects that increasingly rely on the integration of geodetic, civil engineering, and IT systems.

This transformation opens up new opportunities for engineers and researchers in the infrastructure domain, encouraging them to merge technical expertise with creativity and broader societal values in order to develop smarter, more sustainable, and more human-centered monitoring systems.

Table 4 illustrates Industry 4.0 transition to Industry 5.0 in the context of geodetic and geotechnical SHM.

Table 4. Transition of the industrial concept in the context of geodetic and geotechnical SHM

Aspect	Industry 4.0	Industry 5.0
Focus	Automation and optimization of measurement and monitoring processes	Collaboration among surveyors, engineers, and geologists to create innovative solutions
Technology	Remote sensors, IoT devices, robotics, drones, AI for data analysis	Integration of artificial intelligence, robotics, and human skills for accuracy and innovation
Role of Professionals	Supervising automated systems for measurement and data analysis	Human creativity in data interpretation, decision-making, and implementation of tech solutions
Approach to Services & Output	Automated processes in geodetic and geotechnical monitoring, mass data handling	Flexible solutions for precise measurements and personalized monitoring at specific sites
Objectives	Efficiency in data acquisition and processing, error reduction in measurements	Sustainable solutions, data accuracy, increased safety, and ethical application of results
Data & Intelligence Approach	Automated field data analysis, real-time monitoring with minimal human input	Combined machine learning and human interpretation for accurate decision-making in SHM
Ethics & Sustainability	Standardized processes focused on efficiency, with limited attention to social aspects	Active consideration of social and environmental factors in implementing geodetic/geotechnical solutions
Interaction with Technology	Technology automates measurement and data analysis without human involvement	Technology enables informed human decisions and creative field solutions
Personalization	Standardized geodetic networks and measurements with limited adaptability	Customized technologies and methods tailored to client needs and complex geodetic/geotechnical projects

4. CONCLUSION

The implementation of SHM systems has proven essential in urban environments where space is limited and the infrastructure is older and more vulnerable. The integration of geodetic, geotechnical, and environmental sensors into a unified system enables a comprehensive assessment of structural conditions.

Projects such as Crossrail demonstrate that automated monitoring enhances stability during construction, allows for timely response in critical situations, and reduces dependence on the subjective assessment of field engineers. The use of monitorig platforms provides continuous information flow to all project stakeholders through a web interface, accelerating decision-making and improving coordination between design, construction, and maintenance phases. Beyond technical advantages, SHM systems also influence public perception of safety, as they enhance trust in high-risk infrastructure projects.

In the case of Harvard Stadium, the project illustrates how historic structures can be modernized to comply with contemporary safety standards without compromising their authenticity.The project has set a benchmark for monitoring in mega-infrastructure projects that are executed in phases and under operational loads.

The experience at Istanbul Airport demonstrated that seismic monitoring can be integrated into standard geodetic networks without the need for additional seismographs, while simultaneously contributing to the digital transformation of airport operations.

The implementation of Industry 4.0 technologies in the Regent's Park Development project brought significant advancements in the field of structural monitoring. The integration of sensor networks, automated data acquisition, real-time analytics, and cloud-based platforms enabled continuous, high-precision monitoring of complex urban infrastructure, including historical buildings and underground tunnels, during all construction phases. Automated alarms and data fusion from various geodetic, geotechnical, and environmental sensors allowed for timely risk assessments and proactive decision-making, significantly improving safety and operational efficiency.

For the transition toward Industry 5.0, future SHM implementations tend to focus on greater human-technology synergy, ensuring that monitoring systems do not only automate processes but also enhance human decision-making through intuitive visualization, context-aware intelligence, and ethical data governance. In moving toward Industry 5.0, it is essential to adopt human-centric design principles that prioritize ethical safeguards, such as purpose limitation, anonymization of datasets, user rights to data transparency, and independent oversight of SHM data management — to ensure that technological progress respects individual rights and aligns with broader societal values.

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Research paper

OPTIMISATION OF DAYLIGHTING STRATEGIES IN EDUCATIONAL LEARNING ENVIRONMENTS IN NIGERIA: A CASE FOR UNIVERSITY LIBRARY DESIGN

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Abstract

Natural daylighting is a sustainable and cost-effective technique for improving indoor environmental quality in educational buildings, particularly in tropical regions such as Nigeria. University libraries, as centres of knowledge and extended student activity, require excellent visual comfort and low energy consumption. The aim of this study is to analyse and optimise daylighting systems in Nigerian university libraries in order to increase learning outcomes, user satisfaction, and energy efficiency. The objective is to improve the lighting conditions in libraries by implementing efficient and controlled daylighting systems. The research methodology used was a mixed-method approach that included quantitative assessments using questionnaires (n=168) for data collection and case studies of selected university libraries in Nigeria. The study examines current design approaches, daylight availability, and occupant responses. The findings revealed that it is more favourable to consider the use of passive daylighting techniques for library design as a natural way of lighting to create a pleasant environment in libraries and incorporate them into various types of libraries in Nigeria. This would improve users' comfort, reduce the usage of artificial lighting, and increase the energy efficiency of library buildings. The significant of this study is that the outcome would provide appropriate guidance for architectural design decisions and regulatory frameworks that promote daylight-responsive library architecture in Nigerian universities.

Key words: *Daylighting, Education, Learning Environments, Library Design, University, Nigeria*

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1. INTRODUCTION

Daylighting is vital in learning environments such as libraries, where users rely on consistent, evenly dispersed light to complete activities efficiently. According to Flynn *et al.* [1], lighting design has a dramatic impact on human visual experience by guiding movement, directing focus, and changing perceptions of space. Building on this, Rahman and Tuhin [2] emphasise that daylighting is more than just an architectural decision; it is a critical environmental quality that influences user comfort, productivity, and building energy consumption in educational settings. In Nigeria, unstable electricity and high energy prices make daylighting both difficult and advantageous. Despite ample sunlight, many university libraries rely extensively on artificial lighting due to poor architectural design, which increases energy costs and reduces visual comfort. Inadequate daylighting can cause glare, discomfort, and thermal imbalance, all of which interfere with users' ability to complete jobs effectively.

This research tackles these concerns by investigating how spatial orientation, window design, daylight control technologies, and material selection might improve daylighting in university libraries. Its goal is to: (i) Evaluate the effectiveness of current daylighting initiatives in chosen Nigerian university libraries. (ii) Investigate how library illumination affects user pleasure, productivity, and health. (iii) Develop optimal daylighting solutions for new and retrofitting university library designs in Nigeria. Following these goals, the study aims to improve visual comfort, energy efficiency, and overall user satisfaction through optimal daylighting optimisation.

2. LITERATURE REVIEW

Extensive research has shown that daylighting in educational buildings improves visual comfort, cognitive function, mood, well-being, and energy efficiency [3-5]. Notably, Samani *et al.,* [6] discovered that natural light increases reading comprehension and lowers eye strain, while Rahman & Tuhin [2] emphasise its importance in aligning circadian rhythms to promote attention. Optimal daylighting solutions include proper building orientation, window sizing and location, light shelves, clerestories, and advanced glazing [7]. In tropical climates, extra measures such as shading devices, solar-control films, and responsive lighting controls are required to reduce heat gain. Nigeria, with its abounding sunlight, is a significant design opportunity. However, local studies show that university libraries frequently suffer from poor daylight utilisation due to deep floor plans, insufficient window placement, and a lack of daylight control, resulting in an overreliance on artificial lighting and compromised comfort [8-10]. Few post-occupancy evaluations exist, and there is an urgent need for context-specific empirical assessments. Empirical research supports the link between daylight and academic outcomes: Kano classrooms with optimised windows showed a 12-15% increase in test results [11]. Though research on academic libraries is scarce, recent studies indicate that daylight improves reading comfort, circulation flow, and concentration [12]. Despite clear global evidence, there is little documentation on (i) daylighting performance in Nigerian university libraries, (ii) how design parameters (orientation, glazing, shading) relate to actual user comfort and health, and (iii) the use of post-occupancy evaluations and daylight simulations for optimisation. This indicates an important research need: empirical assessments to drive context-specific daylighting methods for Nigeria's educational environments.

3. RESEARCH METHODOLOGY

3.1 Study Location

The study was carried out in Niger State, which is located in North Central Nigeria. Niger State is home to various tertiary educational institutions, including the Federal University of Technology, Minna (FUTMinna), Ibrahim Badamasi Babangida University, Lapai (IBBUL), Niger State College of Education, Minna, and Newgate University in Minna. These institutions were chosen because they have a mix of federal, state, and private ownership and provide various learning environments with varying architectural designs and daylighting tactics in their library buildings. The choice of location enables a comparative investigation of the influence of daylighting in university libraries across various educational environments.

3.2 Research Design

The study used a quantitative cross-sectional survey research design. The method is appropriate for collecting perceptual and experience data from a large number of respondents at a single time [13]. A comprehensive, pre-tested questionnaire was developed and distributed to students and academic staff at the selected institutions. The instrument looked at crucial characteristics like library usage patterns, light source preferences, availability to lighting controls, perceptions of visual comfort, and the psychological consequences of lighting in library environments.

3.3 Population of the Study, Sampling Technique and Sample Size

The target population consisted of academic library users from four selected institutions in Niger State. These included undergraduate and postgraduate students, pre-degree students, lecturers, and non-academic personnel who frequented the library for a variety of reasons, including reading, research, studying, and using ICT resources. The demographic was chosen based on their likelihood of using both natural and artificial lighting systems in university libraries. A purposive sample strategy was employed to choose library users who have extensive experience using their institution's library facilities. This strategy was appropriate for targeting individuals who were most likely to provide credible insights regarding daylighting circumstances and their effects on user experience and productivity [14]. A total of 168 valid responses were gathered from the four institutions selected. This sample size is deemed appropriate based on Kotrlik *et al.'s* [15] recommendations of a minimum of 160 respondents for populations greater than 1,000 at a 95% confidence level and a 5% margin of error.

3.4 Research Instrument

The primary data gathering tool was a structured questionnaire designed to evaluate the use, accessibility, suitability, and impacts of daylighting in university libraries. The questionnaire comprised of both close-ended and Likert-scale items, which were divided into the following sections: (A) Demographic and institutional profile (B) Library usage patterns (C) Natural vs. artificial lighting preferences (D) Lighting control accessibility (E) Illumination adequacy and uniformity (F) Visual comfort and safety (G) Psychological and mood responses to lighting. The measure was created using reviewed literature in daylighting and

environmental psychology Boyce [16] and Li & Tsang [5], verified through expert review in architectural lighting, and pilot-tested for dependability.

3.5 Method of Data Collection and Data Analysis

Over a four-week period, questionnaires were delivered both physically and electronically in the libraries of the selected institutions. Physical administration was aided by research assistants who delivered brief instructions to participants. Online versions were produced with Google Forms and distributed via university email lists and WhatsApp platforms to maximise reach. Participation was optional and anonymous, and all respondents provided informed consent. Only anyone who have utilised the library in the previous 12 months were eligible to answer the questionnaire. The acquired data was coded and analysed using Statistical Package for the Social Sciences. (SPSS) Version 25. The replies were summarised using descriptive statistics including frequencies, percentages, mean scores, and standard deviations. In addition, the Relative Importance Index (RII) was utilised to rate judgements of daylighting sufficiency, visual comfort, and mood effects. Cross-tabulation was utilised to investigate the association between demographics (e.g., level of study or staff category) and lighting preferences. The data analysis supported conclusions about the optimisation potential of daylighting solutions in Nigerian educational library environments.

4. RESULTS AND DISCUSSION

A total of 200 questionnaires were provided; however, only 168 of them were properly completed and returned. This equated to an 84% response rate. This response rate is relatively high, hence the response rate obtained for this study is judged adequate for the analysis, as any survey result with a lower response rate of 30-40 percent is skewed and of lesser significance [17].

4.1. Background characteristics of the respondents

Table 1 shows the characteristics of the questionnaire respondents. A large number of them were students, with only a small percentage working at those institutions.

As can be seen, 35.1% of respondents are from COE, 33.3% from FUT, and 30.4% from Newgate University, with only 1.2% coming from IBBU Lapai. 86.9% are undergraduate students, 6.6% are lecturers, 5.4% are pre-degree students, and 1.2% are master's students. There are 33.3% 100 Level (L) students, 19.6% 500L students, 19% 300L students, and 16.7% 200L students. 3.6% are 200L, 1.2% are Masters students, and 6.5% are academic personnel. The poll also revealed that 51.8% are women and 47% are men. 69.6% are between the ages of 16 and 26, 19.6% between 26 and 36, 8.3% between 36 and 46, and 2.4% between 46 and 56 years old. These findings reveal a well-defined, mostly undergraduate population, with balanced gender representation and a high age concentration in the 16-26 cohort. However, caution should be exercised when extending the findings to postgraduate users or the under-represented IBBU Lapai group.

Table 1. Background characteristics of respondents

Characteristics of Respondents	Frequency	Characteristics of Respondents	Frequency
Institution		**Level (L)**	
FUT	56 (33.3)	100L	56 (33.3)
IBBU	2 (1.2)	200L	28 (16.7)
COE	59 (35.1)	300L	32 (19)
New-gate	51 (30.4)	400L	6 (3.6)
		500L	33 (19.6)
		Postgraduate	2 (1.2)
		Academic staff	11 (6.6)
Status		**Gender**	
Student	157 (93.5)	Male	79 (47)
Staff	11 (6.5)	Female	87 (51.8)
		Prefer not to say	2 (1.2)
Status in the institution		**Age**	
Pre-degree	9 (5.4)	16-26	117 (69.6)
Undergraduate	146 (86.9)	26-36	33 (19.6)
Postgraduate	2 (1.2)	36-46	14 (8.3)
Lecturer	11 (6.5)	46-56	4 (2.4)

4.2. Adequacy of daylight strategies employed in library design

Table 2 displays the suitability of daylight strategies used in the design. Respondents to the survey thought the lighting conditions in the library were good. Specifically, 42.9% assessed the provision of natural light as 'very adequate' and 35.1% as 'extremely adequate,' with only 10.7% expressing displeasure; the mean score of 2.0 confirms that natural lighting is mostly effective. Similarly, consistency of illumination garnered positive comments, with 39.9% rating it 'very adequate' and 28.0% 'quite adequate', and only 10.1% unsatisfied. The corresponding mean of 2.16 indicates that lighting is sufficiently consistent for reading and studying. Finally, 38.1% of respondents rated indoor lighting as 'very adequate', 25.0% as 'extremely adequate', and only 25.0% as 'barely adequate', as seen by a somewhat higher mean of 2.24, showing space for improvement. These findings indicate that, while daylight provision and homogeneity match user needs, certain interior zones could benefit from enhanced lighting interventions."

Table 2. Uniformity of illumination for performing library activities

Level of adequacy	The provision for natural lighting	Uniformity of the illumination	Illumination of the indoor environment
Highly adequate	35.1%	28.0%	25.0%
Quite adequate	42.9%	39.9%	38.1%
barely adequate	11.3%	22.0%	27.4%
Not adequate	8.3%	8.3%	6.5%
Highly inadequate	2.4%	1.8%	3.0%
Mean value	2.0	2.16	2.24

4.3. Impact of library illumination on user's satisfaction

Table 3 depicts the impact of illumination on user satisfaction. Emotional Impact reflects the respondents' happiness and unhappiness. The mean happiness level for 49.4% (29.2% highly, 20.2% high) is 3.45. The mean for high dissatisfaction when there is insufficient light is 3.66. This means that proper daylighting considerably improves consumers' mood, whereas insufficient lighting causes severe discontent.

Table 3. Impact of illumination on User's satisfaction.

Variable	Level of agreement	Frequency (percent.)	Mean value	Variable	Level of agreement	Frequency (percent.)	Mean value
The lighting condition makes me happy when reading	Lowest Low Medium High Very high	19(11.3) 18(10.7) 48(28.6) 34(20.2) 49(29.2)	3.45	I feel relaxed when using the library	Lowest Low Medium High Very high	16(9.5) 29(17.3) 42(25) 41(24.4) 40(23.8)	3.36
I am unhappy when I cannot get sufficient illumination to read	Lowest Low Medium High Very high	14(8.3) 18(10.7) 34(20.2) 47(28) 55(32.7)	3.66	I am stressed when using the library	Lowest Low Medium High Very high	55(32.7) 43(25.6) 37(22) 11(6.5) 22(13.1)	2.42
I am more energetic when in the library	Lowest Low Medium High Very high	14(8.3) 31(18.5) 34(20.2) 42(25) 47(28)	3.46	The lighting conditions make me annoyed visually	Lowest Low Medium High Very high	62(36.9) 34(20.2) 28(16.7) 27(16.1) 17(10.1)	2.42
I am inspired to study more when in the library	Lowest Low Medium High Very high	7(4.2) 26(15.5) 55(32.7) 34(20.2) 46(27.4)	3.51	I suffer from eye fatigue when studying	Lowest Low Medium High Very high	45(26.8) 38(22.6) 39(23.2) 34(20.2) 12(7.1)	2.58
My concentration is higher when using the library	Lowest Low Medium High Very high	10(6) 26(15.5) 43(25.6) 40(23.8) 49(29.2)	3.55	I am distracted when using the library	Lowest Low Medium High Very high	58(34.5) 36(21.4) 40(23.8) 25(14.9) 9(5.4)	2.35

This is consistent with global findings from writers such as Aram and Alibaba [18], who found that well-designed daylight improves mood and user well-being, whereas bad lighting reduces emotional state and perceived visual comfort. This means that library architects should prioritise integrating ample yet glare-free daylight sources, such as north-facing windows or light shelving, in order to sustain good emotional responses and avoid discontent in low-light situations. Energy and inspiration levels are both high, with a mean of 3.46 (53% high or highly energetic) and a mean of 3.51 (48% high or strongly inspired). This means that daylit library spaces promote alertness and motivation, supporting the relationship between daylight and increased cognitive vigour.

This research suggests that strategic daylight penetration—via skylights, clerestories, and reflective surfaces—should be prioritised to improve focus and academic drive. In terms of concentration and distraction, concentration had a mean of 3.55 (52.8% high or maximum), whilst distraction was low (mean = 2.35), with 56.9% indicating little distraction. This means that well-lit environments promote concentrated work while minimising distractions, reflecting findings linking natural light to decreased cognitive fatigue and increased attention span. This implies that libraries should be designed to prevent direct glare and overly bright hotspots. Implementing indirect lighting methods and zoning to provide continuous concentration throughout the space.

Relaxation has a mean of 3.36 (47.7% medium to high), whereas tension has a mean of 2.42. This suggests that daylit situations make people feel more comfortable and less worried. Daylight exposure has been found to help regulate circadian cycles and reduce stress. As a result, visual breaks in the form of views of greenery or outside vistas, as well as moderate indoor brightness, are required to comfort users emotionally. Overall, our data confirm that daylighting improves emotional well-being (happy, inspiration, reduced stress), boosts cognitive performance (energy, attention, fewer distractions), and is critical to the psychological and functional quality of educational library spaces.

4.4 Identify the Impact of Daylight on Health

The results in Table 4 show that the Visual Comfort Against Flicker & Over-Illumination has mixed reactions. 39.9% agree or strongly agree that visual comfort is adequate; 35.1% are neutral, and 25% disagree. The Mean is 3.17, showing a neutral position—neither clearly satisfied nor dissatisfied. This means that people do not significantly like or dislike the current lighting settings, which include flicker and over-illumination. This means that daylighting is adequate but may occasionally cause discomfort, most commonly owing to glare or stray bright spots. On the topic of discomfort caused by flickering or over-lighting, 26.7% agree or strongly agree. 34.5% are indifferent, and 38.7% disagree, with a mean of 2.79. This suggests that a sizable proportion of users are unconcerned about slight pain, while a sizable proportion (38.7%) are not bothered. This demonstrates some variance in sensitivity to flicker or brightness, indicating the need for improved glare reduction. In terms of Glare Perception, 28.5% indicate high glare, 29.8% are neutral, and 41.7% disagree. This means that while 41.7% do not perceive glare concerns, which is good, a significant minority (almost 30%) do. This illustrates that glare is still an issue in some areas. 51.2% agree/strongly agree that illumination improves safe movement. 26.8% are neutral, while 22.2% disagree. This means that more than half of participants are confidence in their ability to move about, implying that daylighting aids navigation. However, about one-fifth feel insecure, indicating the possibility of dim or uneven terrain. On Lighting in Circulation Spaces, 47% agree that daylight architecture improves light distribution in corridors and common areas. 32.7% are neutral, 20.3% disagree. This means that over half of users consider circulation spaces to be well-lit by daylight, while approximately 20% believe there is need for improvement, particularly where routes appear gloomy or patchy.

Based on these findings, the following implications for Library Daylighting Design can be drawn: (i) Balancing Brightness and Glare Control - The presence of neutral and negative reactions regarding comfort and glare indicates an unequal light quality. As indicated in the Whole Building Design Guide (WBDG), high brightness without regulation can cause glare and discomfort. The design focus must include dispersing strategies—such as light shelves, towering clerestories, and matte surfaces—to offer adequate light without glare or flickering. (ii) Improving Visual Comfort Uniformity - Neutral mean ratings for flicker and over-illumination emphasise the importance of even, controlled, flicker-free daylight. The design should prioritise the use of shading devices, glare sensors, and zoned lighting systems (daylight harvesting) to ensure constant, adaptive illumination based on occupancy and daylight availability.

Table 4. Impact of daylight on health

Variable	Level of agreement	Frequency (%)	Mean value
The visual comfort against flickering and over illumination in the library is comforting	Strongly disagree Disagree Neutral Agree Strongly Agree	16(9.5) 26(15.5) 59(35.1) 47(28.0) 20(11.9)	3.17
The visual comfort against flickering and over illumination in the library is discomforting	Strongly disagree Disagree Neutral Agree Strongly Agree	27(16.1) 38(22.6) 58(34.5) 34(20.2) 11(6.5)	2.787
The illumination within the library indoor environment is glaring into my eye	Strongly disagree Disagree Neutral Agree Strongly Agree	21(12.5) 49(29.2) 50(29.8) 36(21.4) 12(7.1)	2.815
The illumination level within the library helps/enhances safety of movement	Strongly disagree Disagree Neutral Agree Strongly Agree	19(11.3) 18(10.7) 45(26.8) 62(36.9) 24(14.3)	3.32
The design of the circulation spaces optimizes the distribution of light in the library	Strongly disagree Disagree Neutral Agree Strongly Agree	9(5.4) 25(14.9) 55(32.7) 64(38.1) 15(8.9)	3.3

The design should prioritise the use of shading devices, glare sensors, and zoned lighting systems (daylight harvesting) to ensure constant, adaptive illumination based on occupancy and daylight availability. (iii) Improving Safety and Circulation Lighting - With approximately 20-22% of respondents disagreeing on safety and corridor lighting, certain zones may lack appropriate brightness, resulting in low visibility difficulties. The design focus should be on using daylighting in corridors and moving areas, such as skylights or window strips, to maintain minimal illuminance levels and visual interest. (iv) Addressing Glare Hotspots – Nearly 30% of respondents reported glare, indicating that bright beams were striking work areas. The design should prioritise precise fenestration placement, the use of indirect illumination (e.g., clerestories), and the use of shading to prevent direct sunlight from reaching desktop surfaces. The overall design implications of these findings are that they correlate with best practices in daylighting: natural light must be controlled, uniform, glare-free, and adaptively managed to ensure both visual comfort and functional safety. For Nigerian university libraries, this entails creating daylighting that is user-centric, well-shaded, zoned, and meets basic safety standards, especially in corridors.

4.5. Visual Comfort in the Library and the Impact of Lighting Condition

To assess whether there is a relationship between users' visual comfort and the impact of lighting conditions in the library. Table 5 shows the findings of Chi-square and Kendall Tau-b analysis. Visual comfort and perceived lighting influence have a moderate positive connection (Kendall $\tau_b = 0.235$, $p < 0.05$). This underscores the idea that optimal daylighting solutions, particularly those that reduce glare, flicker, and uneven brightness, can significantly improve user happiness. However, visual comfort is only one aspect of the lighting experience; other elements such as daylight quantity, homogeneity, and environmental management are likely to be relevant and should be addressed in integrated design guidelines.

Table 5. Relationship between visual comfort and the impact of lighting conditions.

			Visual comfort	Impact of lighting condition
Kendal-tau-b	Visual comfort	Correlation Coefficient	1.000	.235**
		Sig. (2-tailed)	.	.000
		N	168	168
	Impact of lighting condition	Correlation Coefficient	.235**	1.000
		Sig. (2-tailed)	.000	.
		N	168	168

ANOVA (Analysis of variance) was used to see whether there is a significant difference in the impact of lighting on library users across the school. Table 6 displays the ANOVA results for the impact of lighting conditions.

Table 6. ANOVA analysis on impact of lighting condition

Impact of lighting condition in the library					
	Sum of Squares	Degree of freedom	Mean Square	F	Sig.
Between Groups	5.842	3	1.947	6.395	.000
Within Groups	49.943	164	.305		
Total	55.785	167			

Table indicates: (i) Between-group variability: SS = 5.842, df = 3. (ii) Within-group variability: SS = 49.943, degree of freedom (df) = 164 (iii) F-statistic = 6.395, p-value < 0.001. We reject the null hypothesis ($p < 0.05$) and find that there are substantial differences in how users perceive lighting impact across four schools. This means that the effects of lighting conditions on library users across the school are not uniform; they vary by school. Figure 1 depicts the mean graph indicated in red color of the lighting conditions in the libraries across the schools. According to its Statistical Significance, the F-value of 6.395 suggests that differences in mean evaluations among institutions are unlikely to be random, confirming genuine variance in lighting circumstances and/or perceptions. The practical relevance emphasises that variations in perceived illumination quality may be due to site-specific architectural variables, such as window design, shading, orientation, or daylight control systems. The design implications for daylighting optimisation imply the necessity for (1)

tailored daylighting interventions. Because of the wide range of lighting impacts, a "one-size-fits-all" daylighting strategy will fail.

Each library demands context-specific solutions that consider its unique architectural elements and daylight dynamics. (2) Benchmark High-Performing Schools: Determine which institution has the highest mean rating. Use its daylighting design (fenestration arrangement, glazing type, shading devices, interior finishes) as a best-practice example for others. (3) Target Underperforming Libraries - Schools with lower ratings are more likely to experience challenges such as insufficient sunshine penetration, glare, or a lack of control. Optimise via specific treatments such as (i) improving window orientation, adding clerestories, or skylights. (ii) Install shading systems (such as louvres and light shelves), and (iii) use higher-reflectance interior finishes to improve daylight distribution. (4) Implement Data-Driven Design - Repeat daylight simulations with occupant feedback to identify deficiencies and confirm solutions per school.

ANOVA was used to measure the visual comfort of daylight in the library among four institutions. Table 7 shows the results of an ANOVA analysis of visual comfort in the library. The results reveal (i) between-groups SS = 0.585 (df = 3) and within-groups SS = 65.746 (df = 164). (ii) The F-value is 0.486, p = 0.692, which is greater than 0.05. It may be concluded that there is no statistically significant difference in visual comfort scores between the four schools. The following might be seen from the results. (i) Consistent Visual Comfort - The lack of significant variance ($p > 0.05$) indicates that users in all libraries experience similar levels of daylight-related visual comfort, regardless of physical or contextual differences between schools.

Table 7. ANOVA Analysis of Visual comfort.

Visual comfort at the library	ANOVA				
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.585	3	.195	.486	.692
Within Groups	65.746	164	.401		
Total	66.331	167			

(ii) Daylighting tactics Are Comparable - Despite architectural or regional variances, each library appears to use daylighting tactics that result in similar comfortable visual circumstances. (iii) Comparison with Lighting influence - Previous research found disparities in the perceived influence of lighting between schools. However, these do not transfer into variances in basic visual comfort, indicating that ambiance or perceived productivity varies more than core comfort. Figure 1 shows a graph of the mean across the schools indicated in blue color of the visual comfort of daylight.

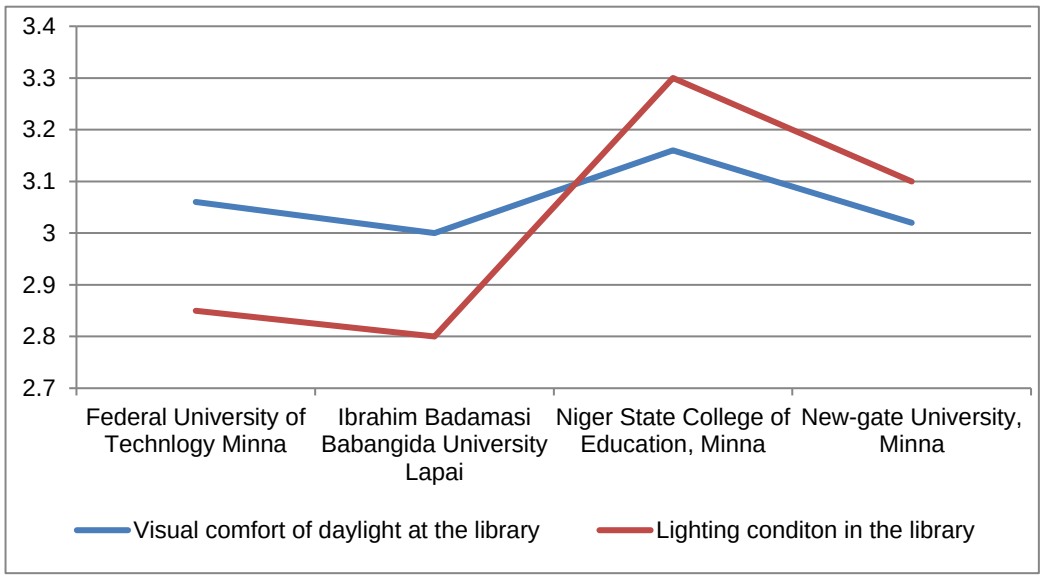

Figure 1. Mean graph of impact of lighting conditions and visual comfort

5. CONCLUSIONS

This study addresses the issue of many Nigerian university libraries relying significantly on artificial lighting due to poor architectural design, resulting in higher energy costs and worse visual comfort. It looked into how spatial orientation, window design, daylight control technologies, and material choices may improve daylighting in university libraries. Based on the research findings, many significant conclusions are derived that are consistent with the goal of optimising daylighting in Nigerian university libraries. First, it is possible to determine that daylighting quality is generally adequate. This is mirrored in users' positive ratings of natural light provision and illumination uniformity, indicating that existing daylighting solutions meet basic comfort criteria. Second, sunshine promotes well-being and productivity, as seen by high scores for happiness, energy, attention, and inspiration, as well as lower stress and distraction, demonstrating substantial positive correlations between daylight and cognitive/emotional advantages in library users. Third, health and safety are mixed, with neutral answers to flicker, glare, and over-illumination, and worries about circulation lighting highlighting opportunities for improvement. Fourth, visual comfort partially predicts positive perception, as the results reveal a moderate, significant association, confirming that improving glare-free, consistent visual comfort improves overall impressions of lighting quality. Fifth, there are institutional differences, as the ANOVA results show substantial changes in perceived lighting impact between institutions, but no significant variance in visual comfort. This shows that basic comfort is stable, while other factors such as ambiance and functional performance differ between school. Finally, this study supports a multidimensional optimisation strategy that includes preserving existing daylight comfort while improving functional, emotional, and safety aspects through tailored, user-centred daylight design—particularly glare control, spatial uniformity, and targeted institutional interventions. This approach is consistent with the best practices for high-performance daylighting promoted by WBDG.

6. RECOMMENDATIONS

The guidelines below are made to optimise daylighting strategies in Nigerian educational learning environments. (i) Prioritise glare control and visual comfort by using exterior/integrated shading devices such as light shelves, overhangs, and louvres to deflect direct sunlight and reduce glare. The use of light shelves is particularly essential as they can prevent glare and allow natural light to penetrate deeper into the space through indirect lighting. This approach is particularly effective for the "soft component" of daylight and is especially suitable for libraries. Choose glass with moderate-to-low solar heat gain coefficients and good visual transmittance; use low-emissivity coatings to reduce glare and thermal gain (ii) Improve Uniformity and Flicker-Free Lighting. To softly diffuse daylight, increase interior reflectance by >80% on ceilings, >50% on walls, and ~20% on floors. Also Use lowering daylight-responsive electric lighting and day-light harvesting controllers to keep illumination levels consistent throughout the day. (iii) Improve Circulation Space Safety - In corridors, supplement glass with skylights or high clerestories to meet minimum illuminance requirements and facilitate navigating. Use zonal daylight control to avoid dark areas while maintaining overall daylight harmony. (iv) Customise Solutions for Each Institution - Use post-occupancy evaluations and post-hoc lighting studies to determine which libraries have a low perceived lighting influence. Implement library-specific interventions, such as adding light shelves or shade to deep layouts and increasing windows in low-light zones. (v) Establish Daylighting Benchmarks - Based on the best-performing institutions, develop site-appropriate criteria (for example, daylight autonomy and illuminance range). Use simulation tools (radiance, climate-based modelling) early in the design process to test shading, glazing, and orientation techniques. (vi) Implement User-Controlled Shading and Smart Glazing by installing adjustable blinds (e.g., bidirectional) and smart glass (electrochromic) to enable occupants to modify daylight based on task and preference. (vii) Conduct regular evaluations - Implement continuous monitoring and feedback loops to adjust daylight system performance after occupancy. Track parameters such as user happiness, illuminance, glare indices, and energy savings to ensure continued optimisation.

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Research paper

EXAMINING THE TANGIBLE AND INTANGIBLE VALUES IN THE ADAPTIVE REUSE OF KHANS IN THE HISTORIC CITY

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Abstract

Adaptive reuse is a significant strategy for the conservation and long-term sustainability of historical buildings like khans, which may become obsolete due to changing economic and social conditions. Traditionally serving as centers for trade, accommodation, and social interaction, khans carry the historical accumulation of their period and contribute significantly to urban identity and memory. The adaptive reuse process engages with both the tangible and intangible values of these structures to ensure their continued relevance and preservation. Tangible values pertain to the physical fabric and characteristics of the khan buildings, including their architectural design, authentic features, construction techniques, materials, form, design, and overall integrity, while intangible values are the non-physical qualities that give meaning and significance to the khan, connecting people to the place and its history. This paper examines the tangible fabric and intangible aspects as inseparable and jointly contributing to the unique meaning and spirit of a historical place. While functional change is often necessary for adaptive reuse, the choice of a new function should be carefully considered to ensure it remains compatible with the building's values and contributes to its significance. The study looks beyond conservation and evaluates based on available literature and onsite observations, how adaptive reuse offers economic benefits by increasing the financial value of khans, creating opportunities for tourism, and contributing to the economic development of local people. It also looks at the environmental advantages by reusing embodied energy and reducing construction waste. Finally, it discusses how successful adaptive reuse requires a holistic approach, balancing socio-cultural, economic, and physical aspects based on detailed analysis and stakeholder collaboration to ensure long-term sustainability and the effective transfer of heritage to future generations.

Key words: *Adaptive Reuse, Cultural Values, Khan (caravanserai).*

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1. INTRODUCTION

Adaptive reuse, the process of repurposing old structures for new uses, has gained importance as a sustainable approach to heritage conservation. Khans, also known as caravanserais, were historically significant commercial inns that supported trade across regions like the Middle East, North Africa, and parts of Southern Europe. Their reuse today reflects broader discussions on preserving cultural identity, promoting sustainable development, and revitalizing urban spaces.

1.1. Understanding Khans and their Heritage Value

Khans typically date back to the medieval Islamic period and were critical infrastructure along major trade routes. Architecturally, they are characterized by large courtyards, robust stone walls, stables, and accommodations. Scholars such as Hill [1] and Grabar [2] emphasize the socio-economic and architectural significance of khans, noting their role not just as inns but also as centers for commerce and cultural exchange.

The historical importance of khans has led to growing interest in their preservation, as discussed by Salah Ouf [3], who points out that these structures offer unique opportunities to maintain tangible links with the past while serving contemporary needs.

1.2. Adaptive Reuse as a Preservation Strategy

Adaptive reuse is widely recognized as a sustainable and economically viable method for preserving historic structures. According to Plevoets & Van Cleempoel [4], adaptive reuse prolongs the life of heritage buildings by giving them new functions that meet current societal needs without significant alteration to their historic fabric. For khans, reuse projects often involve transforming them into boutique hotels, cultural centers, museums, restaurants, or artisan markets.

Yıldırim [5] highlights that successful adaptive reuse projects maintain a delicate balance between preserving a building's original character and introducing new functionalities that ensure economic viability. This is especially crucial for khans located in historic city centers where pressures for modernization are strong.

1.3. Challenges in the Adaptive Reuse of Khans

Several challenges arise in reusing khans:

Structural Integrity: Many khans have suffered neglect and require significant restoration before reuse, as observed in projects reviewed by Ashworth [6].

Cultural Sensitivity: As Daher [7] notes, inappropriate reuse that neglects the historical context can lead to cultural commodification or loss of authenticity.

Legal and Bureaucratic Hurdles: The reuse of khans often faces legal challenges, including unclear ownership, stringent heritage laws and complex approval processes, as discussed by Al-Houdalieh & Sauders [8].

1.4. Best Practices in the Adaptive Reuse of Khans

Community Involvement: Mason [9] stresses the need for engaging local communities to ensure that adaptive reuse projects are culturally appropriate and publicly supported.

Minimum Intervention: Keeping interventions to a minimum ensures that the historical and architectural integrity is respected [10].

Flexible Use: Adaptive reuse strategies should allow for flexible use over time to ensure continued relevance, as noted by Bullen and Love [11].

1.5. Reference Case Studies

Khan Al-Umdan, Acre, Israel: Planned for conversion into a luxury hotel, this project raised debates about public access versus privatization of heritage [12].

Khan As'ad Pasha, Damascus, Syria: Successfully adapted as a cultural and exhibition space, while maintaining much of its architectural integrity [13].

Wakalat Al-Ghouri, Cairo, Egypt: Converted into a cultural venue, hosting musical and cultural events while preserving the building's original design [14].

These examples show the varying degrees of success and the different approaches to adaptive reuse, reflecting the importance of community engagement and careful planning.

2. LITERATURE REVIEW – ANNOTATED BIBLIOGRAPHY

Here is a short, annotated bibliography of the key authors and sources mentioned here:

Ashworth [6] discusses the tensions between preservation and modernization in heritage buildings. His work highlights the challenges of structural rehabilitation and maintaining authenticity, which are critical issues in the adaptive reuse of historic khans.

Bullen & Love [11] explore the sustainability benefits of adaptive reuse and emphasizes the need for flexible use to ensure long-term relevance of heritage structures like khans.

Burns [13] examines how historic structures can serve modern cultural functions while preserving architectural integrity, offering important lessons for similar projects.

Daher [7] discusses the cultural risks associated with commodifying heritage sites. His critique is important for understanding the cultural sensitivity required in reusing khans, especially in tourist-driven economies.

Grabar [2] provides historical and cultural context about Islamic architectural forms, including khans and caravanserais. His work is valuable for appreciating the original functions and cultural meanings of these buildings.

Hill [1] touches on the infrastructure supporting Islamic commerce and trade, offering insights into the original purpose and architectural design of khans, which informs their conservation and reuse.

ICOMOS [10] in this charter stresses the importance of maintaining authenticity in heritage conservation, a principle directly relevant to adaptive reuse practices for khans.

Mason [9] discusses how involving local communities in heritage planning can enhance the success of conservation projects. His insights are key when considering community participation in the reuse of khans.

Plevoets & Van Cleempoel [4] frame adaptive reuse as a growing field in architecture and heritage conservation, providing theoretical foundations for reimagining structures like khans in a contemporary setting.

Raymond [14] discusses the transformation of historic buildings in Cairo, including wakalat (urban caravanserais), offering practical examples of adaptive reuse that respect historical urban fabric.

Salah Ouf [3] emphasizes how adaptive reuse should preserve the 'sense of place' of historic structures. This is particularly important for khans, whose cultural identity is deeply tied to their urban and social context.

UNESCO [12] in this report focuses on projects such as the planned reuse of Khan Al-Umdan, highlighting issues around privatization of heritage spaces and balancing conservation with development pressures.

Yıldırim [5] examines the practical aspects of reusing historic structures, emphasizing the importance of balancing new functions with respect for original architectural and historical values.

More recent sources that delve into the adaptive reuse of khans and caravanserais, offering insights into sustainability, cultural heritage and community engagement, include:

Hassan [15] defines adaptive reuse as the process of modifying old monumental buildings for new, non-destructive uses, ensuring structures maintain their historical integrity while meeting modern needs. He provides a historical overview and discusses contemporary applications in architectural practice.

Hoursan & Mofidi [16] focus on the potential for adaptive reuse of the Golshan and Sharifiyeh caravanserais in Hamadan, Iran. They propose strategies to enliven both sites by creating interconnected spaces that serve contemporary needs while preserving historical value.

Lundgren & Kyrö [17] utilize the social lifecycle assessment (S-LCA) framework to evaluate the social impact of adaptive reuse projects. They emphasize the positive economic and social effects of shared spaces on local communities, highlighting the broader benefits of revitalizing historic structures.

Rezaei et al. [18] examine the adaptive reuse of the Sa'd al-Saltaneh Caravanserai in Qazvin, Iran, through the lens of 'place making'. They investigate users' perspectives on how the site's transformation into a cultural and tourist destination affects their experience and connection to spatial attributes.

Shehada [19] whose study examines the adaptive reuse and conservation of the Al-Khan building in Ramallah, Palestine, dating back to the late 18th century. He highlights how modernization and historic conservation can coexist, especially in conflict zones where resources are strained. The research underscores the potential for conservation projects to integrate historic sites into contemporary society.

The sources above provide valuable insights into the adaptive reuse of khans and similar historic structures, offering perspectives on sustainability, community engagement and cultural preservation.

Consequently, the adaptive reuse of khans presents a valuable opportunity to preserve these culturally and historically significant structures while giving them renewed life in contemporary society. However, success depends heavily on sensitive planning, community engagement, sustainable funding models, and respect for the building’s original character. As urban environments continue to evolve, the adaptive reuse of khans offers a critical model for integrating heritage conservation into modern development strategies.

3. INVESTIGATION METHODOLOGIES AND CONSIDERATIONS

Deciding how to re-use historical buildings can be difficult, especially when the concerns of decision-makers are not aligned. Methodologies for adaptive reuse have been developed and applied to historical patterns. A simple technique can assist decision-makers on the value of adaptive reuse can involve steps, such as assessing the condition of the historical pattern and its environment, the integrity of the place, re-use alternatives and stakeholder

requirements. It also requires knowledge of traditional construction techniques. Analysis of the existing fabric, including original function and physical characteristics, is crucial.

Identifying adaptive reuse potentials, which can be physical, economic, functional, environmental, political, social and cultural, is important for developing suitable strategies. The needs of the broader area should be investigated to inform the decision on the new function. For a successful adaptive reuse project, the heritage building should be economically, socially and physically sustainable. A management plan is recommended for the future use and economic sustainability of the building.

While general frameworks for adaptive reuse exist, there is noted to be a lack of a clear methodology specifically focused on the socio-cultural aspects of heritage buildings. The following case studies on khan reuse have utilized methods, such as a literature review, site surveys, on-site examinations, visual analysis, archive review and interviews with actors in decision-making. The success of adaptive reuse projects can be measured through user experiences, considering sociocultural, economic and physical aspects. Adaptive reuse projects re-functioned with public uses (commercial, cultural, educational) are often more successful in contributing to sociocultural and economic development.

A critical aspect highlighted is the necessity for interventions to be based on documented historical research and to be reversible. Documentation of both the existing condition and the interventions is also crucial for conveying cultural heritage knowledge. It is emphasized that evaluating the success of adaptive reuse projects goes beyond just conservation principles and should include economic sustainability and a management plan. The choice of a new function must take into account the economic and social objectives and the effects of reuse on the urban environment. Multi-criteria decision analysis can be a useful tool in contexts characterized by high complexity for supporting the choice of sustainable alternative functions and guaranteeing transparency.

3.1. Two Case Studies from Cyprus

The adaptive reuse of khans has been explored and implemented, as detailed in several case studies within the sources and in the following two recent examples – the result of international architectural competitions – in Cyprus.

The first case study is of the “Zouchouri” Khan complex (figure 1) which is located within the old town of Larnaca in an area that had developed as the commercial and social center of the city since the Middle Ages. The area was developed based on two main components. The first was the organic and disorderly development of the urban fabric around the important landmarks of the area (churches, mosques, Medieval Castle, etc.), with the natural consequence of the creation of a complex and multiform urban environment. The second component was the contradictory coexistence of the Christian / Western element with that of the Muslim / Oriental, given that the area functioned for centuries as a trading post between the Eastern Mediterranean and the rest of Europe.

These two components formed the basis of the central idea of the proposal. This is in practice attributed with three intersecting curves, which connect the main entrances of the complex with the points of interest (Mosque, Hostels). The curves then evolve into folded surfaces, which develop freely and organically within the strict boundary of the perimeter buildings and create the carvings, the routes and the various levels. This manipulation gives the space a sense of continuous and dynamic "flow" that is reflected, both in the form and in the function of the space, so that there is no distinct spatial boundary that defines the square,

the event spaces, the market, the promenade and that these stop to give way to green space or seating areas for the visitor.

The result of this is the polymorphic - multi-level use of the space and the continuous "movement" of functions, which allows flexibility and easy adaptation to the respective functional needs b. with the amphitheatrical organization of the space in a strategic way in order to emphasize and highlight the points of interest (orientation of uses towards the Mosque, traditional facades, etc.) and not to exclude or overshadow them during the operation of the complex with the use of modern, special, but contradictory forms in the individual elements (shelters, benches, etc.) that enhance a continuous dialogue between the new and the old, the Western with the Eastern. This interaction between such opposite and contradictory elements and the relationship between them reflect the character of the area that has been preserved over time, in a more modern and sophisticated version of it. Finally, the new materials chosen for the proposal are modern but simple and aim to modernize and highlight the special characteristics of the area, without unnecessary elements.

Figure 1. The "Zouchouri" Khan from left to right: Aerial perspective of the proposal; master-plan of the area; diagram of the organization of the various program elements. (Source: Cyprus Architects Association Archives)

The second case study is of the "Ibrahim" Kahn complex (figure 2) in Paphos. The khan was a place where travelers and merchants resided and served as a resting place. A place of exchange of material and spiritual goods between travelers. A funnel of experiences. Its structure consists of architectural members, which have eroded and altered over time and the interventions it has received so far. The purpose of the study is to create an atmosphere in the space where memories of the past will come alive and will redefine the character of the khan and the historical center of the city. In addition to recalling the historical memory of the khan to every visitor, the study aims to achieve business sustainability, economic viability and generally improve the quality of life of Paphos.

The space is defined by two axes and an envelope, which compose a complex of building entities that encloses three open central spaces. One axis defines the entrance with the existing arch, crosses the passage defined by the series of buildings that currently house the carpenter and the car paint shop and ends in the space, which is currently empty and surrounded by a stone wall. The other axis intersects the previous axis, while also facing a blind wall. The very structure of the complex speaks of a dialogue of spaces and uses that may be entangled in a canvas of uses and movement. The very structure of the existing buildings constitutes an evocative building ensemble, which creates a "theatrical setting" and provokes and invites the visitor to use the space.

The proposal has as its theme the overview of the trace of the past and its reading as a dynamic structure that moves between the boundaries, which exist and function in the courtyard. The overall intervention is read as a “flow” within the space of Chania, both in form and function. The three units of space have been translated as “neighborhoods”, where scenes of work - production and projection of cultural work, as well as recreation, take place. The exhibition space opens on the one hand to the event space as a transparent volume and on the other to the workshop-activity space, thus connecting these spaces visually, on a horizontal level and morphologically on a vertical level, thus creating, on both sides, the feeling of a gallery-tunnel.

In addition to the required uses, the free building at the western entrance is converted into an installation room, where it will function as a communication transmitter for the passerby. It will be a flexible space with interactive information screens about events in the space, as well as the history of the khan and the wider area. It will also host exhibits (installations) by local and foreign artists. Also, in the building with the N2 marking, the creation of a restaurant or multi-purpose space with the possibility of expansion, with a number of open-air activities proposed. Copper was chosen as the shell of the new structures, thus highlighting a material used since antiquity in Cyprus in a modern version, integrating it harmoniously with the traditional buildings. In conclusion, due to the limited space, the element of nature is integrated with vertical plantings at the two entrances and in the event area as well as with smaller-scale, more intimate landscape elements.

Figure 2. The “Ibrahim” Khan complex from left to right: Aerial perspective with organizing principles diagram; proposed plan and sections; interior and exterior views with materiality. (Source: Cyprus Architects Association Archives)

4. EXPLORING TANGIBLE AND INTANGIBLE VALUES IN THE ADAPTIVE REUSE OF KHANS

Adaptive reuse of historical buildings like khans is a significant strategy for their conservation, preventing demolition and prolonging their useful life. It's considered a sustainable long-term approach to preservation. Khans, traditionally used for accommodating travelers, traders, animals, and selling goods, may become obsolete due to changing economic practices, demographics, or maintenance costs. Adaptive reuse offers a way to rehabilitate and keep them in use. This process engages with both the tangible and intangible values of khans.

4.1. Tangible Values in the Adaptive Reuse of Khans

Tangible values relate to the physical aspects and fabric of the khan buildings. Adaptive reuse aims to preserve these values by maintaining the structure's inherent qualities through a new use. Preserving the tangible aspects requires knowledge of traditional construction techniques. A crucial first step in the adaptive reuse process for khans is assessing the

condition of the historical pattern. This involves a detailed architectural survey documenting the physical state, original uses, building techniques, plan, architectural details, and materials. Analysis of the existing fabric is essential.

Specific tangible aspects considered important for khans include:

- The building's physical state, condition and environment.
- Its physical characteristics, such as its unique architectural design, authentic features, construction techniques, and materials.
- The form and design of the building, emphasizing respect for the original vernacular form and shapes. Originality in format, elements, and shape contributes to authenticity.
- The material and substance of the building, highlighting the accuracy and perfection of the original material and physical substance. Respecting existing material is important.
- The integrity of the place, encompassing the structural and architectural description of the whole and its existence with all elements that document its heritage status. Assessing integrity can involve considering literal aspects, wholeness, and honesty. Preserving spatial integrity is crucial, as disruption can lead to a loss of values. The legibility of the building's original plan scheme is a component of its integrity.

However, preserving these tangible values during adaptive reuse can be challenging. Some adaptive reuse projects for khans have been implemented without sufficient consideration for spatial and structural features, material, or color texture, leading to incompatible interventions. Interventions should ideally not harm the originality and integrity of the historical fabric and care must be taken not to change or deteriorate the plan, mass, and material properties. Additions that are not compatible or "crush and suffocate" the structure should be avoided. To mitigate these issues, interventions should be based on documented historical research, be reversible where possible, and be thoroughly documented. New applications should be distinguishable from the old fabric and compatible in terms of mass, form, size, color and material.

4.2. Intangible Values in the Adaptive Reuse of Khans

Intangible values are the non-physical qualities that contribute to the significance and meaning of a historical building and its connection to people and its location. Adaptive reuse plays an important role in conserving these values.

Key intangible values associated with khans include:

- *Historical Significance*: Khans embody the accumulation of the period in which they were built, contributing to urban identity. Adaptive reuse helps prevent the loss of this historical value and aims to preserve and enhance the building's cultural significance.
- *Cultural Identity*: Heritage buildings are vital for transferring cultural identity across generations. By preserving heritage buildings and giving them new life, adaptive reuse contributes to the conservation of cultural identity.
- *Social Value*: Adaptive reuse can strengthen social relations and enhance the connection between people and the historical environment. Re-functionalizing khans as cafes, restaurants, hotels, and shopping areas has created socio-cultural spaces in historical city centers, becoming important meeting and visiting points that contribute to the social development of local people. The potential for khans to serve as meeting and socializing spaces is a key value for reuse. Maintaining their use for commercial purposes and keeping them open to the public is important for urban memory. Adaptive reuse can also contribute to community growth and social stability.

- *Memories, Spirit of Place and Genius Loci*: Historical buildings are carriers of collective memories. The tangible fabric and intangible aspects are inseparable, giving meaning to a place and creating its special spirit or genius loci. These associations are integral to the local community, telling a unique story. Adaptive reuse aims to preserve this spirit of place and compel the genius loci. Preserving this intangible memory is a challenging task. Involving the appreciation and opinions of inhabitants, often tied to their memories, is considered crucial for enriching the sense of place and achieving successful conservation. Khans, even with changed functions, can keep the sense of the buildings and memories alive within the space.
- *Intangible Heritage Elements*: This includes customs, oral traditions, music, languages, dance, festivities, and traditional knowledge and skills. Proposed reuses for khans aim to represent and display these intangible values of the context. Adaptive reuse can preserve and promote local skills and cultural identity. Examples include handicrafts and traditional techniques.
- *Function Value*: The concept of "function value" is linked to aesthetic, spiritual, social, historical, and symbolic values, strengthening social relations and connections to the historical environment. While the original function may be lost or changed, the new function contributes to the building's value by ensuring it remains active and integrated into community life.
- *Tradition and Technique*: The historical techniques used in building the khans are part of their intangible heritage. Understanding and respecting these techniques and potentially reviving traditional practices can be incorporated into the adaptive reuse.
- *Location and Setting*: A khan's location, particularly its integration into the historic urban fabric or road networks, is an important value. Adaptive reuse needs to consider this connection. The original location contributes to its authenticity.
- *Creating Bonds*: Adaptive reuse creates a bond with the past, connecting history to the present. It brings together the past and new architectural understanding.

Adaptive reuse of khans also provides economic value, increasing their financial standing and creating opportunities for tourism and local economic development. This economic viability is often crucial for covering restoration and maintenance costs, ensuring the long-term survival of the structure. Environmentally, it contributes to sustainability by reusing embodied energy and reducing construction waste.

Successful adaptive reuse projects require a deep understanding of the heritage values, physical characteristics, and adaptive reuse potentials of the building. The decision on the new function should be based on detailed analysis, considering socio-cultural, economic, and physical aspects, as well as the needs of the district. Collaboration and alignment between various stakeholders, including experts and the local community, are crucial for a truly successful outcome. Methodologies exist to assist in this complex decision-making process, helping to evaluate alternatives and prioritize criteria for the most appropriate reuse that achieves an optimal balance between conservation, usability and the future use and economic sustainability of the building.

5. DISCUSSION OF BEST PRACTICES AND CONCLUSIONS REGARDING THE ADAPTIVE REUSE OF KHANS

Based on the investigations and the bibliographical sources [20, 21, 22, 23, 24, 25, 26, 27, 28], the adaptive reuse of khans in historic cities involves addressing both their tangible

physical properties and their intangible cultural significance to ensure their preservation and continued relevance. Khans historically served as centers for trade, accommodation, and social interaction, contributing significantly to urban identity and memory. Due to changing economic and social conditions, many have lost their original functions and become obsolete or disused, necessitating adaptive reuse for their survival.

The value of adaptive reuse for khans is multifaceted:

Conservation and Sustainability: Adaptive reuse is considered an important strategy for the conservation and long-term sustainability of historical buildings. It prevents the loss of historical value and helps structures survive deterioration. Adaptive reuse is also seen as an environmentally friendly approach by reusing embodied energy, reducing construction waste and extending the useful life of buildings. Successful adaptive reuse projects are often described as socially, economically and physically sustainable.

Economic Benefits: Adaptive reuse can increase the financial value of khans and create new income-generating functions, contributing to their economic sustainability. It creates opportunities for tourism and contributes to the economic development of local people.

Socio-Cultural Value and Intangible Heritage: Adaptive reuse enlivens historical values, allows history to be rediscovered, and maintains the characteristics of the structure. Khans carry the accumulation of their period and contribute significantly to urban identity and memory. Adaptive reuse can preserve and transfer cultural identity to future generations and strengthen social relations by creating socio-cultural spaces and meeting points. The intangible values, such as historical significance, cultural identity, social value, collective memories, the spirit of place (genius loci), and traditional knowledge, are essential to the meaning of the khan and connect people to its history. Adaptive reuse helps to keep these memories and the sense of the buildings alive, contributing to urban memory. They represent and display the intangible values of the local context and promote local skills and cultural identity and preserve shared or communal memories and social meanings.

5.1. Best Practices and Conclusions Regarding Value

When considering the best practices regarding costs and benefits that have a bearing on tangible and intangible values associated with the adaptive reuse of khans in the historic city, the following actions may be taken into consideration:

Holistic Approach: Successful adaptive reuse requires a holistic approach, considering socio-cultural, economic, and physical aspects together. The tangible fabric and intangible aspects are inseparable and jointly contribute to the unique meaning and spirit of a place.

In-depth Analysis: A thorough analysis of the existing fabric, including its physical characteristics, original function, history, and heritage values, is crucial before deciding on a new function.

Selecting an Appropriate and Compatible Function: The choice of a new function should be carefully considered to ensure it is compatible with the building's values, minimizes interference with its originality, and contributes to its significance. The function should contribute actively to the understanding of the heritage value of the place. It is important to understand the significance and meaning of heritage buildings, not just their physical aspects.

Respecting Tangible Integrity: Interventions must respect the physical fabric, materials, and original features of the khan. Changes should be based on documented research and ideally be reversible. Incompatible interventions can negatively impact originality and integrity. Maintaining the legibility of the original plan scheme is crucial.

Preserving Intangible Spirit: Adaptive reuse strategies should actively seek to preserve intangible values like collective memories and the spirit of place. New functions can be designed to maintain or display aspects of the building's intangible heritage.

Stakeholder Involvement: Engaging stakeholders, including owners, users, experts, and the local community, is vital for successful decision-making and implementation. Involving the opinions of inhabitants can enrich the sense of place through their memories, leading to more realistic and successful conservation.

Ensuring Sustainability Beyond Conservation: Successful adaptive reuse projects are not only evaluated on conservation principles but also require a management plan to ensure long-term economic sustainability for maintenance and rehabilitation.

In conclusion, adaptive reuse is a vital method for preserving historical khans by providing them with new life and functions. It adds significant economic, social, and environmental value to these structures and their contexts. However, achieving successful adaptive reuse requires careful planning, in-depth analysis of both tangible and intangible values, selecting compatible functions, respecting the building's physical integrity, and involving stakeholders, particularly the local community whose memories and association contribute to the intangible value and spirit of the place. Failures can occur if the new function is chosen randomly, interventions are incompatible, or future economic sustainability for maintenance is not addressed. The goal is to ensure that khans remain "living assets" that connect the past with the present and contribute to urban sustainability.

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Research paper

INVESTIGATING SUSTAINABLE OPTIONS FOR THE TRADITIONAL MATERIALS IN THE CONSTRUCTION INDUSTRY

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Abstract

The current trends in the construction industry show that the use of sustainable materials is increasing instead of traditional construction materials. Since the construction industry is one of the largest consumers of energy and emitters of carbon dioxide, there is a need for more sustainable materials to be applied in construction. With the advanced technology, many building materials are available as sustainable options. In this study, the application of sustainable materials as a replacement for traditional construction materials is investigated. Sustainable options are considered instead of traditional building materials in the construction industry, including their characteristics and how and where sustainable materials can replace conventional building materials. In particular, bamboo, rammed earth, and mycelium are considered sustainable materials. The common characteristics of these materials are good thermal performance, reduced CO_2 emissions, low energy consumption, low waste generation, and low price. The mechanical characteristics are quite different, as well as the density of materials and performance in earthquakes. The bamboo has quite good mechanical characteristics compared to rammed earth and mycelium-based material, making it earthquake-resistant. However, it is not fungi-resistant or fire-resistant. On the other hand, mycelium-based material is pest-resistant and fire-resistant. The potential to use sustainable materials in the construction industry is rapidly increasing due to modern technology and innovations.

Keywords: *Sustainable materials, Bamboo, Rammed earth, Mycelium, Construction industry*

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1. INTRODUCTION

In total, buildings account for around 40% of global energy consumption, which leads the construction industry to be in the first place in the energy consumption market [1, 2]. According to predictions, this trend of energy consumption in the construction industry will continue to rise in the following decades [1]. Such high energy consumption and greenhouse gas emissions contribute to climate change and global warming, representing the significant threats of modern societies. To reduce this harmful environmental impact, it is of essential importance to incorporate sustainability in civil engineering. The meaning of sustainability is similar to sustainable development. Sustainability means the optimal use of natural resources to avoid decay, depletion, and reaching a point of no return and handing down to next generations by developing them. Similar to sustainability, sustainable development is very common in the current literature. There are many studies that address how to incorporate sustainability in the different research fields, industries, our lives, and systems. The concept of sustainable development refers to meeting the needs of the current generations without compromising the ability of future generations to meet their needs [3]. Sustainability includes three different pillars, environmental, social and economic. The social aspect of sustainability in the construction industry is described as encouraging community involvement, establishing suitable institutional structures, evaluating the influence on the current social context, and assessing the effects on health and well-being [4]. The economic sustainability pillar incorporates external costs, explores alternative financing methods, creates suitable economic tools to encourage sustainable consumption, and evaluates the economic impact on local structures [4]. The environmental aspect of sustainable construction is to decrease material intensity through substitution technology, improve the recycling of materials, minimise the usage of harmful materials, decrease the energy for processing goods and delivering services, back international agreements and conventions, optimisation of sustainable utilisation of biological and renewable resources, and consider the effects of planned project on air, soil, water, flora and fauna [4]. Mitigating towards more sustainable practices and green buildings can reduce energy consumption, decrease construction waste, decrease pollution, and optimise the usage of resources [5].

The most common traditional materials in construction are cement, concrete, and steel. Concrete is the key material in buildings and infrastructure development. It is reported that almost 30 billion tons of concrete are used per year worldwide, taking the first place of material consumption in construction and leaving steel and wood behind [6]. Since concrete comprises aggregates, cement and water, cement production is estimated to be over 4 billion tons annually [7]. Such a large amount of cement production generates 8% of the global CO_2 emissions [8]. Further, the amount of CO_2 emission due to cement production is rising since it is reported that 1.57 Gt of process-related CO_2 emission was in 2019 and 2.9 Gt in 2021 [8, 9, 10]. Cement production and concrete manufacturing cause challenges to modern societies and contribute to climate change and other natural hazards.

The aim of this study is to consider more sustainable options for traditional construction materials, where these options can replace traditional materials and find their application in civil engineering and the construction industry to contribute to sustainable development. In this study, three different sustainable materials are considered: bamboo, rammed earth and mycelium. The bamboo forests are concentrated in the tropical and subtropical regions. The growth of bamboo is influenced by temperature, rainfall, soil type, and altitude [11]. Around 80% of the bamboo forests that contain more than 1200 species of bamboo are located in

Southeast, South, and East Asia, particularly in India, the south of China, Myanmar, Thailand, and other [12]. Bamboo is a renewable material that is an eco-friendly and the fastest-growing plant. Rammed earth is one of the oldest construction methods for many heritage structures, and it is widely found on all continents. Rammed earth structures are found in different historical periods and cultures, including Neolithic, Roman, Chaldean, Yangshao, and Incan cultures [13]. This construction technique uses soil from the ground as the main component for rammed earth and compacts it with optimal water content inside [14]. Recently, rammed earth has been gaining popularity as a renewable material that is locally available, eco-friendly, and cost-effective. The third significant sustainable material that is becoming popular in civil engineering is mycelium-based materials. This biomaterial is a vegetative part of fungi that can be grown on organic substrates such as agricultural waste through mycotecture [5]. Mycelium is a dense network of thin threads named hyphae that grow and intertwine together into solid material [15]. During the growth, self-assembling bonds of tiny white fibres invade and degrade the organic substrate by gradually colonising the organic matter to bind them into strong 3D structural material [16]. Mycelium-based material is renewable, biodegradable and eco-friendly. At the end of their lifecycle, this material can be disposed of without negatively impacting the environment, causing pollution or generating waste.

2. LITERATURE REVIEW

Bamboo is a sustainable material with high potential in green building projects and the construction industry. Similar to rammed earth, bamboo was used for building houses in olden times, especially by people who lived in Southeast Asia, South Asia, and China, where bamboo grows naturally. More often, it was used in combination with grass, wood, clay, and lime to build houses [17]. The example of the traditional bamboo house in the Philippines and the construction of a novel modern bamboo house in Indonesia are illustrated in Figure 1. The first study of bamboo was carried out in 1839 by Ruprecht [18]. Recently, an increasing number of studies have confirmed that bamboo can be a suitable substitute for wood. The manufacturing process for bamboo products in construction includes splitting, glueing, pressing, and heating to produce glued laminated bamboo [19].

Figure 1. Traditional bamboo house in the Philippines [17] and modern bamboo house in Bali [20]

Besides, it is approached to bamboo as a construction material from the different aspects. Some studies and reports evaluate bamboo's mechanical characteristics, compressive strength, tensile strength, and bending [18, 21, 22], thermal characteristics [23], and other.

Due to its excellent thermal properties, a case study from Harbin, Dalian and Shenyang in China shows that residential buildings in cold regions in China can be constructed from bamboo [23]. Also, there are studies regarding the significance of bamboo from social aspects of sustainability [24] and an environmental perspective [25]. Currently, China is the number one producer of bamboo, followed by India.

Figure 2. Traditional rammed earth structure - Basgo fortress in the Ladakh [26]

Applying the rammed earth as a material and a technique for building dates back centuries. There are many examples of this construction method in architecture. By chronological study, it is concluded that this method was first used in construction in China [13]. Settlements during the Lungshan era in China were built from rammed earth. The key component of the settlements was the walls. The earthen walls are made by heaping soil to form a rhomboid section wall, and the base width increases proportionally to the wall height. Some earthen walls as part of the Great Wall of China are placed at the Jiayuguan fortress, which was built in 1372 during the Ming Dynasty. Further, the historical evidence of rammed earth structures is found in the Himalayas [26, 27], such as the Basgo fortress in the Ladakh region in Tibet. This fortress was constructed in 1357. It is shown in Figure 2. As examples from Europe, a few rammed-earth castles from the 14th and 15th centuries were built near Castile in Spain [28]. Fortresses are constructed with lime-crusted rammed earth where putlog holes are passant. It is noticed that castles are influenced by the Islamic Medieval Spanish style (Figure 3).

Figure 3. Traditional rammed earth structure – the castle of Palenzuela in Castile [28]

In the modern period, the rammed earth procedure for construction includes the following steps: a proportion of water is added to the soil, the first layer of moist soil is distributed in a formwork, compacted, the subsequent layers are built up in the formwork until it achieves the

height of the wall [29]. The soil formwork is removed after one day, and the rammed earth can cure.

Compared to bamboo and rammed-earth, which have a long history in the construction process, mycelium-based materials are relatively new and have started to gain attention in recent years due to their characteristics [15, 30]. The first application of mycelium-based material began in 2007 for high-quality packaging products [15]. In the construction industry, there are two approaches to integrating microbes in material production. By the indirect method, the enzymes from microbes are extracted and added to the production process of materials [31]. As a result, bioblock, biocement, bioconcrete and biopolymer can be produced [15]. Also, enzymes can contribute to soil stabilisation. The direct method is based on the direct application of microbes such as mycelium, cell walls, and spores of microorganisms. One example of a mycelium-based structure is the Hy-Fi organic Mushroom-Brick Tower in New York, as given in Figure 4. The environmental assessment of mycelium-based materials was carried out in the previous studies, and it is concluded that they outperform traditional insulation materials [32].

Figure 4. The Hy-Fi organic Mushroom-Brick Tower [33]

3. THE PROPERTIES OF SUSTAINABLE MATERIALS

In this section, different properties of sustainable materials are considered. Firstly, the mechanical characteristics, as the most essential property of each material, are investigated. Compressive, tensile, and shear strengths are estimated for the mechanical characteristics provided in Table 1.

The bamboo specimens were three to four years old. It has been tested using a Universal testing machine (UTM). Two hollow bamboo specimens of 15 cm length are tested for the compressive strength in a UTM machine [18]. The compressive load is applied to the sections until the specimen breaks. For the tensile strength test, the same bamboo specimen was used in a UTM machine [18]. It is measured that the ultimate load which causes specimens to break is 16.6 kN. Similarly, a UTM machine performed a shear strength test on the identical specimens. Bamboo has four times the tensile strength compared to the compressive strength.

For rammed earth, specimens are made of natural soil with 13% water content. The specimens have a cylinder shape with a diameter of 10.1 cm and a height of 11.5 cm for the uniaxial compression test for rammed earth [34]. UTM is also applied to test specimens. To measure tensile strength, the Brazilian test on cylindrical specimens is applied [35]. Cylindrical specimens are designed with the dimensions of 16 cm in diameter, 32 cm in height, and 11% of the water content in rammed earth. For testing shear strength, a simple method based on compressive strength, tensile strength and Mohr's circle theory is applied [35]. It is tested on the wallets made from soil by compacting each layer to a thickness of 15 cm after compaction. The wall's dimension is 100 cm x 100 cm x 30 cm. From the results, it can be concluded that the tensile strength of the rammed earth is 10 times smaller than the compressive strength.

Mycelium-based material is tested with an MTS servo-hydraulic testing machine for uniaxial compression and tension tests [36]. Different specimens are used for the compressive and tensile tests. This experiment uses cubic specimens of dimensions 20 mm x 20 mm x 16mm for the compression strength and dog bone specimens of dimensions 200 mm x 6 mm x 3.5 mm for the tension tests.

Table 1. The mechanical characteristics of sustainable materials [18, 34, 35, 36]

Material	Bamboo	Rammed earth	Mycelium
Compressive strength [kN/cm^2]	1.896 – 2.228	0.136 – 0.14	0.004 – 0.008
Tensile strength [kN/cm^2]	4.018 – 8.302	0.01 - 0.035	0.01 – 0.03
Shear strength [kN/cm^2]	0.409 – 0.586	0.015 – 0.085	/

Besides mechanical properties, thermal properties for each sustainable material are considered, as well as some other specifics of the materials, such as acoustic properties and density. The thermal characteristics of each material are provided in Table 2. There are studies from different aspects of sustainability, such as environmental, economic, and social.

Table 2. The thermal characteristics of sustainable materials

Material	Bamboo [18]	Rammed earth [37]	Mycelium [32]
Thermal conductivity [W/mK]	0.15 – 0.30	1.13 – 1.82	0.043 – 0.056

The thermal properties of bamboo are high since the thermal conductivity is low [18]. This means that bamboo is a good heat-insulating material. The density of bamboo is between 1000 and 1300 kg/m^3. The modulus of Elasticity for bamboo is 12 GPa [17]. The water absorption is between 12% and 26%. The sustainability performance from the environmental aspect of bamboo is as follows: durability, low pollution, energy saving and renewable resource [17]. The contribution to construction pollution is relatively low, meaning bamboo has a good environmental impact. From an economic aspect, bamboo is a cheap material that is locally available in some places. From a social perspective, it has a positive effect on the people. It reduces greenhouse gas emissions by reducing carbon dioxide. The performance of bamboo buildings under earthquakes shows good resistance since the bamboo material is lighter than wood due to its hollow nature [17]. Since it is lighter, it produces a smaller earthquake force, the product of mass and the acceleration generated by the earthquake. It has poor fire resistance and resistance to fungi and bacteria [38].

Samadianfard and Toufigh conducted an experiment under simulated conditions to measure the thermal performance of rammed earth materials [37]. The experiment included a hygrothermal chamber, which was designed, and Fourier's law was used to determine the thermal conductivity of a few rammed earth samples [37]. The rammed earth sample consists of 88% earth and 12% water. The density of rammed earth material differs depending on the soil type and percentage of moisture content [39]. It is estimated that the average is around 2000 kg/m^3. However, the density of rammed earth materials varies between 1700 kg/m^3 and 2200 kg/m^3. The performance under gravity loads of rammed earth is acceptable [14]. However, the seismic behaviour of rammed earth is deplorable regarding lateral resistance, ductility, and displacement capacity [40]. The main reason for poor seismic performance is the low tensile and shear strength of the earth. The local availability of rammed earth makes this material cost-effective. From the environmental perspective, the rammed earth contributes to the following sustainability factors: recyclability, renewability, energy savings in material production, reducing carbon emissions, and outstanding humidity ventilation [41]. Overall, it is an eco-friendly material. The cost of rammed earth construction is relatively low, which gives this material a good performance from an economic perspective of sustainability. Besides, it creates local job opportunities in the construction industry. During construction, it is necessary to have at least one contractor who is experienced in the rammed earth construction method [29].

The thermal conductivity of mycelium-based material is relatively low, and it is among the lowest values for biodegradable insulation material [32]. Mycelium-based materials are lightweight since the density is between 110 kg/m^3 and 330 kg/m^3. The water absorption can be as high as 200%. This material contributes to the environmental aspect of sustainability by reducing carbon dioxide emissions, energy consumption, and construction waste. The other environmental factors of mycelium-based material are recyclable, compostable and biodegradable [15]. After the building lifecycle, the mycelium-based material is fully degradable and can be returned to nature. The main benefits of mycelium are that it captures and stores CO_2 during its growth, which is absorbed from the environment [30]. It is estimated that biological materials used as substitutes for construction materials can reduce CO_2 emissions by about 800 million tons annually [32]. It is available in nature. From an economic perspective, the benefits are low cost and easy production. The production process of mycelium-based material is simple, including moulding and growing [15]. The optimal conditions for mycelium to grow are the air temperature between 25°C and 30°C and humidity of 65% [42]. Mycelium-based materials have excellent thermal and hydrophobic properties. It is fire-resistant and pest-resistant.

4. THE APPLICATION OF SUSTAINABLE MATERIALS

The potential of sustainable materials in construction is increasing. Similar to wood, the options for bamboo in the construction process are wide. It can be applied to house structural parts, such as roof structures, flooring, foundations, and walls. Since it is lightweight, it can be easily installed as roof trusses. A bamboo roof enables protection towards different forces of nature, such as winds, storms, rain, and animals. Bamboo mats are a good choice for flooring due to their good thermal performance, which prevents the floors from getting heated from the warm weather in the summer and keeps the warmth in the winter. Before using bamboo for foundations, it should be treated with certain chemicals that prevent the decaying

property of bamboo when it is in contact with soil. The mass use of bamboo is for constructing walls as an infill in the middle of the framing members. The bamboo scaffoldings for high-rise buildings are gaining popularity in the construction industry in the southern parts of China. As a lightweight material with heavy load-bearing capacity, it is more efficient for scaffoldings than steel scaffoldings. The scaffoldings can be easily assembled, disassembled and transported due to their lightweight. Figure 5 shows the bamboo scaffoldings on one site in Hong Kong. Besides structures, bamboo is used in infrastructure for bridge construction [43] and for reinforcing the embankment in a roadway [44].

Figure 5. Bamboo scaffolding (photo taken by author)

The rammed-earth presents the optimal solution for building houses and small buildings. The most common structural elements easily built with rammed earth are walls. Building walls in rammed-earth are constructed in layers of continuous rows with a thickness of 46 to 60 cm [45]. The thickness of the layers is about 20 cm. After each layer, the compaction is carried out.

Figure 6. Mycelium bricks [33]

Mycelium-based composites, such as mycelium panels, mycelium boards, mycelium bricks (Figure 6), bio-blocks, and bio-polymers, have been successfully developed and

investigated by researchers. The main contribution of the mycelium-based material in the construction industry is to be used as an insulation material due to its excellent thermal and hydrophobic properties.

5. CONCLUSIONS

Bamboo, rammed-earth and mycelium-based materials contribute to sustainability in three aspects: environmental, economic and social. The economic factor is the low price of materials since they can be easily and locally found. From the environmental aspect, sustainable materials are proven to reduce CO_2 emissions and energy consumption during the project lifecycle, increase recyclability, and reduce waste. After the project lifecycle, the material can be returned to nature. The common characteristics of these materials are good thermal performance, reduced CO_2 emissions, low energy consumption, low waste generation, and low price. The mechanical characteristics are quite different, as well as the density of materials and performance in earthquakes. The bamboo has quite good mechanical characteristics compared to rammed earth and mycelium-based material, making it earthquake-resistant. However, it is not fungi-resistant or fire-resistant. On the other hand, mycelium-based material is pest-resistant and fire-resistant. The potential to use sustainable materials in the construction industry is rapidly increasing due to modern technology and innovations.

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Review paper

THE ROLE OF ENMS IN THE APPLICATION OF ISO 50001 IN THE CONSTRUCTION INDUSTRY

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Abstract

The construction industry, as a significant and expansive sector of the global economy, is distinguished by a high level of market risk and competitiveness. In such a demanding environment, construction firms must effectively identify and address emerging needs and challenges in order to enhance their visibility in both domestic and international markets, optimize revenue generation, and minimize operational costs. To manage risk effectively and improve key performance areas such as operational efficiency, inter-organizational collaboration, supply chain management, and the adoption of innovative solutions, one of the relevant strategic instruments is the implementation of the international standard ISO 50001. This standard provides a comprehensive framework for the development and application of systematic energy management practices. Through the adoption of ISO 50001, construction companies are better equipped to comply with environmental regulations, particularly those concerning carbon emissions, thereby enhancing their energy efficiency and overall organizational performance.

Key words: construction industry, ISO standards, energy norms, management.

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1. INTRODUCTION

Energy, as a fundamental input in all forms of business activity, holds a critical position in determining both the operational efficiency and financial viability of modern enterprises. Regardless of the sector, whether manufacturing, services, logistics, or technology, energy represents not only a necessary resource but also a potential bottleneck due to its variable costs, availability, and associated environmental impacts. Therefore, sustainable energy management has become a central strategic concern for organizations aiming to maintain competitiveness and resilience in increasingly dynamic and uncertain global markets.

Sustainable development has led organizations to rethink how they procure, use, and manage energy resources. As energy prices fluctuate and the availability of fossil fuels becomes more constrained, ensuring predictable and optimized energy expenditure is no longer a matter of cost-saving alone, but a determinant of long-term operational continuity. Moreover, the growing societal and regulatory demands for environmental stewardship have added layers of complexity to corporate energy strategies. Energy use is not isolated from its broader ecological and social context; it is intimately linked to carbon emissions, pollution, and broader climate change concerns. Consequently, the pressure on organizations to adopt more transparent, responsible, and future-oriented energy practices is mounting.

In contemporary discourse on sustainability and industrial development, the challenges associated with energy use extend beyond issues of scarcity and cost. A critical concern is the significant role that irrational and excessive consumption of energy, particularly from non-renewable sources, plays in accelerating climate change and exacerbating environmental degradation. Fossil fuel dependence continues to dominate global energy systems, resulting in diminishing resource reserves and escalating energy prices. These trends highlight the urgent need for a paradigm shift in energy governance, emphasizing responsible resource utilization and systemic efficiency across economic sectors.

The interplay between rising energy costs, the imperative for sustainable resource management, and the expanding demands of global trade calls for innovative, structured approaches to energy usage. Urbanization, fueled by demographic growth that has seen the global population double since 1950, with more than half now living in urban areas, has significantly increased the demand for new infrastructure and housing. This growth exerts substantial pressure on the construction industry, a sector central to national economies due to its direct contributions to employment, GDP, and international trade. However, the environmental footprint of accelerated construction activity is substantial, with significant implications for resource depletion, pollution, and overall ecological balance.

Given its dual role as both an economic engine and an environmental stressor, the construction sector is increasingly subject to regulatory and normative pressures to improve sustainability performance. International standards, particularly those developed by the International Organization for Standardization (ISO), have emerged as essential instruments in guiding the construction industry toward more environmentally responsible practices. ISO standards address environmental and energy-related challenges at all stages of the construction lifecycle, promoting efficiency while ensuring compliance with sustainability goals. They provide frameworks for integrating best practices, reducing energy-related externalities, and enhancing overall environmental performance.

One of the prominent standards is ISO 50001, a globally recognized standard that defines the requirements for establishing, implementing, maintaining, and improving an energy management system (EnMS). The primary objective of ISO 50001 is to support organizations

in achieving continuous improvements in energy performance, including energy efficiency, energy use, and energy consumption. The adoption of this standard is not merely a technical measure but a strategic endeavor with both economic and environmental implications.

Economically, the implementation of ISO 50001 allows organizations to systematically monitor and reduce their energy consumption, thereby lowering operational costs and enhancing market competitiveness. These savings, in turn, support reinvestment, innovation, and resilience in the face of fluctuating energy markets. Environmentally, adherence to the standard contributes to a reduction in greenhouse gas emissions and other pollutants, while also mitigating the exploitation of finite natural resources. This aligns organizational practices with broader climate action frameworks and environmental protection mandates.

However, the degree to which energy performance can be enhanced through EnMS implementation is contingent upon the level of institutional commitment, particularly from top management. The establishment of an effective EnMS necessitates an organizational culture that prioritizes sustainability, fosters cross-functional collaboration, and encourages behavioral change at all hierarchical levels. This transformation is not solely procedural but deeply cultural, requiring a shift in how energy is perceived, valued, and managed within the organization.

Ultimately, through their emphasis on process standardization, continuous improvement, and stakeholder accountability, ISO standards contribute to strengthening a company's reputation as a disciplined, transparent, and socially responsible entity. In the construction sector and beyond, the integration of such standards into core operational strategies is a critical step toward aligning industrial growth with sustainable development goals.

2. ENERGY MANAGEMENT SYSTEM – ENMS

The EnMS defines the requirements for establishing, implementing, maintaining, and improving an EnMS, which enables a company to follow a systematic approach to achieving energy performance improvements. As such, an EnMS

- is applicable to any company, regardless of its type, size, complexity, geographical location, organizational culture, or the products and services it provides;
- is applicable to activities that affect energy performance that the company manages and controls;
- is applicable regardless of the amount, use, or type of energy consumed;
- requires continuous improvement of energy performance, but does not define the levels to which energy performance should improve;
- is used independently, or in harmony with, or integrated with other management systems [1].

Accordingly, the company identifies external and internal issues that are relevant to it and that impact its ability to achieve the intended outcomes of its EnMS and improve its energy performance.

The company must identify:

- the stakeholders that are relevant to its energy performance and EnMS;
- the relevant stakeholder requirements;

- which of the identified needs and expectations the company will address through its EnMS.

The company must:

- provide access to applicable legal requirements, as well as other requirements related to its energy efficiency and energy use and consumption;
- determine how these requirements apply to its energy efficiency and energy use and consumption [2].

The company's management must demonstrate leadership and commitment to the continuous improvement of energy performance and the effectiveness of the EnMS by:

- defining the objects and scope of the EnMS;
- ensuring that the energy policy and objectives are compatible with the company's strategic direction;
- ensuring that the EnMS requirements are integrated into the organization's business processes;
- ensuring that action plans are approved and implemented;
- ensuring that the resources needed for the EnMS are available;
- communicating the importance of effective energy management and compliance with the EnMS requirements;
- ensuring that the EnMS achieves the intended outcomes;
- promoting continuous improvement of energy performance and the EnMS;
- ensuring that the energy management team is established [3].

3. ENMS – ISO FRAMEWORK

Companies cannot influence energy prices or government policy, but they can improve the way they manage energy. Such improvements in energy performance can quickly lead to reduced costs and energy consumption in companies, thereby mitigating the harmful effects of global energy use and consumption, global warming, and overconsumption of natural resources.

ISO has identified energy management as one of the five most important areas for the development of international standards, and in 2008 a project committee, ISO/PC 242, was established. The project committee was led by national standardization bodies, ISO members from the United States (American National Standards Institute – ANSI) and Brazil (Associació Brasileira de Normas Técnicas – ABNT). ISO developed the new standard based on guidelines, regulations, and other legislation, as well as standards related to energy management, at the national level of the USA, the European Union, Denmark, Germany, the Netherlands, China, and Japan.

The standard *EN ISO 50001 Energy Management System – Requirements with instructions for use*, was published in 2011 and included in the normative system as DIN EN ISO 50001 [4].

The following international and European standards have been adopted in this field:

- ISO 50002:2015 Energy audits – Requirements with user guide [5];
- ISO 50003:2015 Energy management systems – Requirements for bodies providing verification and certification of energy management systems [6];

- ISO 50004:2015 Energy management systems – Guidelines for the implementation, maintenance and improvement of energy management systems [7];
- ISO 50006:2015 Energy management systems – Measuring energy performance using energy benchmarks and energy performance indicators – General principles and guidance [8];
- ISO 50006:2015 Energy management systems – Measurement and verification of an organization's energy performance – Basic principles and guidance [9].

The Institute for Standardization of the Republic of Serbia (Energy Management Commission, KS A424) has adopted a series of Serbian standards in the field of energy management since 2010.

3.1. SRPS EN ISO 50001:2012 Standard

The SRPS EN ISO 50001:2012 enables companies to establish and maintain systems and processes for continuous improvement in terms of reducing energy consumption, increasing energy efficiency, and improving the way energy is used. The aim of implementing the standard is to establish and maintain an EnMS in companies that will reduce energy consumption and harmful environmental impacts while controlling energy costs [10].

There are various reasons for introducing standards, conditioned by external and internal factors arising from the needs of energy management. External factors include the following: requirements from applicable legislation, application of existing rules, fulfillment of company obligations, certification obligations set by energy suppliers, and financial institutions for loans. The most common internal factors include security of constant supply of energy and energy products, transparent insight into energy consumption in all company subsystems, reduced overall production costs, and increased energy efficiency.

The standard is based on the PDCA cycle methodology, as shown in Figure 1.

Figure 1. PDCA cycle methodology [11]

The following phases are to be completed in a cyclic, continuous way:

- Planning: Implementing energy flows within the defined boundaries of a company's system, defining the baseline of energy consumption and energy efficiency, and establishing goals and action plans to increase energy efficiency.
- Implementation: Realizing the defined action plans.
- Verification: Monitoring and measuring parameters and comparing them against the defined strategic and action plans.
- Action: Defining corrective and preventive measures and their implementation.

The standard covers all factors that may have an impact on energy consumption, with the possibility of adapting the application to the specific requirements of the company.

3.2. Comparison of ISO 50001 with other management system standards

The EN ISO 50001 standard was developed based on common principles and elements found in other ISO management system standards. [12] Table 1 provides an overview of the main provisions of the SRPS EN ISO 50001, SRPS ISO 9001, and SRPS ISO 14001.

Table 1. Comparison of ISO 50001 with other management system standards [13]

Content	ISO 9001	ISO 140001	ISO 50001
Basic concept of the standard	Based on:		
Policy	Client's request regarding quality management	Relevant aspects of environmental protection	Energy consumption of a company or a specific production process
	Meet the client's requirements regarding quality management	The environmental policy illustrates the way the company manages environmental protection, its commitment to environmental protection, and the corresponding guidelines and goals in this field.	The energy policy illustrates the company's strategy regarding energy management.
Strategic approach	Establishing guidelines, goals and plans for quality management	Compliance with relevant regulatory requirements regarding environmental protection	Conducting energy reviews in order to identify activities that lead to significant energy consumption as well as energy consumption indicators
Characteristic profile	There are no such requirements.	There are no such requirements.	Determining the characteristic energy consumption profile is essential in terms of establishing an EnMS.

Management systems based on the PDCA cycle methodology are much easier to implement in companies where one of the management system standards is already applied. The application of the ISO 50001 standard in buildings enables the integration of energy management into existing business practices.

4. CONCLUSION

Introducing an EnMS, particularly one that adheres to internationally recognized standards such as ISO 50001, presents both opportunities and challenges. On the positive side, such systems enable a structured and data-driven approach to energy consumption. They promote a culture of continuous improvement, facilitate benchmarking, and offer verifiable evidence of energy performance to stakeholders. The implementation of a certified EnMS often leads to significant cost reductions through enhanced energy efficiency, as well as reduced greenhouse gas emissions. These benefits extend beyond financial savings and contribute to the organization's reputation, regulatory compliance, and alignment with global sustainability goals.

However, the adoption of an EnMS is not without its limitations. Initial implementation costs, including infrastructure upgrades, staff training, and audit procedures, can be substantial, particularly for small and medium-sized enterprises. Moreover, the success of such systems often depends on the organizational culture and the degree of top management commitment. Without a genuine organizational shift toward sustainability and operational integration, energy management initiatives risk becoming superficial or symbolic, yielding minimal long-term impact. Furthermore, the dynamic nature of energy markets, evolving technologies, and emerging regulations requires that these systems remain adaptive and continuously updated – posing ongoing strategic and financial challenges.

Looking ahead, future directions in energy management are likely to be shaped by technological innovations, digital transformation, and regulatory evolution. Smart grids, real-time data analytics, artificial intelligence, and Internet of Things (IoT)-based monitoring systems are redefining how energy is managed and optimized in real time. These technologies enable predictive maintenance, load balancing, and demand-response mechanisms, enhancing both efficiency and reliability. Additionally, the integration of renewable energy sources, such as solar and wind, into corporate energy strategies is no longer optional but an expected progression toward decarbonization.

In the longer term, energy management is expected to evolve from a standalone operational concern into a core element of corporate strategic planning and sustainability reporting. This evolution will likely rely on interdisciplinary collaboration between engineers, data scientists, economists, and sustainability professionals. Furthermore, organizations will be increasingly required to align their energy management practices with broader ESG (Environmental, Social, and Governance) frameworks to satisfy investor expectations and policy obligations.

In conclusion, while energy is an indispensable asset in business operations, its management is becoming increasingly complex, influenced by economic, environmental, and social considerations. A certified EnMS offers a pathway toward efficiency, accountability, and sustainability, but it demands sustained effort, investment, and adaptability. The trajectory of future energy management will likely be determined by the

ability of organizations to integrate emerging technologies, align with global sustainability agendas, and foster a culture of innovation and responsibility.

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Research paper

RISK ASSESSMENT OF GREEN BUILDING PROJECTS WITH GREY CLUSTER METHOD

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Abstract

With the rise of green building projects in the construction industry, questions of risks in project implementation have become increasingly prominent. The green building industry showcases new design concepts, material applications, innovations in green technologies, energy efficiency and carbon dioxide emission reduction. This study adopts the grey cluster assessment method for risk evaluation to improve the risk management ability of green building projects. Through the theory and method of grey mathematics, the subjective assessment of risk factors is transformed into grey quantitative indicators, and the uncertainty in the evaluation process is effectively dealt with by combining qualitative and quantitative research methods. The green building risk assessment index system is established, the relative importance of each risk factor is judged by experts, and the contribution of each factor to the overall risk is calculated. Finally, the analysis identifies the key risk factors that need to be focused on mitigation and control, and puts forward the corresponding risk countermeasures, which provide scientific decision support for the risk management of green building projects. The key risk factors in green building projects in China are: construction accidents, design errors, inaccurate GB investment estimation, absence of site-specific design considerations, designs with poor constructability and the quality problems of GB materials. While the least critical risks in GB projects are the deterioration of GB materials during the operation and maintenance period, unclear responsibility sharing for future upgrades, absence of regular maintenance of equipment and innovative equipment for assembling GB products.

Keywords: *Green Building projects, Sustainable development, Risk assessment, Grey cluster method, China*

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1. INTRODUCTION

In the 21st century, green building (GB) as a new trend in the construction industry has become an important aspect to promote sustainable development [1]. The construction sector in China has made progress in low-carbon, healthy and high-quality development. The GB industry is promoting new design concepts, energy efficiency, material applications, and technology integration [2]. With the global aim of energy conservation, emission reduction, environmentally friendly materials, and a healthy life, as well as the improvement of policy support, technological progress and public awareness, the GB industry has entered a period of rapid development, and the demand for GB projects will continue to rise [3]. The global investment opportunities in GB projects are expected to reach $24.7 trillion by 2030, with the main potential in Asia [4]. Due to the novel technologies and materials, complexity, uncertainty and innovations involved in GB projects, risks can increase significantly in the implementation phase of a project. As a result, it can lead to project failure, overbudget or delay [5]. For example, 32.3% of GB projects were delayed in Singapore, compared to 15.9% of traditional building projects that experienced time overrun [6]. From this study, it is concluded that GB projects are more prone to delays compared to traditional construction projects. The average delay of GB projects in Singapore was 4.8% of the planned schedule. Due to their uniqueness, their development is challenged by various risk factors, and the success rate is doubtful. The ensuing economic losses and social impacts are profound and hinder the development of the GB industry. According to the analysis of several reasons for the failure of GB projects, one of the key reasons for the failure is the lack of a comprehensive risk assessment and management approach [7]. The current studies show that spending a part of the budget on decision-making for risk management will increase the rate of project successful delivery [8]. To avoid the failure of GB projects, risk assessment and management capabilities must be enhanced to establish risk mitigation, response and control strategies in advance and prevent them from occurring.

The aims of this paper are: (1) to identify the key risk factors through in-depth analysis and assessment of the risks of GB projects in China; (2) to establish a systematic rating framework by constructing a comprehensive evaluation index system including main stages, key links, and related indicators; and (3) to calculate the grey clustering coefficient of each indicator and to reflect the risk contribution of each evaluation index. This study applies the grey cluster evaluation method to conduct an in-depth analysis of the risks in GB projects, aiming to identify and quantify the specific impact of potential risk factors on the implementation of GB projects, so as to provide scientific assessment tools and decision support for project management teams. Grey clustering method is a process of aggregating objects to be evaluated into several categories based on the grey relational matrix and the whitening power function of grey numbers [9]. The coefficients for risk factors can be determined by expert evaluation and actual data, and by performing a comprehensive grey clustering assessment. Based on the assessment results and risk classification, risk management and response measures are proposed to reduce the negative impact on the project. The risk assessment of GB projects is particularly complex because it involves multiple dimensions such as environmental sustainability, economic benefits, social acceptance, policy support and technical feasibility. The importance of risk assessment in GB projects is being taken seriously gradually by the industry.

2. LITERATURE REVIEW

In recent years, there has been growing research interest in the risks associated with GB projects, and discussion around the topic has increased. To reduce the risks existing in GB projects, more reasonable planning and management of projects should be carried out after sufficient risk identification. Zhenxiang Shi et al. have adjusted and modified the project management methods in the whole project lifecycle based on traditional construction projects [10]. To summarise the method suitable for GB project management, the intersection of different disciplines should be considered comprehensively in the early establishment of a project team. Many developed countries have successively issued GB standards and evaluation systems suitable for their respective national conditions, such as LEED developed by the United States Green Building Council [11], BREEAM developed by the British Building Research Centre [12], and CASBEE established by the Japanese Ministry of Environmental Protection [13]. Some countries have developed their national GB standards and assessment systems to promote the development of GB and to deepen the understanding of the role of green. The project lifecycle includes four stages: planning phase, design, construction, and operation and maintenance [14]. The list of risk factors in green building projects is provided in Table 1.

Table 1. The risk factors in GB projects

Groups	Risk factors	Reference
Decision making and planning	R_{11}: Inexperienced green building consultants	[15, 16]
	R_{12}: Incomplete green building law and regulations	[16,17,18]
	R_{13}: Misaligned green building project objectives	[5]
	R_{14}: Inaccurate green building investment estimation	[5,16,19]
Design phase	R_{21}: Poor quality of GB design schemes	[16, 20]
	R_{22}: GB design innovations	[5,16]
	R_{23}: Designs with poor constructability	[19,21]
	R_{24}: Absence of site-specific design considerations	[5,22]
	R_{25}: Design changes	[5,16,19]
	R_{26}: Design errors	[16,21]
Construction phase	R_{31}: Lack of GB construction experience personnel	[5,16,17]
	R_{32}: Innovative equipment for assembling GB products	[17,19]
	R_{33}: Lack of products meeting GB requirements	[16,18]
	R_{34}: Changes in the price of labour	[5,19]
	R_{35}: The quality problems of GB materials	[5,16,19]
	R_{36}: Changes in the prices of GB materials	[5,16,19]
	R_{37}: Construction accidents	[5,16,19]
	R_{38}: Delays in material and equipment delivery	[16,19]
	R_{39}: Influence of weather on GB materials	[16,23]
	$R_{3,10}$: Lack of suppliers for GB materials	[5,24]
	$R_{3,11}$: Force Majeure	[16,24]
Operation and maintenance phase	R_{41}: Lack of experienced property management	[5,16,25]
	R_{42}: Absence of regular maintenance of equipment	[26]
	R_{43}: Unclear responsibility sharing for future upgrades	[27]
	R_{44}: Deterioration of GB materials	[27]
	R_{45}: Lack of maintenance of GB materials	[5,27]

3. METHODOLOGY

The specific steps of the proposed methodology for risk evaluation in GB projects are highlighted in Figure 1. To conduct a reasonable and effective evaluation of GB risks, the first step is to identify all risks that are associated with GB projects. The risk identification process is carried out through a literature review. The selected risks in GB projects are outlined in Table 1. Once the risks are identified, the second step is to establish the risk assessment levels. In this case, the risk factors are divided into groups according to which project lifecycle phase they belong to. The groups represent a higher level of risk. In the hierarchy, the highest level is GB projects. The third is to design a questionnaire. Based on the list of risks identified in the literature review, a questionnaire was created for this study. The questionnaire was structured into two sections: the first section is the background of respondents, including their working experience and education; the second part is to evaluate risk factors. This study uses non-probabilistic sampling methods, including purposeful sampling and snowball sampling, which can identify the key risks in the construction industry. The questionnaire was distributed to construction practitioners, especially those who specialise in GB projects (purposeful sampling). Each expert will answer a questionnaire. They will use a *Questionnaire Star* to answer questions. When data is collected, a grey clustering evaluation method is applied to calculate grey weights for coefficients. By professional judgments in the risk evaluation index system, the evaluation level of each risk in GB projects is calculated.

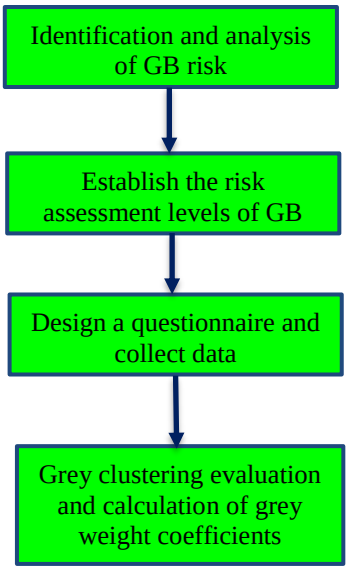

Figure 1. The proposed methodology for identifying the critical risk in GB projects

Grey clustering method is based on an observation index that can be grouped into several categories of definition methods. A clustering process is a collection of observed objects which belong to the same class. The evaluation indicator for clustering is a dynamic interval, referred to as a grey number, denoted by "⊗". The whitening weight function can indicate the degree of closeness of the evaluated object to the grey number within this dynamic interval. In the context of risk evaluation, it is assumed that there are m evaluation objects and n evaluation indicators, with s different grey classes. The clustering sample value of the i (*i = 1,*

2, ..., m) evaluation object concerning j (*j = 1, 2, ..., n*) indicator is represented as D_{ij}. The matrix representation of the evaluation samples is as follows:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Grey class (s = 1, 2, ... w) represents the risk levels of the evaluation indicators. The risk levels in this paper are categorised as very low risk, low risk, medium risk, high risk, and very high risk, corresponding to the "first grey class", "second grey class", ... and "fifth grey class," respectively. The risk level sequence number for each grey class is s = 1, 2, ... 5.

Experts within the dynamic range of grey numbers have different levels of expectation for different values of X, which correspond to the numerical values of the grey variable X at different levels. The typical expressions and schematic diagrams of the whitening weight functions is shown in Figure 2 below：

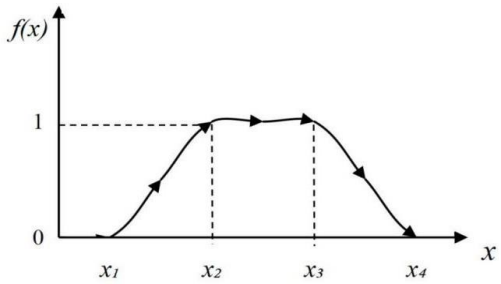

Figure 2. The example of the typical whitening weight function

where, *f* (*xij*) - the weight of the grey number *x*, which can be referred to as the whitening weight function of *x*.

$$f(x) = \begin{cases} 0, & x \notin [x_1, x_4] \\ \frac{x - x_1}{x_2 - x_1}, & x \in [x_1, x_2] \\ 1, & x \in [x_2, x_3] \\ \frac{x_4 - x}{x_4 - x_3}, & x \in [x_3, x_4] \end{cases} \quad (2)$$

The risk level of the first grey category is denoted as “*very low risk*”, and the assigned grey number $\otimes 1 \in [0, 1, 2]$, where numbers represent the threshold and the range of values is between 0 and 2. The whitening weight function is given in equation 3, and the graph for this function is illustrated in Figure 3 below:

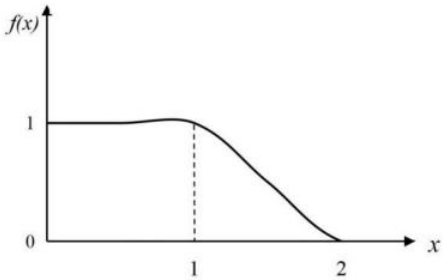

Figure 3. The whitening weight function for grey cluster number $\otimes 1$

$$f_1(x) = \begin{cases} 1, & x \in [0,1] \\ \frac{2-x}{2-1}, & x \in [1,2] \\ 0, & x \notin [0,2] \end{cases} \quad (3)$$

The risk level of the second grey category is denoted as "*low risk*", and the assigned grey number $\otimes 2 \in [0, 2, 4]$. The whitening weight function is given in equation 4, and the graph for this function is illustrated in Figure 4 below:

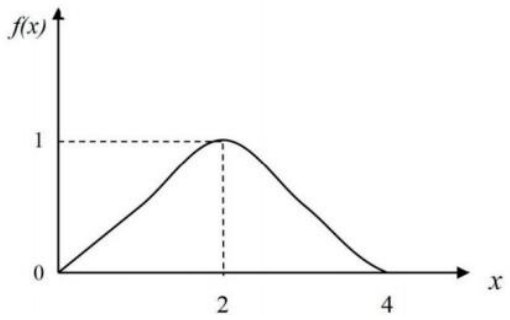

Figure 4. The whitening weight function for grey cluster number $\otimes 2$

$$f_2(x) = \begin{cases} \frac{x}{2}, & x \in [0,2] \\ \frac{4-x}{2}, & x \in [2,4] \\ 0, & x \notin [0,4] \end{cases} \quad (4)$$

Similarly, the risk level of the third grey category is denoted as "*moderate risk*", and the assigned grey number $\otimes 3 \in [0, 3, 6]$. The whitening weight function is given in equation 5, and the graph for this function is illustrated in Figure 5 below:

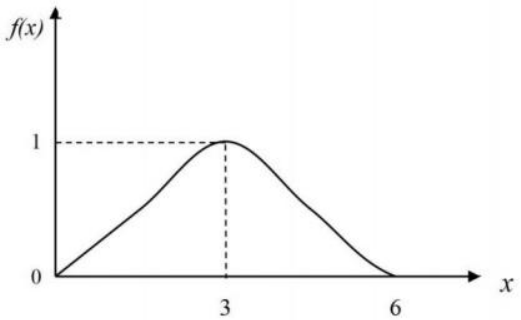

Figure 5. The whitening weight function for grey cluster number $\otimes 3$

$$f_3(x) = \begin{cases} \frac{x}{3}, & x \in [0,3] \\ \frac{6-x}{3}, & x \in [3,6] \\ 0, & x \notin [0,6] \end{cases} \quad (5)$$

Similarly, the risk level of the fourth grey category is denoted as "*high risk*", and the assigned grey number $\otimes 4 \in [0, 4, 8]$. The whitening weight function is given in equation 6, and the graph for this function is illustrated in Figure 6 below:

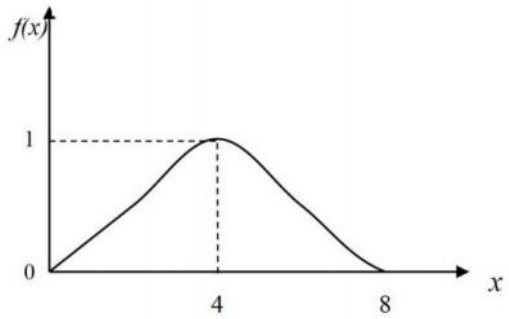

Figure 6. The whitening weight function for grey cluster number ⊗ 4

$$f_4(x) = \begin{cases} \frac{x}{4}, & x \in [0,4] \\ \frac{8-x}{4}, & x \in [4,8] \\ 0, & x \notin [0,8] \end{cases} \quad (6)$$

The risk level of the fifth grey category is denoted as "*very high risk*", and the assigned grey number ⊗ 5 ∈ [0, 5, 10]. The whitening weight function is given in equation 7, and the graph for this function is illustrated in Figure 7 below:

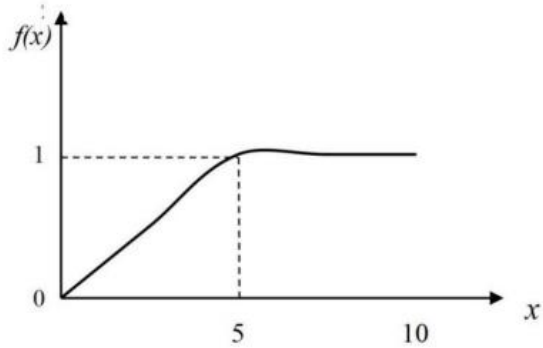

Figure 7. The whitening weight function for grey cluster number ⊗ 5

$$f_5(x) = \begin{cases} \frac{x}{5}, & x \in [0,5] \\ \frac{10-x}{5}, & x \in [5,10] \\ 0, & x \notin [0,10] \end{cases} \quad (7)$$

The evaluation coefficient for the level *s* grey class is denoted as $\eta_{ij,s}$ and the calculation formula is:

$$\eta_{ij,s} = \sum_{k=1}^{m} f_s(\eta_{ij,k}) \quad (8)$$

where, m – the number of experts

The sum of all grey classes in the evaluation index is η_{ij} and it is calculated by the formula:

$$\eta_{ij} = \sum_{k=1}^{s} f(\eta_{ij,k}) \quad (9)$$

The next step is to calculate the grey weight vector for the level s grey class of secondary index:

$$R_{ij.s} = \frac{\eta_{ij.s}}{\eta_{ij}} \quad (10)$$

Then, the weight vector Rij for the *j-th* risk belonging to *i-th* group is:

$$R_{ij} = [R_{ij,1}, R_{ij,2}, R_{ij,3}, R_{ij,4}, R_{ij,5}] \quad (11)$$

The risk evaluation levels are five, and the corresponding numerical values for risk levels are: P = [1, 2, 3, 4, 5]. The evaluation grade G for each risk can be calculated as follows:

$$G_{ij} = R_{ij} * P^T \quad (12)$$

4. RESULTS AND DISCUSSIONS

Table 2 provides information about the respondents' educational background, working experience and job position in the company. Workers in the GB industry show a variety in working experience, job positions and educational backgrounds. In total, 40 professionals in the GB industry have participated in a questionnaire survey. More than half of the respondents, 62.5% of them, have a college degree. Regarding working experience, 50% of them have between 10 and 20 years of working experience in the GB industry. Mainly, 50% of them are employed as project engineers in the company.

Table 2. Respondent's background

Educational Background		Working experience		Job Position	
College degree	25	Less than 5 years	5	Project Manager	6
Bachelor degree	10	5 – 10 years	7	Civil Engineer	20
Master degree	5	10 – 15 years	12	Designer	8
PhD degree	0	15 – 20 years	8	Safety Director	6
		More than 20 years	8	Other	0

Firstly, the clustering coefficient of each index is calculated. For example, the evaluation of risk R_{11} for the grey grade is calculated:

Class s = 1: $\eta_{11,1} = \sum_{k=1}^{40} f_1(\eta_{11,k}) = f_1(\eta_{11,1}) + f_1(\eta_{11,2}) + \cdots + f_1(\eta_{11,40}) = 1.5$

Class s = 2: $\eta_{11,2} = \sum_{k=1}^{40} f_2(\eta_{11,k}) = f_2(3) + f_2(3.5) + \cdots + f_2(3) = 30.75$

Class s = 3: $\eta_{11,3} = \sum_{k=1}^{40} f_3(\eta_{11,k}) = f_3(3) + f_3(3.5) + \cdots + f_3(3) = 27.50$

Class s = 4: $\eta_{11,4} = \sum_{k=1}^{40} f_4(\eta_{11,k}) = f_4(3) + f_4(3.5) + \cdots + f_4(3) = 30.25$

Class s = 5: $\eta_{11,5} = \sum_{k=1}^{40} f_5(\eta_{11,k}) = f_5(3) + f_5(3.5) + \cdots + f_5(3) = 28.5$

The sum of the grey clustering evaluation coefficient η_{11} and the weight vector R_{11} is:

$\eta_{11} = \sum_{k=1}^{5} f(\eta_{11,k}) = 1.5 + 30.75 + 27.5 + 30.25 + 28.5 = 118.5$

$R_{11} = [R_{11,1}, R_{11,2}, R_{11,3}, R_{11,4}, R_{11,5}] = [0.01, 0.26, 0.23, 0.26, 0.24]$

The evaluation grade for risk R_{11} is:

$G_{11} = R_{11} * P^T = [0.01, 0.26, 0.23, 0.26, 0.24] * [1, 2, 3, 4, 5]^T = 3.46$

Similarly, the values for each risk are calculated based on this procedure. The results are shown in Table 3. The experts have evaluated that the most critical risks in GB projects are construction accidents, design errors, inaccurate GB investment estimation, absence of site-specific design considerations, designs with poor constructability and the quality problems of GB materials. Inaccurate GB investment estimation is ranked the highest among the risks in the group decision-making and planning phase. Hence, the accurate budget estimation in the planning phase and allocation of resources are important for the successful completion of the GB project. In the design phase, three risks appear among the critical risks. Site-specific considerations are essential for ensuring that the building is well-suited to the environment and can further affect operational efficiency. Poor constructability can affect the project timeline and cost as well as the ability to execute the design as planned. Design errors can contribute to delays in the project, rework and increased cost. Hence, there is a need for thorough design review and quality control. The highest-ranked risk is construction accidents from the construction phase. Safety on a construction site is essential. Some of the measures are that workers have proper training for the GB industry and wear health and safety equipment during their work. For monitoring workers and inspecting whether they wear proper equipment, the project manager is responsible.

Table 3. The values for risk factors in GB projects

Groups	Risk factors	Value
Decision making and planning	R_{11}: Inexperienced green building consultants	3.46
	R_{12}: Incomplete green building law and regulations	3.13
	R_{13}: Misaligned green building project objectives	3.16
	R_{14}: Inaccurate green building investment estimation	4.10
Design phase	R_{21}: Poor quality of GB design schemes	3.39
	R_{22}: GB design innovations	3.46
	R_{23}: Designs with poor constructability	3.84
	R_{24}: Absence of site-specific design considerations	4.07
	R_{25}: Design changes	3.80
	R_{26}: Design errors	4.41
Construction phase	R_{31}: Lack of GB construction experience personnel	3.39
	R_{32}: Innovative equipment for assembling GB products	2.84
	R_{33}: Lack of products meeting GB requirements	3.48
	R_{34}: Changes in the price of labour	3.29
	R_{35}: The quality problems of GB materials	3.84
	R_{36}: Changes in the prices of GB materials	3.36
	R_{37}: Construction accidents	4.44
	R_{38}: Delays in material and equipment delivery	3.58
	R_{39}: Influence of weather on GB materials	2.92
	$R_{3,10}$: Lack of suppliers for GB materials	3.82
	$R_{3,11}$: Force Majeure	3.55
Operation and maintenance phase	R_{41}: Lack of experienced property management	3.80
	R_{42}: Absence of regular maintenance of equipment	2.84
	R_{43}: Unclear responsibility sharing for future upgrades	2.74
	R_{44}: Deterioration of GB materials	2.74
	R_{45}: Lack of maintenance of GB materials	3.43

On the other hand, the least critical risks are the deterioration of GB materials during the operation and maintenance period, unclear responsibility sharing for future upgrades, absence of regular maintenance of equipment and innovative equipment for assembling GB products. These risks are mainly in the operation and maintenance phase.

5. CONCLUSIONS

In this study, the grey cluster assessment method is used to assess and manage the risks in GB projects. Initially, a combination of literature review analysis and survey methods is employed to identify potential risk factors that could impact the results of the project lifecycle, followed by the development of a corresponding risk assessment structure. Finally, this study applies the grey comprehensive assessment method to explore in depth and assess every risk in GB projects and detect the most critical risks. This study shows that the most critical risks are: construction accidents, design errors, inaccurate GB investment estimation, absence of site-specific design considerations, designs with poor constructability and the quality problems of GB materials. Half of these risks belong to the design phase. Hence, the design phase is a critical phase, and additional attention needs to be paid in the design phase. At the same time, the research also puts forward the corresponding risk mitigation measures and ideas, aiming to provide scientific decision support for the risk management of GB projects. On the other hand, the least critical risks in GB projects are the deterioration of GB materials during the operation and maintenance period, unclear responsibility sharing for future upgrades, absence of regular maintenance of equipment and innovative equipment for assembling GB products. The findings show that the maintenance and operation phase is the least critical phase. The future direction is to implement the combinations of different methods and the grey cluster method to assess the risks in GB projects and the overall risk of a project. Further.

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Research paper

AHP METHOD FOR RISK ASSESSMENT OF THEATRE PROJECTS

Jelena Andrić[1], Boya Yang[2]

Abstract

The construction industry experiences many issues, including high interest rates for project loans, difficulties from carbon dioxide emissions and global warming. Since the number of theatre projects is rising, risk management of theatre-style buildings has become important. This research investigates how to successfully manage risk using the Analytic Hierarchy Process, which is applied as an example on a large theatre project. This method converts subjective evaluations into indicators and combines qualitative and quantitative techniques to reduce uncertainty effectively. A risk assessment framework that ranks each risk factor and determines its importance and weight is developed. Finally, the weight and the contribution of these factors are estimated to propose the corresponding monitoring and control measures and to provide a decision-making basis for risk management of theatre projects. It is concluded that the empirical analysis of this study can help project managers to better understand risks in theatre project construction, as well as to take the corresponding measures for risk management and control. The most important risks in theatre projects are: economic risk, the delivery of stage equipment, the electricity supply to the theatre and concrete encapsulation backfill. For risk groups, the most important risk groups are: economic risk, occupational accidents and stage equipment.

Key words: *Risk Assessment, Risk Breakdown Structure, AHP method, Theatre projects.*

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1. INTRODUCTION

This study uses the Analytical Hierarchy Process (AHP) to analyse the importance of risks in theatre projects, focusing on factors such as artistry, operations, safety, government importance, and social impact [1]. AHP is a quantitative decision-making method that can decompose complex problems into multiple levels and compare and analyse them at each level to find the best solution. This method helps the project management team identify and evaluate project risks more systematically and comprehensively through hierarchical thinking [2]. In theatre projects, artistic and operational factors are the key to the success of the project, while safety is the guarantee for the smooth progress of the project. Government importance and social impact relate to the social value and public acceptance of the project. Through an AHP assessment of these factors, project managers can better understand the relative importance of each factor and their impact on the overall success of the project [3]. The advantage of AHP is its ability to deal with uncertainty and ambiguity, which are common in many decision-making processes. For example, when evaluating the artistic value of theatre design, different stakeholders may have different perspectives, and AHP allows these different perspectives to be integrated and quantified through mathematical models, resulting in a more objective and comprehensive basis for decision-making [4].

2. LITERATURE REVIEW

Risk evaluation in construction projects helps identify potential threats to people, the environment, or materials [5], addressing challenges like rising interest rates, inflation, and COVID-19 [6]. Effective risk management enhances project efficiency, minimises losses, and improves organisational resilience [7]. Risk tracking offers benefits like timely identification, cost reduction, project success, and safety assurance [8]. The integrated risk management procedure [8] is presented in Figure 1.

Figure 1. Integrated risk management

China's building projects often prioritise speed over long-term benefits, leading to a lack of risk management [9]. This lack of awareness is prevalent in the property industry, where engineering projects often face funding and financial constraints [10]. Developers aim to minimise risk and losses while minimising risk management expenses [11]. Companies are reluctant to invest in risk management due to the construction sector's insufficient consideration. The project's life cycle includes planning, design, construction, operation, and maintenance stages, each requiring risk assessment at each stage [12].

Theatre projects are prone to various risks, including design, building, economic, and legal hazards, which can arise from various causes, as illustrated in Table 1. The first column in Table 1 presents the group to which risks are associated, the second column is related to the name of risks and the third column is the source of risk from the reference.

This paper evaluates the AHP method for analysing the weight importance of project factors, aiming to improve expert judgment precision and diversity. Fuzzy models are effective for complex systems; nevertheless, they can be subjective and incorrect [13]. Monte Carlo simulation helps assess sustainability risks, but is resource-intensive and parameter-sensitive [14]. Machine learning automates prediction but can be affected by sample bias and information quality [15]. Current risk assessment methods for building projects lack consistency and accuracy [16].

Table 1. The risk factors in theatre projects

Groups	Risk factors	Reference
Economic	Tight funding supply, Inflation Increase in prices of raw materials and equipment	[9,12,16,17]
Legal	Imperfect laws cause challenges in construction	[16,17]
Social	Acceptance of the project in the local community	[3,16]
Soil	Groundwater causes soil	[2,9,16,18]
Weather	Unfavourable weather, fire, earthquake and other natural causes	[9,16,19]
Environment	Noise	[12,16]
	Construction wastewater	[9,12,16]
	Solid waste	[9,20]
	Dust and waste gas	[9,12,16]
Design phase	Design changes	[12,19,16]
	Delay in the design process	[9]
	Design errors	[16,19]
Earthworks	Breakdown of excavation equipment	[9,16]
	Layout utilities	[12]
	Pipe cushion pouring	[21]
	Installation of pipes	[22]
	Transportation of soil	[23]
Occupational accidents	Concrete encapsulation backfills	[24,25]
	Fall from height	[24,25]
	Electric shock accident	[24,25]
	Crushing and injuring people	[24,25]
	Backfill in soil excavation	[24,25]
Stage equipment	Delay in the delivery of stage equipment	[16,19,26]
	Breakdown of stage equipment	[26]
Concrete works	Poor quality of concrete	[9,16]
	Poor quality of steel bars	[9,16]
Electricity	Construction power access	[27]
HVAC system	Breakdown of HVAC	[28]
Personal management risks	Lack of experience with the project	[9,16]
	Unreasonable work arrangement	[9]
	Lack of strict technical management	[9,16]

3. METHODOLOGY

This study utilises quantitative and qualitative methods to analyse theatrical risk projection levels and priority risks, utilising AHP for comprehensive, accurate, and specific results. The research design is provided in a three-phase method: creating a Risk Breakdown Structure (RBS), designing a questionnaire for AHP and distributing it to the specialists in the construction industry for collecting data, and implementing the AHP method for the calculation of factor weights.

A questionnaire was created to assess key risks in the construction industry, focusing on education, work experience, background, projects, and hazards, using non-probability sampling and Questionnaire Star distribution. The procedure for the AHP method is as following:

The hierarchy of traits was created using empirical data and research, starting with research objectives and progressing to criteria and alternatives. Data collection began with pairwise comparisons to assess trait importance. This involved constructing contrast matrices, determining element significance, and calculating consistency ratios at each level [ref]. The procedure for AHP calculations is:

(1) Establish a judgment matrix as given in equation (1) [29]:

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \cdots & \cdots & \cdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} \quad (1)$$

The comparative importance of c_i and c_j is represented as element c_{ij} in the matrix. If the element is more significant, then the value of $c_{ij} > 1$; otherwise, it is insignificant. In case two risk factors are equally important, then $c_{ij} = 1$.

(2) Judgements of the importance of matrix elements are provided in Table 2.

Table 2. The relative importance ratio standard [29]

Scaling	Meaning
1	Comparing two factors, they have the same importance
3	Comparing two factors, the former factor is slightly more important than the second factor
5	Comparing two factors, the former factor is obviously more important than the second factor
7	Comparing two factors, the former factor is more important than the latter factor
9	Comparing two factors, the former factor is extremely important than the second factor
The reciprocal of the above	The two factors are compared in turn; they are the reciprocals of the original comparison value.

(3) Calculate the weight vector of each indicator:

- Normalise the matrix using the following equation (2):

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2)$$

where, a_{ij} is the element in the i -th row and j-th column of the judgment matrix A, and $\bar{a}_{ij}$ is the data in the i-th row and j-th column of the normalisation matrix.

- Add the elements in the matrix using the equation:

$$\overline{w_i} = \sum_{i=1}^{n} \overline{a_{ij}} \quad (3)$$

- Implement the normalization process using the equation (4):

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_{ij}}} \quad (4)$$

where w_i is the weight of the i-th element

- Calculate the maximum eigenvalue of the judgment matrix as follows:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(Aw)_i}{w_i} \quad (5)$$

Where, n – the order of the matrix, A is the judgment matrix

(4) Consistency tests on vectors and eigenvalues are conducted to ensure a reasonable judgment matrix with explanatory value, using CI as the consistency index, and it is provided in Table 3:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

Table 3. Random Consistency Index

N	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Consistency ratio is the ratio between the consistency index and the random consistency index, CR = CI/RI. The RI is obtained through the n value from Table 3. If the CR < 0.1, the detection meets the requirements.

(5) Absolutely weights:

- The absolute weight of risk factors is calculated as follows:

$$Absolute\ weight\ (risk) = Risk\ group\ weight\ x\ Risk\ factor\ Weight \quad (7)$$

4. RESULTS

In total, 110 experts in theatre projects participated in the questionnaire survey. Their educational background, working experience and job position are given in Table 4. The majority of them, around 54.5%, have graduated with a Bachelor's degree. It is estimated that 65.4% of respondents have working experience between 5 and 15 years. They are mainly working in job positions as a designer, in total 31.81% of them, followed by a civil engineer, around 25.4%.

Table 4. Respondent's background

Educational Background		Working experience		Job Position	
College degree	28	Less than 5 years	6	Project Manager	23
Bachelor degree	60	5 – 10 years	36	Civil Engineer	28
Master degree	21	10 – 15 years	36	Designer	35
PhD degree	1	15 – 20 years	23	Safety Director	24
		More than 20 years	9	Other	

The results of the weight of importance for each risk according to the AHP method are provided in Table 5. Further, the results for each group are considered. Since groups are divided into external and internal risks. The AHP method is estimated for these two groups separately. The results are provided in Tables 6 – 7.

Overall, the most important risk factor is economic risk. Economic risk includes tight funding supply, inflation, an increase in prices of raw materials, equipment and labour. For the successful completion of the theatre project, it is important to provide a sufficient budget that will cover all expenses. In the second place, it is the delay in the delivery of stage equipment. The theatre equipment can be very expensive, and some equipment is rare, and it can be designed only for special purposes. So, the purchase of theatre equipment should be done in a timely manner, giving the supplier enough time to ship the product. The other important risks are the electricity supply to the theatre and concrete encapsulation backfill, which belongs to a group of occupational accidents.

Table 5. The results for risk factors based on the AHP method

Groups	Risk factors	Weights
Economic	Tight funding supply, Inflation Increase in prices of raw materials and equipment	0.292
Legal	Imperfect laws cause challenges in construction	0.035
Social	Acceptance of the project in the local community	0.043
Soil	Groundwater causes soil	0.035
Weather	Unfavourable weather, fire, earthquake and other natural causes	0.036
Environment	Noise	0.020
	Construction wastewater	0.014
	Solid waste	0.020
	Dust and waste gas	0.005
Design phase	Design changes	0.008
	Delay in the design process	0.012
	Design errors	0.005
Earthworks	Breakdown of excavation equipment	0.002
	Layout utilities	0.002
	Pipe cushion pouring	0.002
	Installation of pipes	0.005
	Transportation of soil	0.002
Occupational accidents	Concrete encapsulation backfills	0.054
	Fall from height	0.039
	Electric shock accident	0.021
	Crushing and injuring people	0.017
	Backfill in soil excavation	0.007
Stage equipment	Delay in the delivery of stage equipment	0.070
	Breakdown of stage equipment	0.035
Concrete works	Poor quality of concrete	0.040
	Poor quality of steel bars	0.040
Electricity	Construction power access	0.062
HVAC system	Breakdown of HVAC	0.044
Personal Management Risks	Lack of experience with the project	0.004
	Unreasonable work arrangement	0.010
	Lack of strict technical management	0.015

When different groups are considered, among the external risks, the most significant is economic risk, followed by environmental risk. In case of the internal risks on projects, the most important risk groups are occupational accidents that can occur on the construction site and stage equipment, including delays in the delivery of equipment and the breakdown of equipment.

Table 6. The results for risk groups that belong to external risks

Groups	Weights
Economic	0.584
Legal	0.070
Social	0.085
Soil	0.070
Weather	0.074
Environment	0.117

Table 7. The results for risk groups that belong to internal risks

Groups	Weights
Design phase	0.050
Earthworks	0.030
Occupational accidents	0.276
Stage equipment	0.210
Concrete works	0.161
Electricity	0.125
HVAC system	0.089
Personal Management Risks	0.058

5. CONCLUSIONS

This paper uses the AHP method to determine the most important risks and groups of risks in theatre projects. Studies show that the AHP method is very useful and gives clear results when there is a need for decision-making. Also, the AHP can be applied as an addition to other methods for risk assessment. For example, the AHP can be used for determining the weight importance of risk, and the other method is for determining the risk values. According to the results, the most important risks in theatre projects are economic risk related to providing budget, inflation and changes in the cost of equipment, material and labour. In addition to economic risk factors, other important risk factors are: the delivery of stage equipment, the electricity supply to the theatre and concrete encapsulation backfill. When groups of risks are considered, the most important risk groups are: economic risk, occupational accidents and stage equipment.

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Research paper

ANALYSIS AND COMPARISON OF INFORMATION ON LOAD LIFTING EQUIPMENT - ELECTRIC CRANES

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Abstract

Lifting equipment must be in accordance with safety standards that require conditions or the adoption or use of one or more practices, means, methods, operations, or processes that are necessary or appropriate to ensure safe and healthy workplaces. As a result, to guarantee the free flow of technical products, the European Commission proposed to the Council a new regulatory technique that includes: (1) a New approach to product regulation and (2) a Global approach to product conformity assessment. Three fundamentally new principles were introduced by approval of a new regulatory: (1) Standardization as support for legislation, (2) New type of directive, (3) Presentation of the conformity assessment policy. As part of the standards and directives, mandatory labeling of products with the CE mark (Conformité Européene) is introduced, which indicates that the product meets the requirements specified in EU directives and will not endanger the health or safety of users. All machines and devices that are placed on the territory of the EU/Republic of Serbia must have written warnings and information in a language that the user of the machine understands. Also, all information for operating the machine must be unambiguous, easy to understand, and must not be too extensive, so as not to overload the operator. The machine must contain all the necessary information relevant to its type and use. This research aims to show the significance of CE marking and the importance of machine information, where by choosing electric cranes as an example, the comparative analysis of manufacturers' manuals will be conducted. This will enable the identification of advantages and disadvantages and space for improvement of the given instructions and how much those instructions are by the general principles and content prescribed within the Directive on Machinery 2006/42/EC and the Machinery Safety Regulation.

Key words: *CE mark, Information, Electric Crane, Manufacturer Manual*

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1. INTRODUCTION

All lifting equipment must comply with safety standards that require conditions or the adoption or use of one or more practices, means, methods, operations, or processes that are necessary or appropriate to ensure safe and healthy workplaces [1]. Standards prescribe requirements that must be met to ensure that a particular product or activity is safe and secure, i.e. not dangerous [2].

Until 1985, the policy of the European Union (EU) was reflected in the removal of technical barriers through the harmonization of technical production specifications, which led to the introduction of many special measures whose content was largely related to the technical aspect, of fulfilling the special requirements for each product category. However, due to the excessive content of technical regulations, which are unsuitable for application due to the necessity of adapting the legislation to technical progress, this approach was increasingly difficult to maintain and develop. For this reason, and to ensure the free flow of technical products, on January 3, 1985, the Commission proposed to the Council a new regulatory technique that includes: a New approach to product regulation and a Global approach to product conformity assessment. By adopting the proposal by the Council, this resolution introduced three fundamentally new principles:

- Standardization as support for legislation;
- A new type of directive;
- Presentation of the conformity assessment policy [3].

The basis of the New Approach legislation is legal acts in the form of New Approach directives, which define essential health and safety requirements for products that can affect the health and life of people and domestic animals, as well as the interests of consumers and environmental protection. If a certain product complies with the requirements of the directive, it will have free access to the EU market. Each directive of the New Approach is accompanied by certain harmonized standards, which define all other requirements for products, to fulfill the basic requirements of the directives. The global approach to conformity assessment was adopted in December 1989 and provides conformity assessment through the institution of an independent "authorized body", which is authorized to carry out the conformity assessment procedure. This novelty was adopted to complete the New Approach so that harmonized methods for conformity assessment, and marking, as well as the adoption of a single doctrine for their implementation, would support the directives [4].

Another significant aspect of the "New Approach" directives [5] is reflected in the provision of a declaration of conformity, but also placing the CE mark (Conformité Européene) on the product as proof of conformity – where the product meets the requirements specified in EU directives and will not endanger the health or safety of users. The European legislation on CE marking is limited to the basic legal requirements written in the directives for large groups of products (eg toys or machines), and is an obligation for every manufacturer who places a product on the European market. The specific CE requirements take precedence over the general provisions set out in the General Product Safety Directive. The European Commission defines the general requirements that products must meet when they are placed on the European market within the framework of CE directives. These harmonized standards (at the European level) replaced various national laws and enabled the free movement of products within the Community, taking into

account safety requirements of general interest. This positive integration ensures that national requirements are harmonized with European laws [4].

Characteristic of the legislation of the New Approach is also ensuring the safety of European citizens from unsafe products and associated risks. The New Approach aims to protect public goals related to the safety and health of product users, but also to draw attention to potential hazards [6]. This increases consumer confidence in new products bearing the CE mark, which will lead to an increased volume of product purchases, but also more cost-effective development of new products and increased innovativeness of manufacturers [7]. On the other hand, market surveillance authorities have the right to withdraw unsafe products from the European market and the obligation to provide information on risks and unsafe products [6].

This research aims to show the significance of CE marking and the importance of machine information, where by choosing electric cranes as an example, the comparative analysis of manufacturers' manuals will be conducted. This will enable the identification of advantages and disadvantages and space for improvement of the given instructions and how much those instructions are by the general principles and content prescrtibed within the Directive and national regulations [8, 9]

2. CE MARKING

The CE marking symbolizes compliance with all the manufacturer's obligations relating to the product and the mark is not intended to be used for commercial purposes. Compliance is not only limited to essential requirements related to safety but also to general health and consumer protection. The CE marking is the only marking that certifies that products comply with directives based on a global approach. The CE mark is placed on a product that meets safety standards, which apply in all EU countries, and is designed to facilitate the free movement of goods within the EU [10].

Products that do not bear the CE mark and do not comply with the directives may be prohibited from sale or excluded from the European market. If non-conformities are found, or damages or injuries caused by the product occur, the company-manufacturer or anyone else responsible for selling the product on the European market may bear personal responsibility, that is, they may be prosecuted. The CE mark indicates that the manufacturer has adapted to the requirements of EU legislation and, accordingly, he can sell his products freely within the EU, without further modifications or testing. The CE mark is not a quality mark and does not show compliance with the standard, but rather compliance with the essential legal requirements of EU directives [3, 4, 10].

By placing the CE mark on the product, the EC declaration of the legal or natural person who placed the CE mark or is responsible for its placement, guarantees that the product is adapted to all applicable provisions of the EU directives and that it has been subject to appropriate conformity assessment procedures [4, 10].

All directives of the New Approach provide for the placement of the CE mark, however, in justified cases, the Full Harmonization Directive, which follows the provision 93/465/EEC, may provide for marking with another mark instead of the CE mark. Before placing the product on the market and putting it into operation, the manufacturer must place the CE mark on the product, unless other directives require otherwise. The obligation to place the

CE mark applies to all products covered by the directives, which are intended for the EU, which includes the following products:

- to all new products, manufactured in EU member states or third countries,
- on all used products imported from third countries,
- substantially modified products, which are subject to directives as new products.

Until the conformity assessment procedure is completed, the CE mark cannot be affixed. This is done to ensure that the product is in compliance with all provisions of the relevant directives. CE marking is usually done at the end of the production phase [3].

The CE mark is placed by the manufacturer or an authorized EU representative, directly on the product or on the data plate, although it can also be placed on the packaging or accompanying documentation. When installing, it is necessary to fulfill the requirement for visibility, that is, that it is easily accessible, legible, and indelible, so that it cannot be removed under normal circumstances without leaving visible traces. The minimum height of the sign should be 5 mm [4, 10].

The CE mark can be placed at any other stage of production if it is an inseparable part of the product or its component and if this is justified due to technical or other reasons (for example, the impossibility of meeting the minimum dimensions of the CE mark). In such cases and if the mark is placed on the packaging or accompanying documents, the manufacturer or the authorized body must equally verify the conformity of the product in the production control phase. It is forbidden to omit the CE mark from the product, or to move it to the packaging and accompanying documentation for aesthetic reasons Depending on the applied conformity assessment procedures, the authorized body may be involved in the design phase, the production phase, or in both phases, and the identification number of the authorized body will follow after the CE mark, if the authorized body is involved in the production phase [3]. After the conformity assessment, the notified body issues a certificate of conformity and based on it, an EC declaration of conformity is drawn up, based on which the CE marking is carried out. The last step is placing, that is, marking the product with the CE mark, which must have the shape and dimensions prescribed in the directive and be placed so that it is visible, legible, and indelible. The CE certificate [8, 9] must contain:

- name and address of the certification body,
- name and address of the manufacturer/authorized representative in the EU,
- product description,
- terms with which the product agrees.

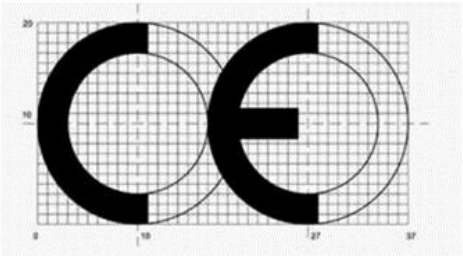

Figure 1. CE mark, source: https://www.paragraf.rs/propisi/t03_0168_s001.gif

3. IMPORTANCE OF MACHINE INFORMATION

According to the Directive and the national regulations [8, 9] information and warnings on the machine must be easily understandable, in the form of symbols or pictograms. All machines and devices that are placed on the territory of the EU/Republic of Serbia (RS) must have written warnings and information in a language that the user of the machine understands. Also, all information for operating the machine must be unambiguous, easy to understand, and must not be too extensive, so as not to overload the operator. Information devices, such as displays and other interactive means of communication between the operator and the machine, must be easy to understand and easy to use.

The machine must be equipped with sound and/or light signaling as a warning in the event that a failure of the machine, which is not under supervision, may endanger the safety and health of persons. Such devices must be unambiguous, and easily visible, and the operator must be provided with auxiliary equipment for checking the operation of the warning device. Warning devices must comply with the requirements of the regulations governing colors and safety signals [8, 9].

Every machine manufacturer is obliged to provide the necessary warnings about the remaining risks, including warning devices for such risks, when the design of the machine, safety protection, and appropriate supplementary protection measures do not eliminate all risks.

The machine must contain all the necessary information relevant to its type and use. The Directive and the national regulations [8, 9] mandate that each machine must be visibly, legibly, and indelibly marked with the following information:

- business name - the name and full address of the manufacturer's headquarters and, when applicable, the address of his representative;
- the marking of the machine;
- sign of compliance;
- series or type designation;
- serial number, if any;
- the actual year of production (ie the year when the production process was completed).

For machines intended for work and use in potentially explosive atmospheres, it is necessary to have the corresponding mark - "Ex" indicating the type of protection applied (eg Ex_D - for an explosion-proof device with impenetrable armor, Ex_E - for an explosion-proof device with increased security). If a part of the machine is handled using lifting equipment, the mass of that part must be marked legibly, unambiguously, and indelibly.

3.1 General principles and contents of the instructions

Every machine that is put on the market/put into use on the territory of the EU/RS must contain with it the original instructions of the manufacturer/its representative in the Serbian language with the indication "original instruction" or a translation of that instruction into the Serbian language with the indication "translation of the original instructions" together with the original instructions in the language of the manufacturer/its representative if the machine is imported into the territory of the Republic of Serbia.

The manual for the machine is drawn up by the manufacturer, and the translation of the manual is provided by the manufacturer/its representative or the importer. On the other hand, maintenance instructions intended for specialized personnel who are foreign nationals, employed by the manufacturer or its representative, may be written in one of the official languages of the EU member states.

The Directive and the national regulations also prescribe the necessary elements of the instructions for use, which must contain the following information:

- Business name, that is, the name and full address of the seat of the manufacturer and his representatives;
- The marking of the machine, which is indicated on the machine itself, except for the serial number;
- Declaration of conformity or other document containing data from the declaration of conformity where the characteristics of the machine are specified, except for the serial number and signature of the person who made the declaration of conformity;
- General description of the machine;
- Drawings, diagrams, descriptions, and explanations required for use, maintenance, and repairing the machine, as well as checking its correct functioning;
- Description of the workstation assumed to be occupied by the operators;
- Description of the intended use of the machine;
- Warnings regarding unauthorized use of the machine, which have been shown as possible based on experiences;
- Installation, installation and connection instructions, including drawings, diagrams, and means of attachment, as well as determining the base or installation to which it is attached the machine must set;
- Instructions related to the installation and assembly of the machine, to reduce noise or vibration;
- Instructions for commissioning and use of the machine and, if necessary, training instructions for handlers;
- Information on the remaining risks and in addition to the measures foreseen in the machine project, security protection and appropriate supplementary protection measures;
- Instructions on safety measures to be taken by the user, including, when appropriate, provision of personal protective equipment;
- Essential features of tools that can be placed on the machine;
- Conditions under which the machine meets the stability requirements during use, transportation, assembly, disassembly, when it is not in use, during testing, or for the time of foreseeable breakdowns, failures, or damages;
- Instructions for ensuring safe transportation, handling, and storage, with the indication of the mass of the machine and its different parts, when they are usually used and transported separately;
- Procedure in the event of an accident, breakdown, or damage, in the event of blocking, as and the procedure that enables safe unblocking of the equipment;

- Description of setup and maintenance procedures that must be performed by the user, as well as preventive maintenance measures to be taken into account;
- Instructions for safe setup and maintenance, including safeguards that should be undertaken during those procedures;
- Specifications of spare parts to be used when affecting health operator safety;
- Information on values of air-borne emissions,
- Information for the operator and exposed persons regarding the emission of radiation, when there is a probability that the machine will emit non-ionizing radiation that may cause harm to persons, especially persons with active or passive medical aids, information related to the radiation emitted for the operator and exposed persons [8, 9].

4. COMPARATIVE ANALYSIS OF INSTRUCTIONS

When a comparative analysis of instructions for electric cranes from different manufacturers - ISKRA, WOMAX, WORKSHOP, VILLAGER, STAR LIFTKET [11-15] is performed, with each other and with the content of the instructions [8, 9], significant advantages and disadvantages are recognized, based on which suggestions for improvement are given, which are shown in Table 1.

Table 1. Comparative analysis of electric hoist instructions

ELECTRIC CRANE	CONTENTS OF THE INSTRUCTIONS	
	ADVANTAGES	SUGGESTIONS FOR IMPROVEMENT
ISKRA Models: EV-125-250, EV 200-400, EV 250-250, EV 300-600	The sentences are short, clearly formulated, and concise, do not tire the user while reading, and the necessary information can be easily found	Reorganizing the content, more visual sketches, diagrams, and pictures are needed for a better understanding of the content A table with common failures, causes of those failures, and measures in case of failure is missing The section related to responsible behavior towards the environment, i.e. dealing with the product after the end of the device's working life, is missing Declaration of conformity is missing
WOMAX Models: W-SHZ 600, W-SHZ 1200 W-SHZ 1600	Excellently organized content Clear, short, meaningful sentences Extensive use of images, drawings, and diagrams, which makes the instructions easier to understand and apply	Given that there are no significant deficiencies, it can serve as an adequate example for the correction of other instructions

	A very well-structured table with an overview of the most common failures, causes and measures in case of failures	
WORKSHOP Models: PA 100/200, PA200/400, PA 400/800	The content is well-organized Sentences are clearly defined, understandable All necessary information is provided Clear and comprehensible insight into the most common faults, causes of faults, and assistance in case of faults	It is necessary to insert more illustrations, pictures, and diagrams to facilitate understanding
VILLAGER Models: VEH 250, VEH 500, VEH 800	The instructions are well-defined, and all sentences are clear and understandable. An insight into the basic types of failures, their causes, and practical solutions that must be implemented to repair is provided	A better organization of the content is needed, divided into appropriate subheadings for easier navigation and understanding, adapted to all users (both beginners and those who have been working with the given equipment for a long time) Given that there are certain technical terms that may be unknown to a wider range of users, it is necessary to add a glossary of terms for the technical terms used. Illustrations, drawings, pictures, and diagrams should be added to facilitate the understanding of the use of the equipment.
STAR LIFTKET	Very detailed data and instructions on assembly, use, and maintenance Technical - safety measures described in detail Sentences are clear, concise, well defined The importance of periodic checks and maintenance is emphasized A large number of illustrations for assembly and replacement of parts	Too much textual content, which can cause disinterest and fatigue in the reader of the manual It is necessary to insert pictures, drawings, and diagrams in the safety instructions, to facilitate understanding and clarity Extensive use of technical terms, so it is necessary to add a glossary of technical terms It is necessary to carry out a better overview of the types of failures, their causes, and solutions for eliminating them There is a lack of clearly specified procedures in cases where the equipment is not used in accordance with the instructions

Figures 2, 3 and 4 highlight the characteristic shortcomings of the given instructions, while Figure 5 shows a good example of the practice of creating operating instructions.

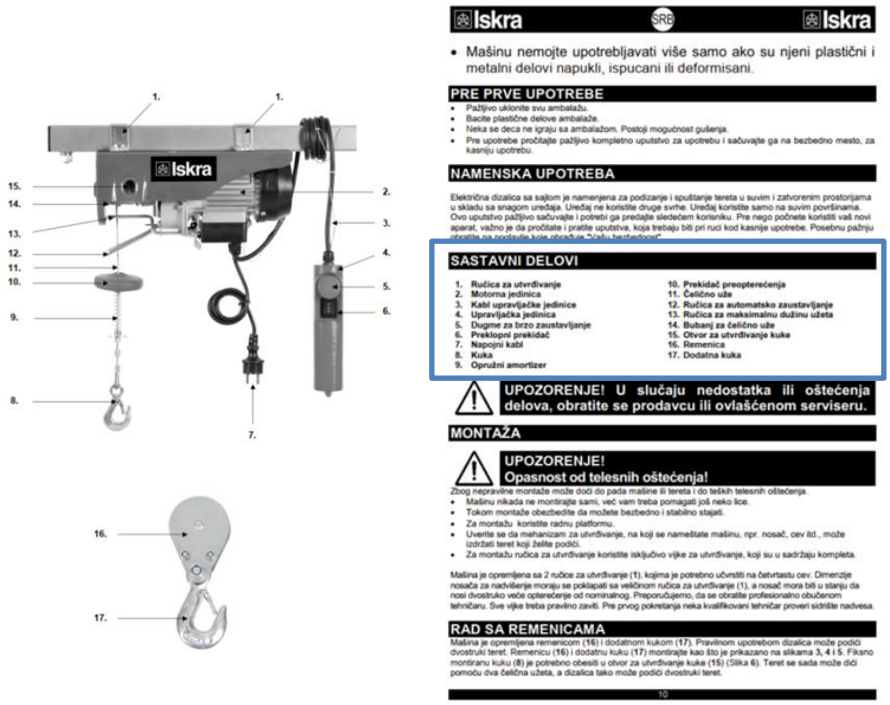

Figure 2. Instructions from the manufacturer ISKRA - The sketch of the marked parts of the electric hoist is at the very beginning of the instructions, while the meanings of those parts are only given at the end of the instructions (framed in blue)

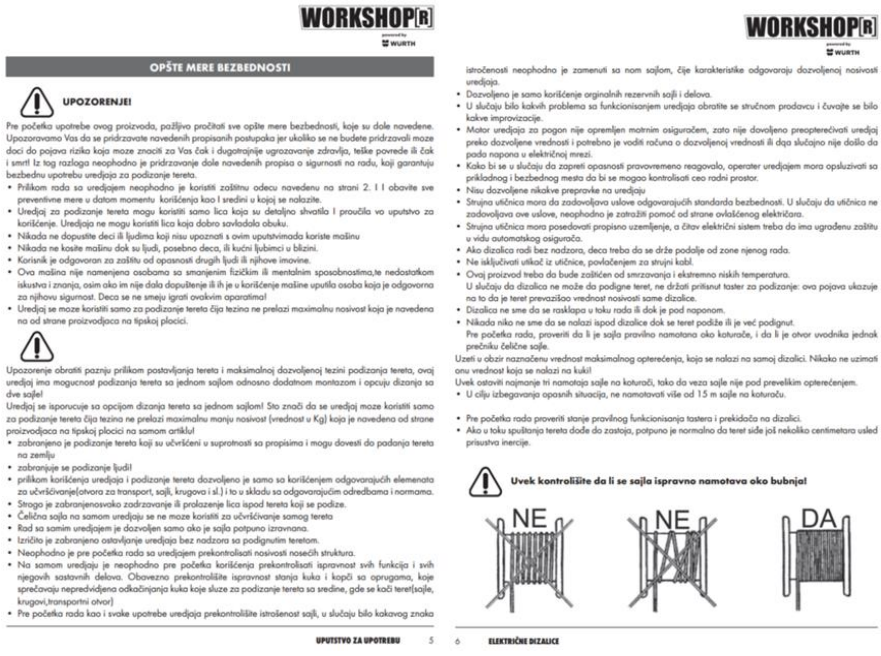

Figure 3. Instructions from the manufacturer WORKSHOP - Lots of textual content

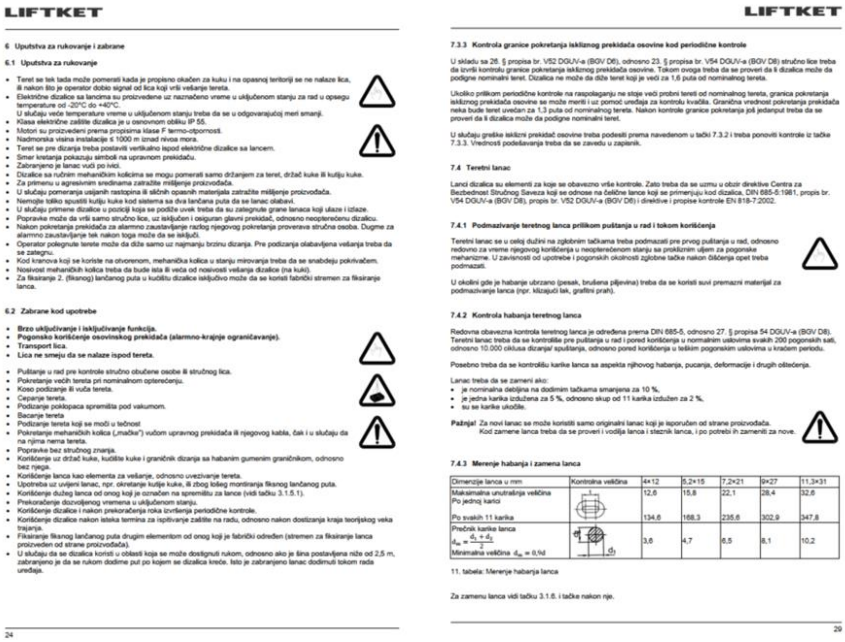

Figure 4. Instructions from the manufacturer STAR LIFTKET - In addition to the given textual content, it is necessary to include appropriate pictures and illustrations that would facilitate the safe use of electric hoists, there is also an overabundance of technical details and terms for which an adequate dictionary of technical terms is lacking.

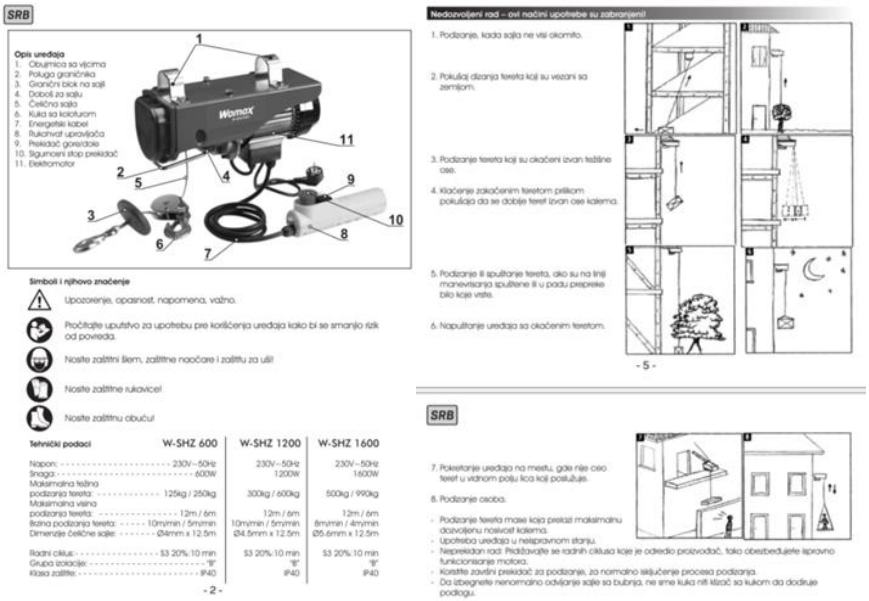

Figure 5. Instructions from the manufacturer WOMAX - Correctly formed content, meanings of parts with the sketch they represent, technical data at the beginning of the instructions (left), illustrations of illegal work - facilitate understanding and application (right)

Based on all of the above, as a conclusion from the comparative analysis of instructions for electric hoists from different manufacturers, the best-organized instruction is from WOMAX, for the reason that it is sufficiently concise, and clear, with all essential elements and by the aforementioned Directive. On the other hand, the instructions from the manufacturer ISKRA require a lot of reorganization, changes, and additions, in order to comply with the Directive [8]. Also, within the instructions from the manufacturer ISKRA, a formal non-conformity was observed - the lack of a declaration of conformity of the product and the CE mark, which represents a significant deficiency that requires immediate action by the manufacturer. Finally, it is important to point out that in all the instructions there is a lack of illustrations, pictures, and diagrams, the increase of which would have a significant effect on easier navigation and understanding when using the instructions for use.

5. CONCLUSION

The process of harmonizing lifting machines with the Directive and the national regulations, harmonized standards, and all other valid regulations in the given area is a key factor in ensuring the safety of lifting machines.

Special attention during the research was devoted to the analysis and comparison of instructions for the use of electric hoists from five different manufacturers (ISKRA, WOMAX, WORKSHOP, VILLAGER, and STAR LIFTKET), during which mutual comparisons were made of the quality of workmanship, content, organization of information, as well as comparisons with the basic principles and content of the instructions according to the Directive and the national regulations. Based on the comparison, it was concluded that certain manufacturers provide clear, structured, and illustrated instructions (e.g. WOMAX, WORKSHOP), while instructions from ISKRA require significant changes and improvements in terms of content reorganization and various additions (illustrations, tables), as well as removal of formal non-compliance (lack of Declaration of Conformity).

The research indicated that the Declaration of Conformity, CE marking, and correct preparation of instructions play an important role, both in fulfilling the requirements when placing the product on the market, and for increasing the safety of product users, better application of regulations, easier use of cranes and reducing the risk of injuries at work.

ACKNOWLEDGMENTS

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Research paper

CONSTRUCTION MATERIALS HANDLING SIMULATION – EFFECT ON PARTICULATE MATTER EMISSIONS

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Abstract

Airborne particulate matter, particularly PM10 represents a significant environmental and occupational health concern on construction sites. The research explores how different construction materials effects PM10 generation during handling activities. In the absence of field measurements, a simulation-based approach was applied using emission factors defined by authoritative sources, including the EMEP/EEA Guidebook and USEPA AP-42 methodology. Seven widely used materials were selected to represent diverse physical properties and usage profiles: Portland cement, gypsum board, sand, aerated concrete blocks, clay bricks, polystyrene insulation, and gravel. For each material, multiple simulations were performed under controlled assumptions, incorporating realistic background PM10 levels to replicate urban construction site conditions. A PM10 Emission Index was defined to normalize emission potential per unit mass of material handled. Results indicate that fine, low-density materials such as Portland cement and gypsum board exhibit the highest emission intensities, while coarse, dense materials such as gravel and clay bricks contribute significantly less to airborne particulate concentrations. The findings highlight the substantial variability in emission potential across materials and emphasize the importance of material selection in sustainable construction planning. These insights can guide policymakers and construction professionals in adopting low-emission materials and better on-site dust control strategies.

Key words: *PM10, Construction Site, Material Selection.*

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1. INTRODUCTION

Construction activities are among the most significant contributors to ambient air pollution in urban environments, especially in rapidly developing regions [1], [2]. Recent researches show that construction sites actively participate in particle pollution around 20% [3]. Among the various pollutants emitted, particulate matter with an aerodynamic diameter of 10 micrometers or less marked as PM10 is specific concern due to its adverse effects on both environmental quality and human health. PM10 can easily due to its size penetrate into the respiratory system, intensify chronic diseases, and reduce air quality far beyond the construction site perimeter [4], [5], [6], [7]. While legislative attention is traditionally focused on traffic, industry, and residential heating, recent studies underscore the growing role of construction sites as localized "hotspots" of dust and airborne particulate emissions [1], [8].

PM10 emission generated on construction sites has a wide range of sources: excavation, demolition, vehicle movement, and handling and processing of construction materials. Despite the availability of general emission factors and occupational exposure studies, relatively few researches have observed how the type of construction material itself affects dust emissions under typical site conditions. The lack of specificity limits the ability of planners and regulators to implement effective source-based mitigation strategies. The growing need to quantify and compare the emission potential of different materials, especially those commonly used in urban constructions across Central and Eastern Europe is essential for prevention model development.

The research addresses the gap by evaluating the influence of material choice on PM10 emissions during manual handling activities. The primary focus is on identifying which materials contribute most significantly to airborne PM10 concentrations in realistic site scenarios. The practical and logistical challenges of measuring emissions directly on active construction sites - especially those with high variability in operation, weather, and equipment indicated the utilization of a simulation-based approach grounded in internationally recognized emission modeling frameworks.

1.1. Material PM Emission Potential

Construction materials vary in their physical and chemical characteristics, which influence how easily they generate dust. Finer materials with low cohesion, such as cement and dry sand, are inherently more susceptible to wind erosion and mechanical disturbance. Equally, bulkier materials with larger particle sizes, such as gravel and solid bricks, tend to exhibit lower dusting potential due to their mass and structure [9], [10].

Recent researches have often addressed PM generation in the context of specific processes (e.g., concrete mixing, demolition), rather than attributing emissions to the material itself ([11], [12]). The researches rarely normalize emissions by the quantity of material handled, which limits comparability. As such, construction planners lack an evidence-based metric to assess the PM potential of materials when evaluating procurement options or preparing environmental impact assessments.

1.2. Limitations of Existing Data and the Role of Simulation

Field data on particle matter emissions from specific materials are scarce due to both technical and practical barriers. Construction sites are dynamic environments, with constantly changing activities, machinery, and meteorological conditions. Instrumentation capable of

distinguishing emissions from a single material amidst multiple sources is not only expensive but also requires specialized expertise. The challenges make field studies difficult to replicate and limited in scope.

In order to overcome mentioned limitations, simulation-based modeling has become an increasingly accepted method for emission estimation, particularly in planning and policy contexts. Emission models, such as those proposed by the U.S. Environmental Protection Agency [10] and the European Environment Agency [13] provide structured methodologies for determining emissions based on activity type, material properties, and environmental conditions.

2. MATHERIALS AND METHODS

2.1. Selection of Construction Materials

Seven construction materials commonly used in Central and Southeastern European building projects were selected based on their physical characteristics and relevance to typical construction phases (e.g., structural work, interior finishing, and insulation). The materials include:

- Portland cement (CEM I 42.5 R)
- Gypsum board (12.5 mm thick)
- Dry sand (0–2 mm)
- Aerated autoclaved concrete (AAC) blocks
- Clay bricks (standard perforated)
- Expanded polystyrene insulation (EPS)
- Gravel (16–32 mm aggregate)

The materials were chosen to reflect a range of particle sizes, densities, handling mechanisms, and application domains. All materials were assumed to be dry and handled in an open environment under typical dry-weather conditions, without mechanical dust suppression.

2.2. Simulation Design and Framework

Due to the lack of accessible, site-specific empirical measurements of PM10 emissions in Serbia and similar contexts, a simulation approach was implemented. The method allows for controlled, repeatable estimates of particulate emissions based on established emission factors and assumed conditions. It also aligns with recognized methodologies such as those in the EMEP/EEA air pollutant emission inventory guidebook [9] and the USEPA AP-42 Compilation of Air Pollutant Emission Factors (US EPA, 2011).

The simulation was built on the following steps:

- Baseline Background Concentration

The typical urban background PM10 level was assumed to be 75 $\mu g/m^3$, with a standard deviation of ± 5 $\mu g/m^3$, based on regional urban measurements near construction sites [1], [14], [15], [16].

- Activity Scenario

Each material was modeled under a standardized manual handling event (e.g., lifting, dumping, or pouring), replicating activities such as material transfer from pallet to site or from bag to mixer.

- Simulated PM10 Emissions

For each material, three simulated measurements were generated, incorporating variability due to handling intensity, particle cohesion, and environmental micro conditions. Values were generated based on known emission behavior (e.g., cement as a high-dust material) and informed by literature estimates where available [12], [17], [18], [19], [20], [21], [22].

- Net PM10 Concentration

The net PM10 contribution of each material was calculated (1) as the difference between the simulated measured concentration and the background value:

$$\text{Net PM10} = \text{Measured PM10} - \text{Background PM10} \quad (1)$$

- Normalization via Emission Index (EI)

To enable meaningful comparison across different material masses, a Particle Matter Emission Index (EI) was defined as:

$$EI = \frac{\text{Net PM10}(\mu g/m^3)}{\text{Mass handled (kg)}} \quad (2)$$

The index (2) expresses emission potential per kilogram of material and facilitates cross-material comparison.

Assumptions and Constraints were defined in order to provide case efficient modeling results:

- Dry Handling: All materials were assumed to be handled in dry conditions, maximizing potential dust generation (i.e., worst-case scenario).
- Open Site Conditions: Emissions were simulated for open-air handling with no dust suppression (e.g., no water spraying or enclosures).
- Short-Term Exposure: Simulations reflect momentary concentration spikes during material handling rather than long-term average exposure.
- No Wind or Atmospheric Dispersion Effects: Since the goal was relative comparison of emission potential, atmospheric dispersion modeling was not included.

Data simulation was carried out using custom scripts developed in Python, using pseudo-random number generation to represent variability in measured values. Mean and standard deviation parameters were assigned per material category based on review of prior literature and expert judgment. Each simulation consisted of three iterations per material to reflect handling variability.

3. RESULTS AND DISCUSSION

The simulation results revealed significant differences in PM10 emissions across the seven selected construction materials. Both the mean PM10 concentration during handling and the emission index (EI)—representing normalized emissions per kilogram—varied widely, reflecting distinct material characteristics and handling behavior (Table 1.).

Table 1. Modeling results for seven selected materials

Material	Mean PM10 (μg/m³)	SD PM10	Handled Mass (kg)	Mean EI (μg/m³*kg⁻¹)	SD EI
Portland cement	306,70	8,34	10,00	30,67	0,84
Gypsum board	135,28	15,22	12,00	11,27	1,27
Dry sand	116,26	10,31	15,00	7,75	0,69
AAC blocks	93,45	6,98	20,00	4,67	0,35
Clay bricks	60,94	9,55	30,00	2,03	0,32
Polystyrene (EPS)	47,90	47,90	5,00	9,58	0,67
Gravel (16–32 mm)	33,86	33,86	25,00	1,35	0,25

Portland cement simulation produced the highest mean PM10 concentration (306.70 μg/m³) and the highest emission index (30.67 μg/m³*kg⁻¹), defining its status as a primary source of airborne particulate matter on construction sites. The fine powdery texture and dry handling conditions make it highly susceptible to becoming airborne during mixing and transfer operations.

Gypsum board and dry sand also exhibited elevated emissions, with mean PM10 concentrations of 135.28 μg/m³ and 116.26 μg/m³, respectively. Their emission indices were substantial, emphasizing that not only fine powders, but also granular and friable materials, contribute to particulate release. Notably, gypsum board emissions likely result from mechanical degradation during cutting and fitting, which can vary depending on the condition and density of the material.

Surprisingly, polystyrene (EPS)—despite its low bulk density—exhibited a relatively high emission index, due to its tendency to fragment into micro-sized particles during trimming and installation. While the total PM10 concentration was modest (47.90 μg/m³), this finding supports concerns raised in recent literature regarding polymer-based materials as a source of non-mineral PM and microplastics in the air [23].

On the other end of the spectrum, gravel, clay bricks, and AAC blocks were found to emit the least particulate matter. Gravel's coarse particle size and cohesive structure contributed to its low mean PM10 concentration and the lowest EI making it an environmentally favorable material from an air quality perspective. Similarly, clay bricks and AAC blocks produced moderate absolute emissions but low emission indices suggesting they are relatively stable during handling.

The standard deviations in both concentration and EI highlight the variability introduced by material form and handling method. Materials with uneven surfaces or brittleness, such as gypsum board and bricks, showed greater variability in emissions, which could reflect differences in breakage or dust dispersion during handling (figure 1.).

These results highlight a few critical patterns. The most prominent is that emissions correlate strongly with material friability, particle size, and dryness rather than just the quantity handled. High EI materials pose significant environmental risks even at low usage volumes (e.g., EPS), whereas bulk materials like gravel or bricks contribute far less PM per unit mass. The emission index (EI) serves as a valuable normalization tool, enabling comparisons across diverse materials and facilitating more accurate planning and mitigation strategies.

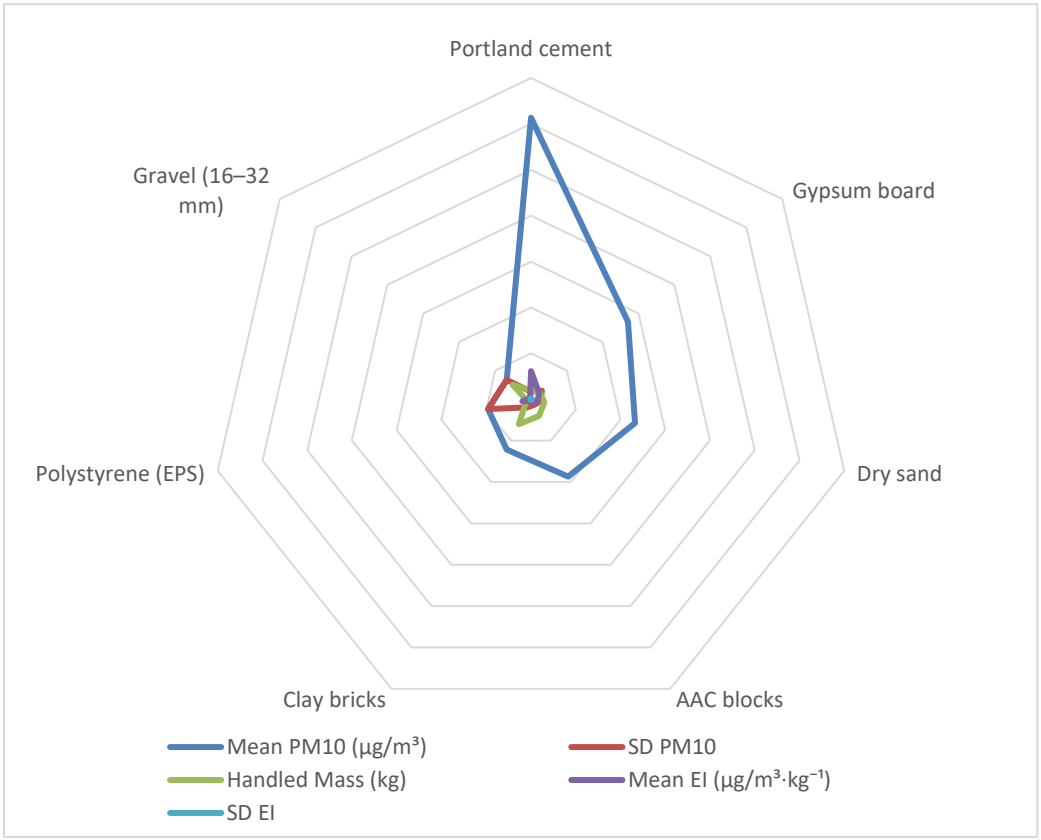

Figure 1. Selected materials modeled comparison.

The simulation model, although idealized, offers practical insights where empirical monitoring is constrained. It allows researchers and experts to estimate material-level impacts and prioritize dust control strategies based on simulated behavior.

4. CONCLUSION

The research demonstrates how the choice of construction materials significantly influences PM10 emissions during site handling operations. Fine-grained, dry, and friable materials such as Portland cement and gypsum board are major contributors to particulate pollution, whereas denser, coarser, and more cohesive materials like gravel and clay bricks pose a substantially lower emission risk.

The introduction of a simulated emission index (EI) provides a practical and scalable tool for comparing emission potential per kilogram of material, offering new insights for environmental impact assessments and construction site planning. While further validation against field data is needed, these results underscore the importance of integrating material-based emission factors into sustainable construction management and urban air quality mitigation efforts.

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Research paper

ENHANCING THE LEARNING ENVIRONMENT AND USERS EXPERIENCE IN ARCHITECTURAL EDUCATION AT NILE UNIVERSITY OF NIGERIA

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Abstract

As architecture education requires more dynamic, collaborative, and technologically linked environments, many Nigerian institutions continue to rely on traditional pedagogical models and ineffective physical infrastructure, limiting innovation and engagement. This study seeks to critically examine and improve the learning environment and user experience in architectural education at Nile University in Nigeria. The objective is to investigate how spatial design, learning environments, and user-centred strategies might be combined to provide more successful educational experiences for students and faculty. Following the theoretical underpining of constructivist learning theory, environment-behavior studies, user-centred design, and educational ergonomics, the study used a quantitative approach to collect empirical data through questionnaires (N=158) and spatial analyses to assess the current state of the Department of Architecture's learning environment. Indicative findings indicate the necessity for a comprehensive design and policy framework adapted to Nile University architecture students' particular needs and the university educational approach. The paper made recommendations for a design modelled after a 21st-century architectural learning environment that fosters creativity, well-being, multidisciplinary collaboration, and academic excellence. The significant of the study is that the structure will serve as a model for architecture education reform in Nigeria.

Key words: *Architectural Education, Design Studio, Learning Environment, User's Experience, Nigeria.*

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1. INTRODUCTION

Architectural education is essentially dynamic, requiring students to acquire theoretical knowledge as well as practical design abilities through experiential learning. It is a discipline that flourishes in settings that encourage creativity, critical thinking, and collaborative participation. In the framework of the 21st-century learning paradigm, institutions of higher education are increasingly being evaluated not only by their academic curricula but also by the quality of their learning environments and how well they support students' total educational experience [1,2]. In Nigeria, architecture education is at a critical juncture, demanding environments that stimulate creativity, critical thinking, and practical skills while simultaneously imparting theoretical information. The learning environment has a tremendous impact on students' academic achievement and overall experiences.

At the heart of architectural education is the design studio, a physical and intellectual place in which students interact, explore, and develop ideas under the guidance of mentors. The quality of this setting has been demonstrated to have a considerable impact on students' academic performance, creativity, and mental health [3-5]. However, anecdotal reports and preliminary observations from several Nigerian universities indicate that contemporary architectural learning spaces do not fully meet the pedagogical needs of students. Limitations in spatial flexibility, indoor environmental quality (IEQ), availability to digital design tools, and poor student-centered pedagogical practices all have an impact on the entire learning experience.

There is limited empirical information to determine if present architectural learning settings are optimised for such results. While national literature has revealed comparable tendencies [6-8], there is a lack of context-specific studies focusing on the lived experiences of students and faculty in many private university settings. Furthermore, there is limited empirical information to determine if present architectural learning settings are optimised for such results. Meanwhile, there are potential to improve these environments to better serve architectural students. At Nile University of Nigeria, there is a strategic opportunity to review and improve the current architectural learning environment in order to comply with global best practices while also responding to local contextual factors.

This study aims to critically examine the nature and quality of the learning environment, as well as the experiences of its users—both students and faculty—in order to propose actionable design and pedagogical interventions that are consistent with current global practices while taking into account local institutional realities. In addressing this issue, the study posed crucial issues such as (i) what are the current spatial, environmental, and pedagogical restrictions in the architecture department at Nile University? (ii) How do students and faculty view and interact with the current learning environment? (iii) What techniques might be recommended to improve the physical, digital, and experiential aspects of architecture education at the university?

The study tackles the critical need to examine, evaluate, and improve the learning environment and user experience in architecture education at Nile University, with the goal of aligning it with current worldwide trends while taking into account local institutional constraints. This study seeks to investigate strategies for improving the learning environment and user experience in architectural education at Nile University, with the objective of generating competent and innovative architects.

2. LITERATURE REVIEW

The effect of the learning environment on students' academic achievement has been extensively investigated. For example, Taylor [9] claimed that active learning activities can be adopted and supported in a conducive studio setting, hence improving the student's learning experience. In their study, Obeidat & Al-share [10] focused on the relevance of environmental variables such as the positive influence of lighting, noise management, and chair comfort while building the studio classroom. Meanwhile, Afara [11] explored how sitting design in the architectural studio influences creativity and productivity. This was regarded as the most significant for policy makers and educators. On the other hand, Alhusban et al., [12] highlighted important influential elements such as physical and administrative aspects that affect students' productivity in architectural design studios. The analysis revealed thermal comfort as the most prominent indices and most dominant among the numerous sub-factors of design.

Recent research in Nigeria have shown shortcomings in architectural education environments. These include restrictive studio layouts, poor interior environmental quality, outmoded teaching equipment, and inadequate digital integration [6,13,14]. Numerous writers [15-17] discovered that students' perceptions of their learning environment, such as participation in studies and perceived assistance, influenced their academic achievement. Furthermore, they discovered that the conducive and interactive nature of the learning environment has a significant impact on student satisfaction and academic success. Nonetheless, many architecture faculties continue to operate under old pedagogical models, with few changes to address the evolving demands of learners in a post-pandemic digital environment. Sen [6] researched architecture students' impressions of their learning environment in South-South Nigeria, and discovered that characteristics such as excellent teaching, collaborative learning, and academic organisation have a substantial impact on academic outcomes.

The integration of virtual learning environments has also been investigated and particularly accelerated by the covid-19 pandemic which brings about the transition toward blended learning. Owoseni et al. [7] and Mohammed et al., [8] investigated the impact of virtual learning during the covid-19 lockout, finding considerable gains in students' digital design capabilities and autonomous learning capacities.They discovered that, while virtual learning improved architectural students' autonomous learning and digital design skills, it also showed infrastructural and pedagogical deficiencies. The findings of their study imply the necessity to combine physical and virtual learning settings in order to improve architecture education; yet, this has added complexity.

In the domain of environments for increased learning in architecture, Akande et al. [5] contended that interactive spaces inside architectural departments have an important role in improving learning outcomes. In their research, they emphasised the significance of design studios in architecture education, advocating for environments that encourage immersion and collaboration. Because the design studio is central to architectural education while also serving as a hub for creativity, collaboration, and practical skill development, Owoseni et al., [3]; Gana & Akande [4] and Akande et al., [5] emphasise that well-designed studios improve student immersion and collaboration. They advocate for adaptable places that support a variety of learning activities and encourage connection. In addition, Al-Jokhadar et al., [13] and Asaju et al., [14] emphasise the importance of indoor environmental quality (IEQ) in

studio settings to improve academic performance, pointing out that factors such as lighting, ventilation, and acoustics have a direct impact on students' well-being and productivity.

2.1. Theoretical Framework

This study is based on numerous hypotheses that revolve around the intersection of three key dimensions: the physical environment, pedagogical practices, and user experience, all of which interact to define the quality of architectural education. To frame the analysis, the study uses principles from constructivist learning theory, environment-behavior studies, and user-centred design. According to constructivist learning theorists [18, 1], learners actively construct knowledge through spatial immersion, contextual experiences, and social interactions with their surroundings. This highlights the necessity for architectural studios to be adaptable and interactive in order to facilitate experience and collaborative learning. In architecture education, this entails engaging students in active, collaborative, and reflective learning experiences. The design studio, as highlighted by Akande et al., [5] is an important venue in which students can engage in problem-based learning and gain practical skills.

The environment-behaviour theory [19,20] investigates how spatial configurations, environmental quality (lighting, ventilation, and acoustics), and built-environment affordances influence human behaviour and performance. This is important in determining how the studio environment influences students' focus, creativity, and involvement. Donald [21] introduced the user-centred design framework, which emphasises developing places and systems around users' requirements, capabilities, and experiences. Using this premise, the study looks into how architectural learning spaces at Nile University may be improved based on feedback from both students and teachers. These theories contribute to a comprehensive framework in which the architectural learning environment is viewed as an active participant in the educational process rather than a passive container.The integration of physical, digital, and social learning aspects will be assessed in terms of how they improve—or degrade—user experience and academic results.

3. METHODOLOGY

3.1. Study Location

The study was done at Nile University of Nigeria in Abuja. Abuja is located in the Federal Capital Territory (FCT), Nigeria having latitude and longitude 9° 10' 32" N / 7° 10' 50" E. Nile University is a private post-secondary institution noted for providing architectural education in a modern campus setting. The university's Department of Architecture was chosen as the focal point due to its connection to the research issue and accessibility to the target audience (students and faculty).

3.2. Study Location

This study used a descriptive cross-sectional survey research approach, which is ideal for gathering quantitative data from a specific population at a single point in time [22]. The design enables the detection of patterns, linkages, and areas for development in the architectural learning environment and the user experience.

3.3. Study Location

A systematic questionnaire was created using relevant literature on architectural education, learning settings, and user-centred design [1,23]. The instrument was divided into these five sections: (i) Section A: Respondent information (status, age, gender, level/designation, and years of experience). (ii) Section B: Studio environment: space adequacy, lighting, acoustics, furniture, and preferred layout. (iii) Section C: Workshop and practical spaces, including availability, frequency of usage, equipment, and safety. (iv) Section D: Digital facilities, including computer labs, software access, and internet quality. (v) Section E: Overall learning experience - perceptions of learning support and opportunities for development.The questionnaire used Likert-scale questions, rating scales, and multiple-choice items to assure uniformity and ease of quantitative analysis [24]. A pilot research was done with 15 respondents (students and staff) from the department who were not included in the main sample. The pilot intended to identify unclear questions, ensure clarity, and assess the time required to complete the survey [25]. Minor changes were made based on feedback to improve the language and flow of the questions. The questionnaire was transformed into a Google Form and delivered digitally via a variety of communication channels (emails and WhatsApp groups). This method was chosen because of its low cost, extensive reach, and safe administration, which ensures prompt responses from both staff and students [26].

3.4. Study Location

The target population consisted of students and academic personnel from Nile University's Department of Architecture in Nigeria. The sample population survey ranged from responses from 100level to 400level undergraduate students, as well as academic professionals such as lecturers, professors, and studio/workshop coordinators. A purposeful sample strategy was used to ensure that only those actively involved in architectural teaching and learning took part. This strategy enabled data gathering from persons with firsthand knowledge and educated perspectives regarding the learning environment [27]. The study included a sample size of 158 people, including students and staff. The sample size is statistically sufficient to generalise findings within the department using confidence intervals [28,29]. The ratio of student to staff respondents represented their proportional distribution within the department.

3.5. Study Location

Over the course of three weeks, data were collected utilising a Google Form questionnaire. Automated data export allowed replies to be sent directly into an Excel file, which could then be loaded into SPSS for cleaning and analysis. Participation was optional, and ethical considerations were followed in accordance with the university's research ethics committee. The data was analysed with SPSS version 25. Responses were summarised using descriptive statistics including frequencies, percentages, mean scores, and standard deviations. Likert-scale responses were treated as interval data when comparing means.

3.6. Study Location

Cronbach's Alpha was employed in SPSS to assess the internal consistency of the Likert-scale items in order to ensure questionnaire reliability. A threshold of $\alpha > 0.70$ was deemed

appropriate [30]. The pilot investigation produced an alpha value of 0.866 (Table 1), indicating strong dependability.

Table 1. Reliability and Validity of the Questionnaire

Section	Cases	Reliability	Interpretation
Section B Q8	6	0.828	Strongly Reliable
Section B Q11	7	0.715	Strongly Reliable
Section C Q15	4	0.845	Strongly Reliable
Section C Q18	5	0.858	Strongly Reliable
Section E Q19	3	0.825	Strongly Reliable
Section E Q20	6	0.921	Highly Reliable
Overall	31	0.866	Strongly Reliable

For content validity, specialists in architecture education and research methodology assessed the questionnaire to verify that it included all essential features of the learning environment [31]. In terms of face validity, pilot study participants agreed that the questionnaire was clear, relevant, and representative of the domain under research.

4. RESULTS

4.1. Demographic information of the respondents

Table 2 shows the demographics of the respondents. The following findings are extracted from the table (i). The user composition revealed that 96.2% of responders are students, with only 3.8% being instructional personnel. This clearly demonstrates a student-centric feedback pool, implying that any changes to the learning environment should prioritise student requirements, perceptions, and learning styles. (ii) Gender representation is 50% male and 50% female. This equal gender representation enables the findings to be regarded as gender-neutral, resulting in inclusive design recommendations. This finding is consistent with that of Dovey and Fisher [32] who found that gender equity in educational contexts had a favourable effect on engagement and satisfaction. As a result, design interventions must take into account both genders' spatial, ergonomic, and social preferences. (iii) The age distribution shows that 80.4% of respondents are under the age of 20, 15.8% are between the ages of 21 and 30, 1.3% are between the ages of 31 and 40, and 2.5% are 41 and older. The age profile suggests a largely young student population, most likely in their early academic years. Jamieson et al. [33] and Jelić et al. [34] found that younger architecture students require more direction, flexible learning spaces, and engaging studio experiences to stimulate creativity and collaboration.

Table 2. Reliability and Validity of the Questionnaire

Demography	Frequency	Percentage
Status		
Student	152	96.2
Teaching Staff	6	3.8
Gender		
Male	79	50
Female	79	50
Age		
Under 20	127	80.4
21-30 Years	25	15.8
31- 40 Years	2	1.3
41 And Above	4	2.5
Academic Level		
100l	68	43
200l	45	28.5
300l	21	13.3
400l	24	15.2

(iv) Academic level distribution: 43% at 100 level, 28.5% at 200 level, 13.3% at 300 level, and 15.2% at 400 level. This means that a sizable proportion of responses are first-year (100 level) students, implying that first impressions and foundational experiences in studio settings are critical. According to Zeisel [20] physical learning settings have a substantial impact on newcomers' comfort and involvement. As a result, the design studio should be carefully constructed to help early-stage students transition into architectural thinking and practice.

4.2. Suitability and Functionality of the Architectural Design Studio Environment

To evaluate the suitability and functionality of the architectural design studio environment in terms of space, lighting, ventilation, furniture, acoustics, and technical infrastructure, a 5-point Likert scale was used with ratings of 'excellence', 'good', 'fair', 'poor', and 'very poor'. The ratings were assigned weights of 5, 4, 3, 2, and 1, respectively. Table 3 displays the functionality of the architectural design studio setting as reported by respondents. The judgement for each scale is presented as (5. ≤x ≤ 4.51) as excellence, (4.45 ≤x ≤ 3.51) as good, fair as (3.45 ≤ x ≤ 2.51), bad as (2.45 ≤ x ≤ 1.51), and very poor as (1.44 ≤ x≤ 0), where x is the variable of interest. As seen in Table 3, the lighting (mean = 4.20 - good). The vast majority (84.8%) assessed the illumination, both natural and artificial, as good or excellent. According to Jamieson *et al.,* [33] well-lit learning spaces boost concentration and mental health. The findings imply that the architectural studios at Nile University are visually conducive to design activities, which is vital in architectural education where visual clarity is important. The ventilation component (mean = 3.47 - fair) had the lowest average assessment, with just 53.2% rating it as good or excellent and more than 30% expressing displeasure.

Table 3. Adequacy and functionality of the architectural design studio environment

Feature	Excellent	Good	Fair	Poor	Very Poor	Mean value	Decision
Natural and artificial lighting	62 (39.2)	72 (45.6)	19 (12)	3 (1.3)	2 (1.2)	4.2	Good
Ventilation	26 (16.5)	58 (36.7)	48 (30.4)	17 (10.8)	9 (5.7)	3.47	Fair
Acoustics	19 (12)	91 (57.6)	37 (23.4)	7 (4.4)	4 (2.5)	3.72	Good
Furniture (tables/chairs/desks)	25 (15.8)	69 (43.7)	48 (30.4)	11 (7)	5 (3.2)	3.62	Good
Power outlets and Wi-Fi access	23 (14.6)	48 (30.4)	45 (28.5)	23 (14.6)	19 (12)	3.21	Fair
Cleanliness and maintenance	37 (23.4)	76 (46.1)	33 (20.9)	8 (5.1)	4 (2.5)	3.85	Good

According to environmental behaviour theory [35], insufficient ventilation can cause pain, weariness, and limited creativity, particularly during protracted studio sessions common in architecture education. Acoustics (mean = 3.72 - good): Almost 70% of respondents assessed acoustic functionality as good or outstanding. This is consistent with Salama's [1] argument that favourable acoustic settings promote focused work, effective communication, and collaborative learning, particularly in studio-based courses. However, acoustic concerns may still exist for the remaining 30%, particularly in open-plan studios. Furniture (mean = 3.62 - good) was rated "good," but only 15.8% rated it excellent, and 10% rated it bad or extremely poor. This is consistent with Vygotsky's Constructivist learning theory (1978), which states that adaptive and ergonomic furniture promotes peer interaction and active learning. Inadequate or stiff furniture may impede creative development and prolonged studio use. Power outlets and Wi-Fi (mean = 3.62 - decent) Only 45% ranked this as good or excellent, but more than 26.6% rated it bad or very poor, indicating widespread unhappiness. In the digital age of architectural education with software like AutoCAD, Revit, Rhino, and cloud-based tools, access to reliable electricity and internet is crucial (Jelić et al., 2016). These low ratings point to a serious deficit in technological infrastructure. Cleanliness and maintenance (mean = 3.85 - good): Nearly 70% of respondents rated this component good or outstanding. According to Zeisel [20] clean and well-maintained rooms generate a sense of ownership and professionalism among architecture students, increasing productivity and learning pleasure.

To examine how the functioning of the design studio setting affects students' academic productivity, creativity, and collaborative learning experience. Kendall's Tau-b correlation results were conducted, and the results are shown in Table 4. Kendall's Tau-b correlation analysis demonstrates statistically significant links between numerous physical qualities of the design studio setting and important components of students' learning experiences, such as academic productivity, creativity, and collaborative learning. Significant positive relationships were discovered between natural and artificial lighting, collaborative learning (τ =.212, p =.003), and access to online tools (τ =.186, p =.007). This shows that well-lit spaces promote better peer interaction and provide digital learning assistance. Ventilation significantly correlated with academic productivity and creativity (τ =.178, p =.009),

collaborative learning (τ =.249, p <.001), and online tool availability (τ =.233, p <.001). These findings demonstrate that thermal comfort and air quality have a substantial impact on cognitive function and social engagement in studio environments. Acoustics had a positive correlation with academic productivity and creativity (τ =.160, p =.023), collaborative learning (τ =.299, p <.001), open-plan layout preference (τ =.146, p =.037), and access to online tools (τ =.166, p =.016). This emphasises the requirement for well-balanced soundscapes that promote focus and communication.

Cleanliness and maintenance were significantly associated with academic output (τ =.245, p <.001), collaborative learning (τ =.181, p =.009), and access to internet tools (τ =.182, p =.007). Thus, a clean, well-maintained environment promotes physical well-being and long-term involvement. The results can be understood through multiple theoretical lenses: (i) Maslow's Hierarchy of Needs (1943), which states that physiological comfort and safety—facilitated by sufficient ventilation, lighting, cleanliness, and ergonomics—are requirements for cognitive and creative endeavours in education [36]. (ii) These findings confirm Kolb's Experiential Learning Theory of 1984, which states that physical contextual elements promote active, reflective, and collaborative learning processes that are essential to architecture education [37]. (iii) Piaget and Vygotsky's Constructivist Learning Theories are also consistent with these findings, as the physical learning environment influences how students interact, co-create knowledge, and learn socially in the design studio [38-39].

4.3. Availability, Suitability, and Effectiveness of Workshop and Practical Spaces

To assess the availability, suitability, and effectiveness of workshop and practical spaces (e.g., modelling studios, 3D printing, wood/furniture workshops) in facilitating hands-on learning and architectural model creation. Respondents were asked to list the practical and workshop facilities accessible to them. As shown in Table 5, the analysis indicated that all key workshop and practical spaces were allegedly available and in active use, indicating that Nile University's architecture curriculum has adequate infrastructure. The breakdown of usage patterns demonstrates a diverse interaction throughout the available facilities. The Modelling Workshop Studio was identified as the most frequently used space, with 20.67% (117) of replies indicating its use. This emphasises the ongoing necessity of physical model-making in developing spatial reasoning, creativity, and architectural conceptualisation. Following that, 16.96% (96) of respondents reported using 3D Printing/Fabrication Labs, indicating a rising integration of digital fabrication technologies within the curriculum, which is consistent with global movements towards computational design and digital production. The Photographic Studio was responsible for 13.07% (74) of consumption. Its significance in visual recording and presentation promotes reflective practice and the creation of professional portfolios.

Table 4. Influences students' academic productivity, creativity, and collaborative learning experience

Functionality of the design studio environment			The current studio environment impacts my academic productivity and creativity	The current design studios adequately support collaborative learning and peer interaction	Open-plan collaborative workspaces types of studio layout best enhance my learning, creativity and productivity	Individual enclosed workspaces type of studio layout best enhances my learning, creativity and productivity	A combination of open and enclosed spaces types of studio layout best enhances my learning, creativity and productivity	I prefer the design studio should integrate outdoor learning spaces	Student have access to online architecture learning tools
Kendall's Tau_B	Natural and Artificial Lighting	Correlation Coefficient	.131	.212**	.113	.093	.121	-.008	.186**
		Sig. (2-Tailed)	.066	.003	.109	.179	.084	.911	.007
	Studio Space Per User								
	Ventilation	Correlation Coefficient.	.178**	.249**	.128	.174**	.130	.039	.233**
		Sig.	.009	.000	.059	.009	.053	.567	.000
	Acoustics	Correlation Coefficient.	.160*	.299**	.146*	.064	.102	.101	.166*
		Sig.	.023	.000	.037	.354	.143	.146	.016
	Furniture	Correlation Coefficient.	.205**	.229**	.140*	-.018	.139*	.026	.136*
		Sig.	.003	.001	.041	.790	.042	.708	.044
	Power Outlets and Wi-Fi Access	Correlation Coefficient.	.148*	.227**	.198**	.097	.132*	.118	.178**
		Sig.	.029	.001	.003	.139	.048	.077	.007
	Cleanliness and Maintenance	Correlation Coefficient.	.245**	.181**	.080	.075	.132	.113	.182**
		Sig.	.000	.009	.245	.267	.054	.099	.007
		N	158	158	158	158	158	158	158

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).

Furthermore, 12.72% (72) of students used Virtual Reality (VR)/Augmented Reality (AR) studios, demonstrating that immersive technologies are increasing popularity as powerful tools for spatial visualisation, user experience simulation, and participatory design.

Table 5. Availability, Adequacy, And Use of Workshop and Practical Spaces

Workshop and Practical Spaces	Frequency	Percentage
Modelling Workshop Studio	117	20.67
Photographic Studio	74	13.07
Wood/Furniture Workshop	59	10.42
3D Printing/Fabrication	96	16.96
Masonry Workshop	26	4.59
Building Material/Systems Lab.	56	9.89
Exhibition Workshop Space/Room	62	10.95
Virtual Reality/Augmented Reality Studio	72	12.72
Others	4	0.71

The Exhibition Workshop Space was used by 10.95% (62%) of respondents, demonstrating the importance of design critiques, public participation, and peer-to-peer learning through exhibitions. The Wood/Furniture Workshop (10.42%, 59 respondents) and Building Materials/Systems Laboratory (9.89%, 56 respondents) were also moderately used, highlighting the importance of tactile learning settings that allow for material experimentation and building detailing. The Masonry Workshop, albeit the least used (4.59%, 26 responders), demonstrates an ongoing desire for traditional and structural material handling procedures, albeit on a lesser scale.

4.4. Assessment of Priority Areas for Urgent Intervention in the Architectural Learning Environment

To better determine areas that require essential improvement, students were asked to rank the urgency of intervention across various components of Nile University's architectural learning environment. As shown in Table 6, the replies provide useful information about user experiences and the perceived adequacy of infrastructure and pedagogical resources. According to the data, Wi-Fi and internet infrastructure were identified as the most crucial subject requiring immediate attention, with 50.0% of respondents rating it as extremely important and a mean score of 4.03, the highest of any category. This emphasises the critical role of internet connectivity in facilitating architectural research, digital design workflows, and access to online educational resources. Closely following this, digital software access (mean = 3.67), mentorship and practical sessions (mean = 3.76), and workshop/model-making space (mean = 3.64) were also rated highly for perceived necessity. These findings indicate that students want both technical tools and practice-oriented interaction with the architecture curriculum. The design studio environment, the traditional centre of architectural education, had a mean score of 3.58, indicating that a sizable proportion of students (31.6%) believe its urgent repair is critical. While this remains a priority, it has been eclipsed by worries about digital infrastructure and experiential learning assistance. Computer laboratories, on the other hand, received a middling rating, with a mean score of 3.46, indicating that, while still relevant, students may prefer access to personal or mobile computing tools over traditional

lab settings. This trend shows a shift in learning preferences towards adaptable and personalised digital settings.

Table 6: Priority Areas for Urgent Intervention in the Architectural Learning Environment

Priority Areas	EI	VI	MI	SI	NI	Mean Value	Decision
The Current Design Studio Environment	50 (31.6)	38 (24.1)	36 (22.8)	22 (13.9)	12 (7.6)	3.58	Very Important
The Workshop/ Model-Making Space	46 (29.1)	52 (32.9)	26 (16.5)	25 (15.8)	9 (5.7)	3.64	Very Important
The Computer Laboratory	39 (24.7)	42 (26.6)	42 (26.6)	26 (16.5)	9 (5.7)	3.48	Moderately Important
The Digital Software Access	49 (31)	48 (30.4)	30 (19)	22 (13.9)	9 (5.7)	3.67	Very Important
The Wi-Fi And Internet Infrastructure	79 (50)	39 (24.7)	15 (9.5)	15 (9.5)	10 (6.3) S	4.03	Very Important
The Mentorship and Practical Sessions	58 (36.7)	40 (25.3)	35 (22.2)	14 (8.9)	11 (7)	3.76	Very Important
NI= Not at all important, SI= Slightly Important, MI= Moderately Important, VI= Very Important and EI= Extremely Important							

The relative importance index, calculated using the formula below, was used to prioritise the parts of the architectural learning environment that require immediate intervention based on students' and staff opinions.

$$\mathrm{RII} = \frac{\sum \mathrm{W}}{\mathrm{A}*\mathrm{N}} \quad (1)$$

where:
w = weight given to each statement by the respondent
a = highest response integer which is 5
n = total number of respondents = 158

Table 7 shows the ranking of areas requiring immediate attention. A comparative analysis of architectural learning environment components reveals a prioritised hierarchy of

needs as viewed by students and faculty. Wi-Fi and Internet infrastructure were ranked first in terms of the necessity of intervention, followed by mentorship and practical sessions, digital software access, workshop/model-making facilities, and computer laboratories. Wi-Fi and Internet Infrastructure – Ranked first, this indicates the growing reliance on cloud-based design tools, digital collaboration platforms, and remote access to resources. The mean score of 4.03 supports this priority, demonstrating that connectivity is not only supplementary, but also necessary for effective architectural learning.

Table 7: Ranking of areas requiring urgent intervention

Areas requiring urgent intervention	ΣW	RII	RANK
The current design studio environment	566	0.716	5
The workshop/model-making space	575	0.728	4
The computer laboratory	550	0.696	6
The digital software access	580	0.734	3
The wi-fi and internet infrastructure	636	0.805	1
The mentorship and practical sessions	594	0.752	2

Mentorship and Practical Sessions – The second-ranked component emphasises the importance of hands-on experience and exposure to the real world. The prioritisation of mentorship implies a realisation of gaps between academic learning and practical application, emphasising the importance of enhanced student-mentor engagement. Digital Software Access — This outcome, ranked third, demonstrates the critical importance of access to specialised software in modern architecture education. This desire is reinforced by the use of powerful digital design tools, graphics programs, and simulation software. Workshop/Model-Making Spaces — Despite being placed fourth, these spaces remain significant. Model-making serves as a concrete link between conceptual thinking and physical realisation, which is a fundamental element of architectural education. Computer Laboratories — The least prioritised, this reflects a larger trend towards mobile computers and decentralised access. Students are increasingly reliant on personal devices and flexible access, rather than fixed-location labs.

5. DISCUSSION

The demographic data revealed that the architectural learning environment at Nile University is mostly inhabited by young, entry-level students, the majority of whom are under the age of 20 and in their early years. This conclusion emphasises the importance of a student-centered design strategy in which physical spaces are customised to promote exploration, guided mentorship, and collaborative learning [18,1]. Given the developmental stage of these students, the studio and digital settings must encourage curiosity, creativity, and comfort by providing access to natural light, current equipment, adaptable furniture, and designated areas for individual and group activity. The implication is consistent with Environmental Behaviour Theory [35], which argues a reciprocal interaction between users and their surroundings. The evaluation of the physical learning environment shows that while students expressed general satisfaction with studio lighting, acoustics, cleanliness, and furniture quality, major concerns were raised about insufficient ventilation and unreliable technological infrastructure. These shortcomings are especially concerning given that

architectural pedagogy relies largely on continuous digital access and physical comfort for creative output [40-41]. According to Constructivist Learning Theory [18], physical impairments limit the learner's ability to fully connect with their surroundings and impede experiential learning. As a result, fixing these infrastructural gaps through user-centred, theory-driven design would improve academic performance and learner satisfaction. In terms of the role of hands-on learning and studio culture, the research findings support the importance of experiential and reflective learning processes in architectural education. The regular use of conventional model-making rooms, wood workshops, masonry labs, and photographic studios lends credence to Kolb's [37] Experiential Learning Theory. Furthermore, the presence of exhibition studios and criticism sessions is consistent with Schön's [42] Reflective Practitioner Model, which emphasises iterative learning via feedback and representation. The adoption of digital tools such as VR/AR studios, 3D printing laboratories, and parametric software aligns with Oxman's [43] call for hybrid learning ecosystems that mix analogue and digital abilities. This change is not only necessary, but also represents current architectural practices. The digital gap is centred on infrastructure, access, and autonomy; a striking finding from the survey is that students place a high priority on enhanced Wi-Fi and digital access. According to Siemens' [44] Connectivism Theory, digital networks are now essential for knowledge creation and collaboration. The study's findings indicate that having access to a dependable internet connection, design tools, and collaborative digital platforms is crucial for studio success and peer-to-peer learning. Interestingly, the low priority given to computer laboratories reflects a paradigm shift towards personalised, mobile learning environments, compatible with the Student-Centered Learning Model [40]. Students appear to prefer the liberty and convenience of using their own devices to typical lab settings. Students emphasised the importance of mentorship and experiential learning, ranking it second only to internet infrastructure in terms of intervention priority. This identifies a critical pedagogical need in architectural education: structured, experiential contact with professors and industry experts. Kolb's [37] theory states that learning is most effective when students actively participate in tangible situations and receive guided reflections. This desire is consistent with the need to improve faculty-student connection through crit sessions, design reviews, and collaborative projects, which are essential components of a strong studio culture [1]. The synthesis of priorities and strategic implications demonstrated that prioritising needs—Wi-Fi, mentorship, software access, workshop/model-making spaces, and computer labs—provides a strategic intervention roadmap. It illustrates the essential realignment of resources to meet changing student expectations and modern teaching approaches. These findings are consistent with Salama [1] and Owoseni et al., [3], who emphasised the necessity of balancing physical comfort with spatial and pedagogical flexibility. Furthermore, Wong [41] emphasised that often-overlooked factors such as acoustics and cleanliness have a substantial impact on students' cognitive and emotional states in educational settings. This conversation demonstrates a distinct movement in Nile University's architecture education towards hybrid, experiential, and student-centered learning. Addressing infrastructure inadequacies and integrating the studio setting with current educational theories would improve learning outcomes and user happiness.

6. RECOMMENDATIONS

The following recommendations are presented to improve the quality of architecture education and learning at Nigeria's Nile University. (i) Future studio space designs and adaptations should focus on modular, adaptable studios outfitted with ergonomic and gender-inclusive furnishings. Spatial zoning should be implemented by defining critique, focus, and cooperation zones. Biophilic characteristics (natural lighting, indoor plants) should be prioritised to improve user well-being. In addition, lighting, ventilation, and acoustic systems should be upgraded to increase user comfort and cognitive performance. (ii) To improve the user's learning experience, digital infrastructure and technology integration must be strengthened, including Wi-Fi bandwidth and power infrastructure throughout. There should also be provisions for universal access to important software (for example, current versions of AutoCAD, Revit, Rhino, and Adobe Suite). In addition, the institution should encourage cloud-based access and virtual desktop infrastructure for off-campus use. (iii) Emphasis should be placed on continual curriculum and learning. Innovation that should promote multimodal learning by combining physical model-making with digital simulations and mixing real-world transdisciplinary projects into several workshop settings. (iv) Staff and student co-design engagement should be encouraged through the creation of platforms that enable staff and students to collaborate on learning environments. Furthermore, professors should participate in design feedback loops and space planning. (v) The value of mentorship and industry connections should not be underestimated; this might be accomplished by developing a mentorship program in the department that includes professional and practicing architects as well as alumni. Externships and practical sessions should also be scheduled on the academic calendar. (vi) Feedback and monitoring measures, as well as semesterly spatial satisfaction surveys and usage evaluations, should be conducted on a regular basis. A student-staff committee should be formed to assess facility needs and make timely recommendations to management as needed. By combining these physical, digital, pedagogical, and administrative measures, Nile University can create a dynamic, inclusive, and future-ready architecture education environment.

7. CONCLUSION

This study investigated strategies for improving the learning environment and user experience in architectural education at Nile University, with the objective of generating competent and innovative architects. Improving the learning environment and user experience in architectural education at Nile University of Nigeria necessitates a planned and multidimensional approach. The study finds that, while present studio conditions support basic functionality, there are severe inadequacies in digital infrastructure, ventilation, and spatial adaptability. A user-centred, theory-informed design of learning environments, which incorporates environmental psychology and constructivist concepts, can greatly boost student engagement, creativity, and academic achievement. Prioritising digital access, ergonomic studio upgrades, and mentorship opportunities will align Nile University's architecture education with worldwide best practices, creating a more accessible, innovative, and forward-thinking academic environment.

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Research paper

AN EXAMINATION INTO THE ARCHITECTURAL ELEMENTS THAT PROMOTE ENERGY EFFICIENCY IN RESIDENTIAL BUILDINGS IN ABUJA, NIGERIA.

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Abstract

The steady rise in energy usage within Nigeria's residential building sector has raised concerns about sustainability, cost-efficiency, and environmental damage. This paper examined the architectural features that contribute to energy efficiency in residential structures in Asokoro, an affluent neighbourhood in Abuja, Nigeria. The objective was to evaluate how design elements including building orientation, fenestration, shading devices, insulation, natural ventilation, and material choices influence energy demand for lighting and cooling. The study uses field questionnaires (N=140) to identify current design approaches and assess their effectiveness in reducing energy use. The findings show that completely integrated passive design in residential buildings is rather uncommon in Abuja, Nigeria. This reveals a considerable disparity between the building's design aims and performance achievements for decreasing energy use. This is attributable to a variety of causes, according to the findings, including the perception of high initial costs, which discourages developers and clients who prioritise short-term budgets above long-term energy savings. Other issues include overreliance on mechanical systems and insufficient regulatory enforcement. The study proposes context-specific design principles for improving energy performance, reducing reliance on fossil fuel-based energy, and improving environmental sustainability in Abuja's residential sector. The study's significance lies in the fact that architects, developers, and policymakers would be more informed about adopting energy-efficient architectural design, practices, and construction, particularly in increasingly urbanising countries like Nigeria.

Key words: *Architectural Elements, Energy Efficiency, Passive Design, Residential Buildings, Nigeria.*

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1. INTRODUCTION

There is a global problem, as well as a unique concern in Nigeria, with regard to energy usage in residential buildings. According to the International Energy Agency, buildings account for around 40% of total global energy consumption, with residential buildings accounting for the vast majority of this consumption in Nigeria [1]. The built environment is currently thought to be the world's largest single user of energy, with residential buildings making significant contributions. Chen *et al.* [2], expressed that buildings account for around 40% of global energy consumption, with heating, cooling, lighting, and residential appliances accounting for a significant portion of overall energy demand. In Nigeria, growing urbanisation has produced an urgent demand for home energy, putting strain on the national infrastructure and resulting in frequent power outages [3]. The residential sector accounts for approximately half (50%) of Nigeria's overall energy use, mostly through heating, cooling, lighting, and appliances [4].

In parts of Nigeria's climates with exceptionally high temperatures, air conditioning is a significant energy consumer. However, when properly used, shading devices and cross-ventilation can significantly reduce indoor temperatures and energy demand. Yusuf and Akande [5], opined that material choices, notably high-performance insulation, energy-efficient glass, and locally produced materials, can improve a building's thermal efficiency and sustainability. As a result, architectural design is critical to achieving energy efficiency in residential buildings. According to Akande [6] and Yusuf & Akande [7] studies on passive design principles, good building orientation, thermal mass utilisation, the use of shading devices, and facilitating cross-ventilation have all proved effective in reducing reliance on mechanical heating and cooling systems. Abuja requires between 400 and 500 MW of energy every day, but only receives 200 to 300 MW, resulting in unpredictable power interruptions.

The argument and the emphasis of this study predicated on the importance of promoting energy efficiency in buildings, particularly residential buildings where people spend the majority of their time. Meanwhile, research on architectural components that promote energy-efficient housing in Abuja is severely inadequate, despite the fact that energy-efficient housing solutions are desperately needed [8]. Furthermore, compliance with current energy-efficiency requirements is often low. In accordance with the Nigerian Building Energy Efficiency Code (BEEC), energy efficiency was not attained throughout the mass construction of Abuja housing developments, revealing a significant gap between policy and reality [5]. Thus, the existing dearth of research into energy-efficient design aspects in Abuja structures is most likely contributing to the ongoing energy problem [8]. Again, without context-specific methods, architects and politicians will lack the tools required to implement effective energy-saving measures in residential structures [8].

This study aims to close the gap by looking into architectural elements that reduce energy efficiency. The purpose is to research architectural components that promote energy efficiency in residential building designs in Abuja, Nigeria, with the intention of lowering energy usage. The objectives are to: (i) determine the extent to which energy-efficient architectural components are integrated into residential buildings. (ii) investigate the impediments to the implementation of energy-efficient architectural features. (iii) evaluate the use and efficacy of smart building technology.

2. LITERATURE REVIEW

Existing research [6,7,9-15] have extensively investigated both passive and active solutions for lowering energy usage in Nigerian residential structures. One major limitation in these studies is the limited evaluation of passive design solutions in Nigeria's high-income residential neighbourhoods. For example, Yusuf and Akande [7] did a study on passive cooling solutions but purposefully excluded urban areas like Abuja from their coverage. This omission creates an important study gap on the effectiveness of passive cooling techniques, such as shading devices, natural ventilation, and thermal mass, in Abuja's high-density housing complexes. While these solutions have been successful in other places with similar conditions, their applicability in Abuja's current architectural context is unknown. The dearth of empirical studies on how passive energy-saving methods interact with new dwelling typologies in Abuja emphasises the importance of context-specific research.

Other studies have focused on broad theoretical frameworks or foreign case studies, with little research on their usefulness in Nigeria's unique meteorological and socioeconomic settings [16,17]. As a result, there is a scarcity of localised data on how energy-efficient architectural elements function in Abuja's urban housing sector, where factors such as high energy consumption, financial limits, and policy limitations influence the adoption of sustainable building methods. In terms of active energy-efficient technologies, such as smart building systems and renewable energy integration, Oyedepo [18] evaluated the feasibility and economics of current building technologies in Nigerian homes. The available studies primarily focus on commercial or public structures, with little emphasis on high-end dwellings. Meanwhile, the financial consequences, technical limits, and policy support needed to integrate smart energy management systems, automated shading, and renewable energy solutions into Abuja's housing constructions are largely unknown [19,20]. This creates another significant gap in the assessment of active energy-efficient technology, such as smart building systems and renewable energy integration, in Nigeria's luxury residential market. Thus, understanding the viability of these technologies in Abuja's socioeconomic setting is critical for supporting sustainable residential architecture in Nigeria.

There may be a further deficit in policy-related studies on energy-efficient housing in Abuja. While worldwide studies such as the IEA [1] have emphasised the relevance of government incentives and regulatory frameworks in encouraging sustainable architecture, little study has been conducted to investigate how Nigerian policies influence the adoption of energy-efficient home design. Numerous researchers [21,22] have noticed insufficient building code enforcement, a lack of financial support for households investing in green technologies, and ineffective awareness initiatives. According to their results, these factors have contributed to a sluggish adoption of sustainable housing options in places such as Abuja. Addressing these policy gaps will provide valuable insights into how regulatory measures might be enhanced to help with the transition to energy-efficient residential buildings.

Despite the rising amount of knowledge on energy-efficient architecture design, there are substantial gaps in the implementation of energy-efficient solutions in high-end residential neighbourhoods like Abuja. This study intends to fill these research gaps by investigating the viability of energy-efficient architectural features in residential structures in Abuja. It gave empirical data on the feasibility and environmental benefits of passive and active design solutions in high-end urban housing in Nigeria. Finally, the findings will help to produce

context-specific suggestions for improving energy efficiency in Nigeria's high-income housing sector, while also addressing important implementation challenges.

2.1. Theoretical Framework

The theoretical frameworks for this study are based on sustainable architecture and energy efficiency concepts in the context of building design and performance in hot, humid climates. It gives a understanding through which this study can be examined and comprehended. For this investigation, the following theories are deemed most appropriate: Bioclimatic Architecture Theory (BAT), Sustainable Architecture Theory (SAT), Energy Performance Theory (EPT), and Ecological Modernisation Theory (EMT). BAT was proposed by scholars including Olgyay [23] and Givoni [24]. It focusses on how buildings interact with their surrounding climate conditions. Its significance to this study stems from its emphasis on climate-responsive building design (for example, Abuja's hot-humid conditions) through the use of passive methods such as shade, orientation, natural ventilation, thermal mass, and green roofing. Scholars such Edwards and Turrent [25] and Kibert [26] are prominent scholars known for SAT. The theory focusses on incorporating the environmental, social, and economic aspects of sustainability into architectural design. The fundamental elements of the theory are resource efficiency, low-carbon design, and life cycle analysis. It is relevant to this study because it provides advise on the selection and usage of architectural features (such as insulation, materials, shape, and glazing systems) to reduce energy consumption.

The EPT is well-known among scholars, including Santamouris [27] and Crawley *et al.* [28]. The theory focusses on assessing the relationship between building design elements and energy consumption. It is relevant to this study because it allows for a quantified assessment of architectural components (for example, window-to-wall ratio and orientation) in terms of energy efficiency. Scholars such Mol and Sonnenfeld [29] and Spaargaren [30] advocate for the EMT. The goal of this approach is to encourage the use of technology and innovation to lessen environmental problems while promoting development. Its significance to this study stems from its emphasis on incorporating modern energy-efficient technologies into domestic architecture without sacrificing comfort or aesthetic appeal.

3. METHODOLOGY

3.1. Study Area

The study was carried out in the Abuja metropolitan. Nigeria's capital city, Abuja, is located in the country's centre region, between latitudes 8.25°N and 9.20°N and longitudes 6.45°E and 7.39°E. It lies in the tropical savannah climate zone, which is distinguished by high temperatures and distinct wet and dry seasons. Abuja's location within Nigeria's climatic zone is characterised by extreme heat throughout the dry season, making it an ideal case study place for investigating energy-efficient residential design solutions. Abuja is divided into six area councils, but the study is conducted in Asokoro, a well-known residential sector in Abuja, Nigeria. The region is distinguished by modern residential estates, government-owned quarters, and privately-owned dwellings. As a result, it is suitable for analysing a wide range of architectural styles and energy saving measures.

3.2. Population and Sample Selection

The research population consists of occupants of high-end, low-rise residential buildings. The target demographic includes homeowners and residents of both new and older buildings, with a focus on identifying energy-efficient architectural features and determining user knowledge. A purposive sample strategy was used to focus on residential buildings in the study area that were relevant to the study's aims. Random sampling was utilised to pick respondents from various neighbourhoods and dwelling types, including duplexes, bungalows, and flats, to provide a representative view of the district's residential categories. The study's sample size is 140 responders, based on participants' practical accessibility and the volume of distributed questionnaires. This number is within the permissible range for exploratory survey-based research on categorical data, which requires a minimum of 100-200 respondents for significant analysis [31]. The respondents were largely homeowners, tenants, and caretakers, ensuring a diversified viewpoint on building practices and energy consumption.

3.3. Development and Description of Questionnaire

This study's fieldwork consisted of a questionnaire survey. Questionnaires were used because they provide a highly structured method of data collection, which improves answer consistency and facilitates analysis [31]. They were also ideal for this study because of their low cost, ease of distribution, and capacity to cover a large community sample while minimising researcher bias. Furthermore, prior research [10,13] on energy use in residential buildings have successfully used questionnaire-based methodologies. The questionnaire was created using literature from the BAT, SAT, EPT, and EMT frameworks [23, 29, 32]. It contains eight sections: Section A: Demographics and Housing Type. Section B: Examined energy-efficient architecture features; Section C: Preferences and perceptions about energy-efficient features. Section D: Natural Ventilation Features Section E: Shading Devices and Their Effectiveness Section F: Smart Building Technologies. Section G: Renewable Energy Use and Challenges; Section H discusses overall energy performance and recommendations. Standardised analysis was conducted using Likert scale items (1-5), whereas contextual insights were gained using categorical and multiple-choice questions.

3.4. Data Collection Methods

The major data collection instrument was a standardised questionnaire, which was administered in person and, where practicable, online. In addition to the survey, non-intrusive observations were carried out to confirm physical characteristics such as orientation, shading, and visible smart technology installations. The questionnaire was created to assess occupants' impressions of natural ventilation, building attributes, energy consumption behaviour, and awareness of energy-efficient design measures. Given the difficulties in obtaining physical building performance data and the lack of detailed utility records for the majority of residents, the study relied on self-reported data. The decision to use an online distribution platform was based on cost-effectiveness, ease of management, and the opportunity to reach a larger audience quickly. Respondents were encouraged to engage willingly, and 140 valid replies were collected. This strategy guaranteed that data were collected with minimal logistical constraints while retaining consistency and organisation in responses.

3.5. Spaces Evaluated and Subjects Investigated

This study examined the four primary residential typologies in Asokoro, Abuja: detached houses, semi-detached houses, apartments, and duplexes. These building types were chosen specifically because they represent the district's primary dwelling forms and provide a variety of architectural layouts, construction materials, and energy-use characteristics. Evaluating a variety of typologies provided a more comprehensive understanding of how different residential designs affect energy efficiency and indoor comfort in Abuja's tropical environment. Furthermore, these housing styles serve a broad socioeconomic demographic, which aligns with the study's goal of documenting tenant views and practices across numerous residential situations. The study included adult male and female citizens over the age of 18. This age group was deemed appropriate for providing reliable and knowledgeable replies about their homes' thermal comfort, indoor air quality, and energy saving features. The responses received were crucial in determining user perception and satisfaction across the various architectural typologies under consideration.

3.6. Validity, reliability of the instrument and ethical considerations

Experts in sustainable architecture, building service engineering, and environmental design reviewed the content to confirm its authenticity. The instrument was tested against BAT, SAT, EPT, and EMT to determine that it was consistent with theoretical structures. The Cronbach's alpha coefficient was used to examine the internal consistency of the questionnaire's scale-based items (Table 1). A reliability coefficient of 0.653 (Table 1), indicating moderate dependability, was deemed satisfactory for the investigation [33]. Participation was voluntary in terms of ethics, with anonymity and confidentiality guaranteed. Respondents were notified of their rights, and the data was utilised solely for academic purposes.

Table 1. Reliability test

Section	Cases	Reliability	Interpretation
Section A	5	0.855	Highly reliable
Section A2	5	0.851	Highly reliable
Section A3	4	0.949	Highly reliable
Section B	5	0.648	Moderately reliable
overall reliability, cases = 19 reliability = 0.653, which moderately reliable			

3.7. Data Analysis Techniques

To evaluate correlations between architectural aspects and perceived energy efficiency, data were analysed using descriptive statistics (mean, standard deviation, frequency distribution). The spatial orientation data were analysed using frequency mapping.

4. RESULTS

4.1. Demographic information

Table 2 presents the demographic information of the respondents. It could be observed that 46.4% of respondents are between the ages of 18 and 30, 26.4% are between the ages

of 31 and 45, 15% are between the ages of 46 and 60, and 12.1% are 60 years and over, implying that there are more responses from the ages of 18 and 30 and 31 to 45. The percentage of male respondents was 55.7%, while female respondents were 44.3%.

Table 2. Demographic information

Demographic of the respondents	Frequency	Percentage
Age		
18-30	65	46.4
31-45	37	26.4
46-60	21	15
60+	17	12.1
Gender		
Male	78	55.7
Female	62	44.3
Type of residence		
Detached house	43	30.7
Semi-detached house	25	17.9
Apartment	28	20
Duplex	44	31.4
How long have you lived in this residence?		
Less than a year	16	11.4
1-5 years	54	38.6
6-10 years	36	25.7
More than 10 years	34	24.3

4.2. Application of Energy-Efficient Architectural Elements

A 5-point Likert scale was used to measure the extent to which energy-efficient architectural components are incorporated into Abuja's residential buildings. Respondents were asked to score their agreement with various assertions about energy efficiency elements including as orientation, ventilation methods, and insulation. The scale ranged from strongly disagree (1) to strongly agree (5), and the weighted mean values were interpreted as follows: 4.51–5.00 = Strongly Agree; 3.51-4.50 = Agree; 2.51-3.50 = Neutral; 1.51-2.50 = Disagree; and 0.00-1.50 = Strongly Disagree. According to the data in Table 3, 34.3% agreed and 32.9% strongly agreed that their living rooms had big windows for natural and cross ventilation, with a mean score of 3.81. Regarding bedroom ventilation, 41.4% agreed and 15.7% strongly agreed on the existence of large bedroom windows (mean score 3.51). The total natural ventilation design shows that 30% agreed, 25.7% strongly agreed, and 26.5% disagreed. The average score of 3.47 indicates a neutral view overall. Regarding wall insulation, 22.1% agreed, 5.7% strongly agreed, and 37.9% opposed or strongly disagreed. Despite this, the mean score was 3.81, showing agreement that wall insulation was present. The findings are consistent with BAT in terms of living room and bedroom ventilation, with high agreement scores (3.81 and 3.51, respectively), indicating intentional design components that encourage airflow, such as big windows. However, the neutral posture (3.47) on the general integration of cross ventilation (e.g., courtyards, window placement) suggests that, while some bioclimatic principles are used, the strategy is not fully implemented across all architectural sections.

Table 3. Energy Efficient Architectural Elements

Energy Efficient Architectural Elements	SD	D	N	A	SA	Mean value	Decision
My building has proper orientation that reduces direct sunlight exposure into my house	9 (6.4)	15 (10.7)	30 (21.4)	50 (35.7)	36 (25.7)	3.64	Agree
My living rooms have large windows that allows for natural and cross ventilation	8 (5.7)	11 (7.9)	27 (19.3)	48 (34.3)	46 (32.9)	3.81	Agree
My bedrooms have large windows that allows for natural and cross ventilation	9 (6.4)	13 (9.3)	38 (27.1)	58 (41.4)	22 (15.7)	3.51	Agree
Generally, my house is designed to use natural and cross ventilation (i.e., having large windows, courtyards, etc.)	11 (7.9)	26 (19.6)	25 (17.9)	42 (30)	36 (25.7)	3.47	Neutral
The walls of my house have high-performance insulation	20 (14.3)	33 (23.6)	48 (34.3)	31 (22.1)	8 (5.7)	3.81	Agree

The low usage of wall insulation (only 27.8% agreed/strongly agreed) and neutral ratings for passive design indicate a moderate alignment with SAT. While some energy-saving methods (such as natural ventilation) exist, irregular insulation application and the likely absence of renewable systems reduce the buildings' sustainability profile. The agreement on living room (3.81) and bedroom windows (3.51) suggests that natural ventilation can be used effectively to reduce cooling demands. However, neutral responses to overall design integration (3.47%) and poor adoption of insulation (although a mean of 3.81, real agreement levels were low) indicate inconsistent implementation of energy-saving components. The mean insulation score of 3.81 is deceiving, as more than 37.9% disagreed, indicating poor perception or insufficient application of proper insulation practices. The low adoption of improved insulation, as well as the anticipated limited usage of smart technologies or renewable systems (which are not addressed here), indicate that EMT principles are not fully implemented. The neutral or negative views of particular traits may represent a lack of institutional support or economic incentives, which is consistent with EMT accusations of poor policy backing in developing countries.

4.3. Barriers to Adoption of Energy-Efficient Architectural Elements

Using the Relative Importance Index (RII), the study identifies and classifies major barriers to the adoption of energy-efficient architectural elements. Using the Relative Important Index, identify important impediments to the adoption of energy-efficient design features.

$$RII = \frac{\sum W}{A * N} \quad (1)$$

Where: W = Weight given to each statement by the respondent, A = Highest response integer which is 5, N = Total number of respondents = 140.

The study identified five major impediments to the use of energy-efficient architectural components in residential buildings. According to Table 4, lack of awareness (RII = 0.49) was identified as the most significant barrier, implying that many citizens and possibly experts are unaware or confused about the long-term benefits and implementation of energy-efficient architecture.

Table 4. Key barriers hindering the adoption of energy-efficient architectural elements

Key barriers hindering the adoption of energy-efficient architectural elements	$\sum W$	RII	Ranking
High Initial Cost	255	0.364	3
Lack of Awareness	242	0.49	1
Resistance to Change by Homeowners	312	0.446	2
Limited Availability of Materials	312	0.446	2
Poor Government Policies and Incentives	238	0.34	4

Resistance to change and low material availability (RII = 0.446) are both placed second, indicating behavioural and supply-chain restrictions in the construction industry. High initial costs (RII = 0.364), while significant, were not the most relevant factor, showing that while costs inhibit adoption, socio-cultural and informational difficulties are more prevalent. Poor Government Incentives (RII = 0.34) had the lowest ranking, probably reflecting respondents' lack of awareness of policy frameworks or the absence of effective measures.

4.4. Adoption and effectiveness of smart building technologies

To determine the level of adoption and effectiveness of smart building technologies (e.g., smart thermostats, lighting, automated blinds) in improving residential energy efficiency. Table 5 summarises the findings on the uptake and perceived effectiveness of smart technology in improving energy efficiency in residential structures in Abuja, Nigeria. Out of 140 respondents, 65 (46.4%) claimed no use of smart technology. 23.68% used smart thermostats, 8.42% automatic blinds, and 33.64% smart lighting. Combinations of devices were also reported, with 6.4% using all three technologies and 20% adopting both smart thermostats and automated blinds. Other combinations were less common.

Table 5. Adoption and effectiveness of smart building technologies

Adoption of smart technologies	Frequency	Percentage
None	65	46.4
Smart thermostat	6	4.3
Smart thermostat and Automated blinds	28	20
Smart thermostat, automated blinds and Smart lightings	9	6.4
Smart thermostat and Smart lightings	2	1.4
Automated blinds	3	2.1
Automated blinds and smart lightings	1	0.8
Smart lightings	26	18.6

In terms of perceived effectiveness, Table 6 shows that 18.6% found smart technologies somewhat useful, 16.4% found them very effective, 15.7% found them highly effective, and 1.4% considered them ineffective.

Table 6: Effectiveness of smart technologies

Effectiveness of smart technologies	Frequency (percentage)
Not applicable	65 (46.4)
Not Effective	2 (1.4%)
Slightly effective	2 (1.4%)
Moderately effective	26 (18.6)
Very effective	23(16.4)
Highly effective	22 (15.7)

According to Bioclimatic Architecture Theory (BAT), natural environmental factors such as ventilation, solar orientation, and passive cooling measures can be used to increase energy efficiency [23]. The comparatively low acceptance rate of smart technology among respondents (53.6% claimed nil or moderate use) reflects a continued dependence on old bioclimatic solutions or a failure to integrate these modern technologies into bioclimatic design principles. This is largely consistent with BAT, but it highlights missing potential for hybridisation [34]. From the standpoint of Sustainable Architecture Theory (SAT), which emphasises reducing environmental impact through design innovations, material selection, and energy efficiency [32]. Smart lighting (33.64%) had the greatest adoption rate, indicating an increasing awareness of energy-saving technology. However, the poor overall integration (only 6.4% accepted all smart systems) indicates challenges to comprehensive sustainable design implementation, such as cost and awareness [35]. Users' response suggests a mainly positive assessment of the effectiveness of smart technologies, with 50.7% rating them as somewhat to highly successful. This validates EPT's claim, as asserted by Cabeza *et al.,* [36], that such technologies boost performance; yet, the low adoption rate contradicts its premise that high-performance tools should be integrated into building design. The moderate adoption of smart technologies and their perceived effectiveness are consistent with EMT's concept, which states that economic and environmental progress may coexist through innovation and green technologies [29]. However, the findings show that there are infrastructural and socioeconomic impediments, such as affordability and awareness, indicating that modernisation is incomplete.

5. DISCUSSION

This study's findings show varying degrees of alignment between residential building design practices in Abuja and four theoretical frameworks: Bioclimatic Architecture Theory (BAT), Sustainable Architecture Theory (SAT), Energy Performance Theory (EPT), and Ecological Modernisation Theory (EMT).Bioclimatic theory promotes architectural design that adapts to local climatic conditions, emphasising passive techniques such as natural ventilation, daylighting, and thermal comfort while avoiding overreliance on mechanical systems [23, 24]. The study's findings—particularly the high agreement scores on living room (3.81) and bedroom ventilation (3.51)—indicate that these principles are partially integrated, most likely via features such as big movable windows. However, the neutral mean score of 3.47 for the overall integration of cross-ventilation methods (e.g., strategic window placement, usage of courtyards) implies an inconsistent use of BAT. Furthermore, respondents' emphasis on hurdles such as "lack of awareness" and "resistance to change" contradicts BAT's assumption of cultural embeddedness. This demonstrates a gap between traditional climatic understanding and present architecture methods, undermining Abuja's overall acceptance of bioclimatic principles. Sustainable Architecture Theory emphasises ecologically responsible and resource-efficient design to reduce negative consequences throughout a building's life cycle [37, 26]. While natural ventilation elements appear to be marginally embraced, the studies highlight deficiencies in other crucial areas. The restricted usage of wall insulation—despite a mean score of 3.81, only 27.8% of respondents agreed or strongly agreed with its presence—indicates a distorted view of energy efficiency. Furthermore, the inconsistency with which various passive design principles are applied, as well as the potential absence of renewable energy sources, weaken these buildings'

sustainability credentials. High initial costs, limited availability of sustainable materials, and a lack of regulatory incentives all pose challenges to SAT's practical implementation in Abuja. Though energy conservation may provide long-term cost savings, the initial financial load remains a substantial barrier. These obstacles suggest that, while SAT principles are theoretically recognised, their actual implementation is hampered by socioeconomic and institutional constraints. The Energy Performance Theory emphasises the technical optimisation of building components such as insulation, orientation, fenestration, and ventilation in order to increase energy efficiency and lower operational costs [38, 39]. The strong agreement on the existence of ventilation-enhancing design in living rooms (3.81) and bedrooms (3.51) suggests partial adherence to EPT. Nonetheless, neutral responses to cross-ventilation integration and low adoption of wall insulation indicate insufficient use of performance-based design concepts. The high mean score for insulation (3.81) is opposed by the fact that more than 37.9% of respondents disapproved or strongly disagreed with its presence, demonstrating a mismatch between perceived and real application. Furthermore, insufficient stakeholder awareness, a lack of appropriate materials, and high upfront costs impede the implementation of advanced energy-efficient technologies such as high-performance glass and smart systems, undercutting EPT's technological goals. According to Ecological Modernisation Theory, environmental sustainability may be achieved alongside economic progress by leveraging technical innovation, institutional reform, and policy-driven modernisation [29]. However, the study's findings indicate poor alignment with EMT. The low Relative Importance Index (RII) score for government incentives (0.34) and broad opposition to change point to a lack of institutional structures and favourable policy contexts. The absence of smart technology and renewable systems in studied households shows that technological modernisation is taking place without corresponding ecological innovation. This circumstance exemplifies one of the most common criticisms levelled at EMT in developing countries: legislative stagnation and ineffective regulatory engagement limit the realisation of long-term transformations. Overall, the findings indicate that, while passive features such as natural ventilation are partially integrated into Abuja residential architecture, other critical elements such as high-performance insulation, courtyard design, and smart energy systems are either underutilised or poorly understood. Informational, behavioural, and institutional limitations tend to be more substantial than strictly economic limits, preventing the successful implementation of sustainable and energy-efficient design theories.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

This study investigated architectural components that enhance energy efficiency in residential structures in Abuja, Nigeria, using Bioclimatic Architecture Theory (BAT), Sustainable Architecture Theory (SAT), Energy Performance Theory (EPT), and Ecological Modernisation Theory (EMT). The findings suggest a partial but inconsistent use of energy-efficient design solutions, particularly in areas like natural ventilation and insulation. While living rooms and bedrooms were somewhat optimised for natural cross ventilation in accordance with BAT principles, the neutral position on the general use of passive ventilation solutions indicates that bioclimatic concepts are not fully integrated. Wall insulation practices were inconsistently reported, with a paradoxical mean agreement of 3.81 and high

disagreement rates, indicating misunderstanding or insufficient insulation use. This represents a moderate alignment with SAT, in which sustainable design concepts are present but not fully implemented. EPT's emphasis on performance-driven technologies was partially supported by user evaluations of smart technology effectiveness, but adoption remained low (only 6.4% adopted all available systems), contradicting the theory's central claim of broad integration of high-performance tools. Finally, EMT's vision of innovation as a bridge between environmental protection and development was not fully realised due to institutional, socio-cultural, and economic constraints that hampered deeper technology integration. Key challenges identified included a lack of awareness, opposition to change, restricted material availability, and poor government incentives.

6.2. Recommendations

The recommendations listed below are intended to guarantee that energy efficiency is integrated into residential building design in Abuja, Nigeria. (I) Abuja architectural designs should be optimised holistically to incorporate passive cooling measures such as strategic window placements, courtyard systems, shaded apertures, and natural ventilation paths. (ii) Planning authorities should create design guidelines that promote the use of bioclimatic components appropriate to Abuja's climate zone. (iii) Policies should encourage the use of environmentally friendly building materials, insulation systems, and integrated passive and active energy-saving measures. (iv) Green building certification programs should be implemented or strengthened in Abuja to promote holistic sustainable practices. (v) There is a need for more adoption and education on the performance benefits of smart technology such as lighting, thermostats, and blinds. (vi) Developers should be encouraged to incorporate smart energy systems into the design stage, together with real-time monitoring systems to measure and improve performance. (vii) Government and institutional policies should prioritise reducing economic and informational barriers by giving subsidies, tax breaks, or grants for energy-efficient technologies. (viii) Public-private collaborations should be promoted to ensure the availability of sustainable technology and to foster innovation ecosystems in the construction industry. Overall, Abuja's residential architecture shows scattered progress towards energy-efficient design. A coordinated and theory-informed approach integrating natural and technical solutions, supported by strong institutional frameworks, can dramatically enhance building energy performance while also complying with national and global sustainability goals.

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Research paper

SITE CHARACTERIZATION OF STRONG MOTION STATIONS IN NORTH MACEDONIA

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Abstract

This study focuses on the site characterization of strong motion stations in North Macedonia using H/V spectral ratio analysis of both microtremor measurements and recorded earthquake data. It presents a methodology for calculating the H/V spectral ratio from earthquake recordings, with results compared to those obtained from microtremor measurements (available for most stations) to assess consistency and reliability. Currently, thirteen strong motion stations are operational across the country, with additional data available from thirteen non-operational stations. Several sites have been previously investigated through geophysical surveys and borehole geotechnical studies, which are also utilized in this study for comparison with the newly conducted H/V analyses. The analysis emphasizes the influence of local site conditions on recorded ground motions and identifies potential site amplification effects. These findings will serve as a basis for defining appropriate frequency ranges in the calculation of the high-frequency decay parameter, kappa (κ), for the territory of North Macedonia. Future work will explore the potential correlation between the fundamental site frequency and the site-specific attenuation component (k_0) of kappa, aiming to improve the understanding of local site effects. These insights could contribute to the refinement of site classification schemes for the next generation of Eurocode 8.

Key words: *Earthquake Recordings, Horizontal-To-Vertical Spectral Ratio (H/V), Site Effect, Site Response, Strong Motion Stations*

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1. INTRODUCTION

Strong motion play a crucial role in seismic hazard assessment, emergency response, damage evaluation, the improvement of building codes, the development and calibration of ground motion prediction equations (GMPEs), and for the advancement of further research studies. Subsurface conditions at the seismic station locations significantly influence the amplification and attenuation of seismic waves, affecting structural responses and potential damage. Understanding the site effects and their correlation with earthquake damage is crucial for site classification in accordance with seismic design codes requirements.

Various parameters are used to classify site conditions, with the most commonly adapted being the average shear wave velocity in the upper 30 meters of soil (V_{S30}). The current EC8 code [1] defines five site classes for soil classification based on V_{S30} values: A (>800m/s), B (360-800 m/s), C (180-360 m/s), D (<180 m/s), E (-).

V_{S30} *can be determined* through geophysical and borehole geotechnical investigations, as well as using horizontal-to-vertical spectral ratio (H/V) analysis. H/V analysis of microtremor or earthquake data enables estimation of the fundamental site frequency (f_0), and provides insights into local site effects, soil resonance characteristics, and amplification.

The low-cost microtremor horizontal-to-vertical (H/V) method, introduced by Nogoshi and Igarashi 1970 [2] and popularized by Nakamura 1989 [3], assumes that horizontal ground motions are amplified around the fundamental frequency, while vertical motions remain relatively unaffected [4]. It has been widely applied in seismic microzonation studies to assess local site response, resonance frequency of soft sediments, and spectral H/V peak amplification, which reflects the impedance contrast between soft sediments and bedrock [5,6]. If a H/V curve exhibits a clear peak, the frequency corresponding to the first dominant peak ($f_{0H/V}$) can be considered as the fundamental resonant frequency of the site (f_0). While the ability of H/V to accurately retrieve f_0 is widely accepted, the interpretation of the amplitude of the H/V curve remains a subject of debate. [5,7,8].

Studies confirm that this method is effective for both microtremor and strong ground motion data, yielding consistent results across different datasets [7,9,10,11]. Conducting extensive H/V data analysis recorded across an entire seismic network, combined with f_0 estimation, enhances site response analysis and helps identify potential local effects. Recent research [12-15] suggests that integrating both f_0 and V_{S30} provides a more comprehensive understanding of site response.

In addition to V_{S30} and f_0, the high-frequency attenuation parameter kappa (κ) - particularly its site-specific component k_0 - is increasingly accepted as a key indicator of site effects. Kappa describes the decay of spectral amplitudes at high frequencies and reflects the damping characteristics of near-surface materials. Accurate determination of κ requires detailed knowledge of the subsurface conditions beneath each station and the ability to avoid frequency ranges influenced by site resonances, which can bias kappa estimates.

In this study, earthquake acceleration data from the UKIM-IZIIS strong motion network in North Macedonia were analyzed. The research begins with an overview of the study area and instrument placement. It then outlines the site characterization methods and available data, followed by an analysis of microtremor measurements and H/V analysis using earthquake data. Finally, the study presents and discusses the results on fundamental site frequency (f_0) and V_{S30}, exploring their correlation and drawing appropriate conclusions for future applications in kappa calculation and correlation to the site-specific component k_0.

2. STRONG MOTION NETWORK

IZIIS strong motion network was established in 1972 as part of the Yugoslavian seismic network. Initially, the network consisted of analog instruments, which were later digitalized. Currently, there are seventeen active strong motion stations. Figure 1 shows the station locations and names where accelerometric data are available, including both active and inactive stations. All instruments operate at a sampling rate of 200 Hz. The accelerometers are installed in free-field conditions, in the basements of small buildings, or on the ground floor and are presented with different colors in Figure 1. Regarding soil characteristics, the instruments are placed on bedrock and characteristic soil types.

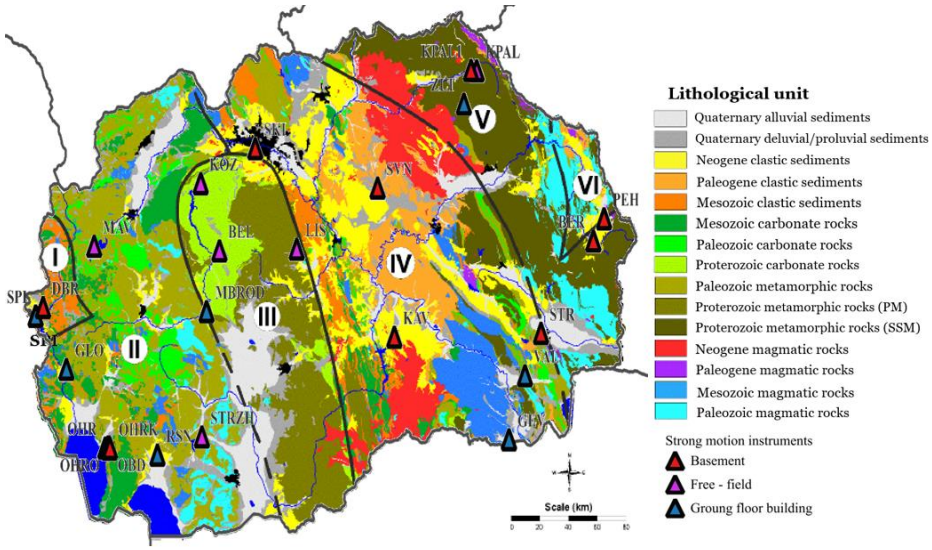

Figure 1. Simplified geological map of the Republic of Macedonia Tectonic units (according to Arsovski, 1997): I – Cukali-Krasta zone (CKZ), II – West-Macedonian zone (WMZ), III – Pelagonian massif (PM). IV – Vardar zone (VZ), V – Serbo-Macedonian massif (SMM), VI – Kraishtide zone (KZ). Updated map from Petrusev et al. 2021 [16] with strong motion instrument's location

Figure 1 illustrates the geological and tectonic units in the study area. The figure is an updated version from Petrusev et al. 2021 [16] and serves as a basis for characterizing strong motion station locations and correlating them with local geological conditions.

The instruments are placed in different tectonic units and geological settings. Installing instruments in various geological conditions, including bedrock and characteristic soil, is crucial for assessing local site effects and understanding how soil properties influence ground motion acceleration.

3. SITE CHARACTERIZATION - DATA

Site characterization is based on data from both active and passive surveys. Active methods include geophysical techniques such as seismic refraction tomography (SRT) and multichannel analysis of surface waves (MASW) [17–22], as well as borehole geotechnical investigations [23]. Passive methods involve single-station H/V spectral ratio analysis using both microtremor and earthquake recordings.

3.1. Geophysical investigations

Geophysical surveys were performed using Seismic Refraction Tomography (SRT) and/or the Multichannel Analysis of Surface Waves (MASW) method at eight existing stations OHR, DBR, PEH, KPAL, LIS, SKI, VAL, OHRK [17-22]. The site parameter V_{S30} is provided in Table 1. Figure 2 illustrates a 3D display of the seismic refraction profiles from the surveys at the PEH station.

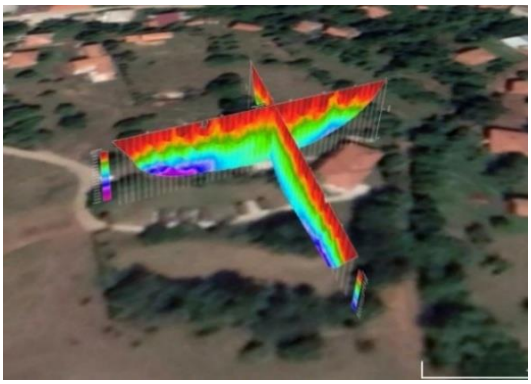

Figure 2. 3D display of the seismic refraction profiles – PEH station

3.2. Borehole geotechnical investigations

The available data from borehole geotechnical investigations date back to the 1980s and were carried out at a maximum depth of up to 120 meters [23]. This data is available only for three stations OBD, OHRK and OHRT. The average shear velocities in the upper 30 m, V_{S30} according to these investigations, are shown in Table 1.

3.3. Site classification based on fundamental frequency

3.3.1. Single station H/V spectral ratio using microtremor measurement data

Single-station H/V microtremor measurements using a TROMINO seismometer were conducted between 2024 and 2025 at twenty-three different locations, in addition to three earlier measurements carried out in 2021. The recording duration for each measurment was 20 minutes, with a sampling frequency of 128 Hz.

Data processing was carried out in accordance with the SESAME H/V User Guidelines [5], using the Grilla software developed by Micromed S.p.A. (2008a). A manual window selection was applied to exclude transient vibrations caused by nearby traffic, incidental movements, or footsteps near the sensors. The average H/V spectral ratios were computed using the Fourier Amplitude Spectrum (FAS) for each component, with smoothing applied following the method of Konno and Omachi (1998) [10]. These results were then used to identify clear H/V spectral peaks, representing the fundamental site frequency and its corresponding amplitude. An example of a microtremor result for STR station is presented in Figure 3.

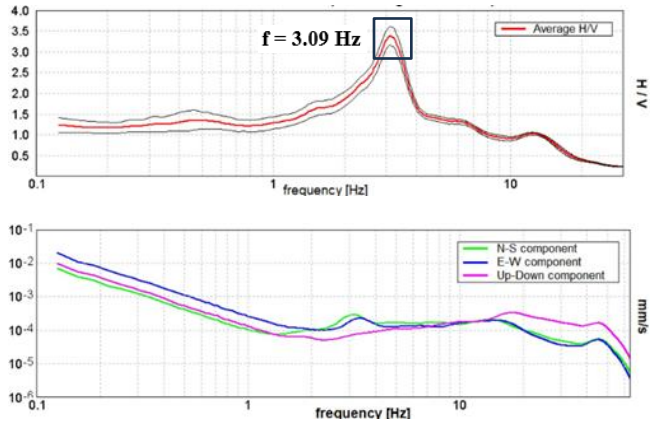

Figure 3. H/V curve and Fourier Amplitude Spectra obtained from microtremor measurements for STR station

3.3.2. Single station H/V spectral ratio using earthquake data

The single-station H/V spectral ratio analysis was performed on recorded earthquake data between 2011 and 2024 within the strong motion network in IZIIS, Skopje. The calculation was based on 5 to 102 earthquake events per station. Before the H/V analysis, the data were visually inspected, baseline corrected, and a bandpass filter ranging from 0.1 to 100 Hz was applied. Bad quality data, and data with SNR < 3 were excluded from the analysis.

The following procedure for H/V was used: different window lengths depending on the earthquake duration were selected, starting before S-wave onset and continuing until the end of the coda wave (Figure 4, a) yellow window). Fourier transformation was used to calculate the Fourier amplitude spectrum (FAS) for each component, two horizontal and one vertical of the earthquake records. Next, smoothing using the Konno and Omachi (1998) [10] window (using bandwidth b=20) was applied. At the end, the average H/V curves were obtained from the horizontal amplitude spectra (using mean value from both horizontal components) and vertical amplitude spectra. The corresponding frequency to the largest amplitude was determined as a dominant, fundamental frequency (Figure 4, b)).

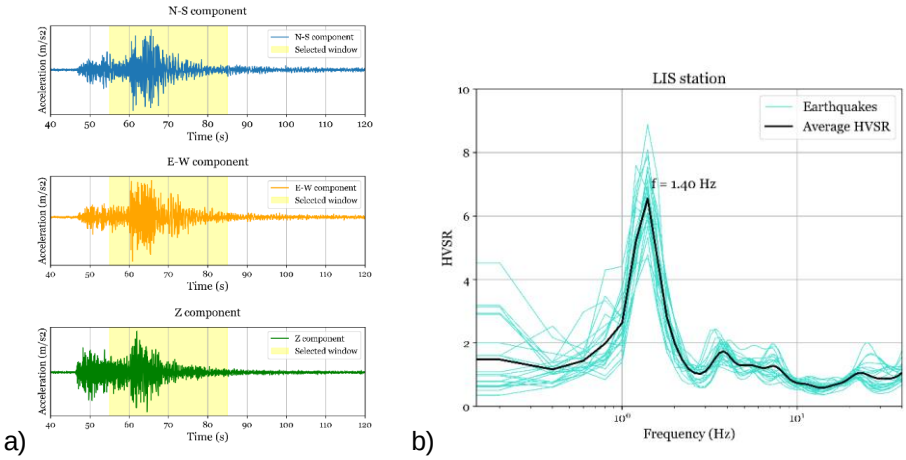

Figure 4. Procedure for H/V calculating using earthquake data, a) strong motion record (earthquake event occurred on 25.04.2022 with magnitude M_w = 4.26, and epicentral distance R_{epi} =111 km) with window chosen (S-wave and coda wave), b) average H/V curve from multiple events

Figure 5 present the obtained H/V curves using microtremors (red color) and earthquakes (black color) for four stations. Four types of results are shown: flat curve with low amplitude values for rock sites (Figure 5, a), clear peak curve (Figure 5, b), multiple peaks curve (Figure 5, c), and high-frequency peak curve (Figure 5, d).

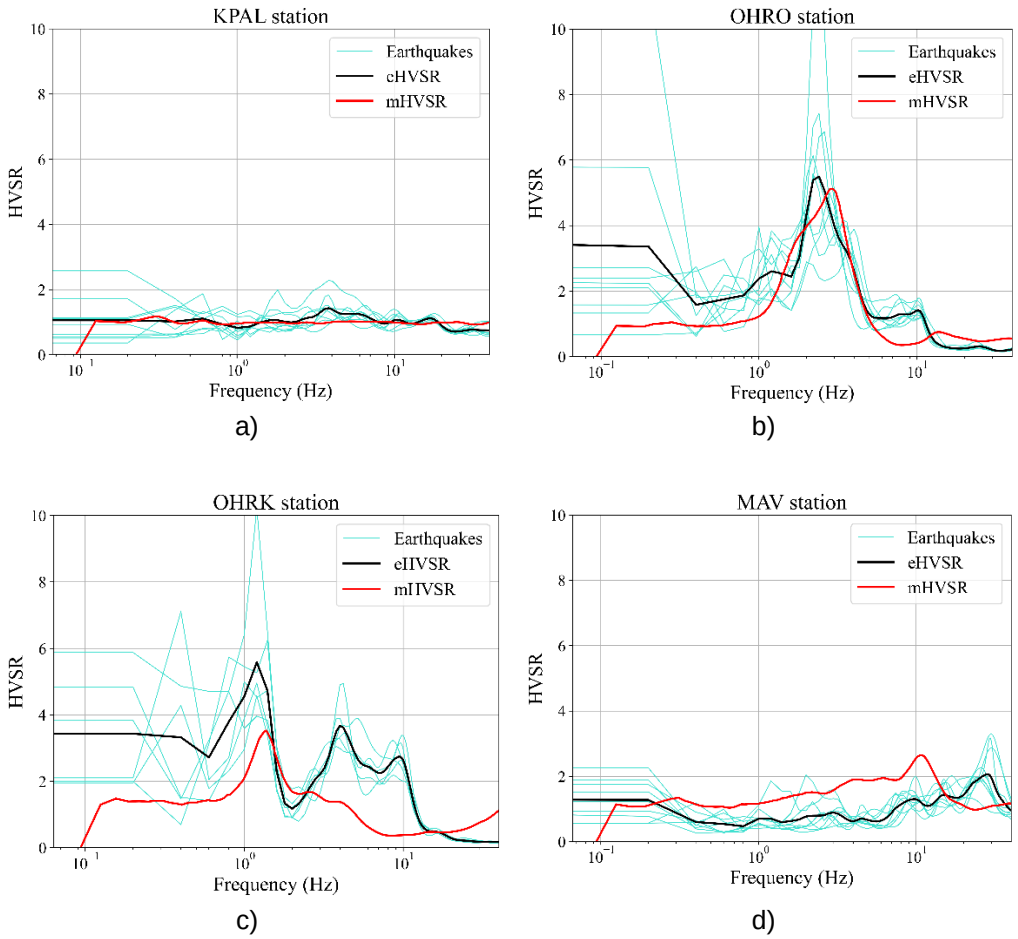

Figure 5. Example of earthquake (eHVSR) and microtremor (mHVSR) H/V spectral ratio – a) flat curve, b) clear high peak, c) multiple peaks, d) high-frequency peak

4. RESULTS

Table 1 presents the station name, V_{S30} values, EC8 site class, fundamental frequencies from H/V analysis (microtremors and earthquakes), number of earthquakes used, and lithological units (with markers matching Figure 1). V_{S30} values retrieved from the USGS V_{S30} Map Viewer [24] are marked with an asterisk (*).

Table 1. Station information, soil characterization type 1[1]- geophysics SRT, 1[2]- geophysics MASW, type 2 – H/V microtremors, type 3 – H/V earthquakes, type 4 – borehole investigations, N_{eq} number of earthquakes included in the H/V analysis using earthquakes, geological setting corresponding to lithological units in Figure 1. "f" means flat curve, while the symbol "/" indicates no available data. V_{S30} values from USGS are marked with ""*

Station	V_{S30} (m/s)	Site class	Investigation type	f_{0m} (Hz)	f_{0e} (Hz)	N_{eq}	Geological setting
BEL	800*	A	3	/	f	7	
BER	500*	B	2,3	4.2	3.4	25	
DBR	400-450	B	1[1],1[2],3	/	1	102	
GEV	350-380*	B	3	/	f	14	
GLO	800*	A	2,3	11.8	f	5	
KAV	350-380*	B	2,3	F	0.5	9	
KOZ	800*	A	3	/	f	11	
KPAL	>800	A	1[1],1[2],2,3	f	f	9	
KPAL1	350*	C	2,3	4.5	3.5	26	
LIS	350	B	1[1],1[2],2,3	1.5	1.4	23	
MAV	800*	A	2,3	10.7	28.5	9	
MBROD	380-400*	B	3	/	5.8	44	
OBD	350-400	B	2,3,4	1.1	1	36	
OHR	>1000	A	1[1],2,3	f	f	54	
OHRK	350-400	B	1[1],1[2],2,3,4	1.4	1.2	6	
OHRO	350-400	B	2,3	2.9	2.4	9	
OHRT	350-400	B	2,3,4	1.1	1	13	
PEH	380-450	B	1[1],1[2],2,3	f	0.8	47	
RSN	360-400*	B	2,3	0.6	0.6	82	
SKI	330	C	1[1],1[2],2,3	f	f	13	
SPI	800*	A	2,3	21.2	14.4	8	
STR	350-380*	B	2,3	0.9	0.8	28	
STRZH	600-800*	A	2,3	12	10.2	9	
SVN	500*	B	2,3	3.1	1.2	7	
VAL	774	A	1[1],2,3	40	10	24	
ZLT	800*	A	2,3	13.4	f	7	

Figure 6 represents H/V curves obtained from earthquake data recorded at twenty-six different locations. Horizontal black line at H/V=2 represents the non-amplification amplitude following the SESAME criteria [5].

Stations LIS, KPAL1, MBROD, OHRO, and DBR exhibit significant peak amplitudes (H/V > 4) in the frequency range of 1 to 5 Hz, indicating a possible large impedance contrast between the sedimentary cover and the bedrock. It is very likely that ground motion is amplified at these stations.

In contrast, earthquake records from stations GLO, KOZ, BEL, KPAL, and OHR show flat H/V curves, with amplitudes consistently below 2 across the entire frequency range. This indicates insignificant site amplifications, even at higher frequencies.

The SKI station exhibits a flat H/V curve, typically indicative of rock or stiff soil. However, geophysical data reveal unconsolidated sediments extending to depths up to 30m (e.g., V_S < 600 m/s in the upper 12-30 m), explaining the absence of a clear peak. This behavior aligns with the SESAME classification of ~5% of sites showing flat responses despite non-rock conditions.

Stations MAV, SPI, STRZH, and VAL show indications of possible site amplification effects at higher frequencies (20–30 Hz), which may be due to layered weathered rock on the surface. However, the overall site conditions are expected to be predominantly rock.

Stations OHRK, OHRT, OBD, and BER exhibit multiple significant peaks in the H/V spectral ratios derived from earthquake data, while only a single dominant peak is observed from the corresponding microtremor H/V spectral ratio. This difference arises because microtremors mainly consist of surface waves, which do not efficiently exite higher-mode resonances, unlike earthquake-induced motions which contain a broader range of wave types and energy. These peaks, occuring in the frequency range of 1 to 10 Hz, indicate expected site amplification effects caused by the presence of layered, heterogeneous soil structures with varying share-wave velocities. Borehole and geophysical data from the surveys at OHRK, OHRT, and OBD confirm multiple impedance contrasts (e.g., soft surface layers overlying stiffer sediments and bedrock), supporting the interpretation of higher-mode peaks observed in the eHVSR spectra.The observed amplification likely spans a broad frequency range, beginning at the fundamental frequency f_0 and extending to higher modes such as f_1 and f_2.

Stations PEH, STR, KAV, and RSN exhibit an unclear low-frequency peak with small amplitude values (H/V < 4). The absence of a distinct H/V peak may indicate a lack of significant impedance contrast at the site, such as a gradual, normally dispersive profile. According to SESAME [5], this could be due to a moderate impedance contrast depth, a velocity gradient, or low levels of low-frequency ambient vibrations.

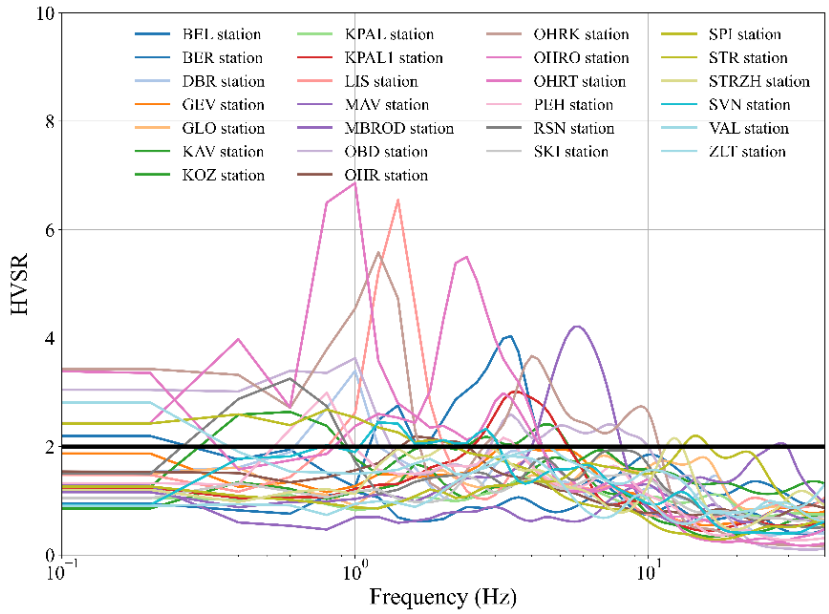

Figure 6. H/V curves for twenty-six stations obtained from earthquakes

The strong motion stations are classified based on their fundamental site frequency determined from earthquake data (marked with different colours), and the soil type according to EC8, V_{S30} parameter (marked with different symbols). The results are illustrated in Figure 7.

The fundamental site frequency (f_0) from H/V spectral analysis is compared with the average shear wave velocity in the upper 30 m (V_{S30}). Figure 8 shows the correlation between

f_0 (from microtremor and earthquake data) and V_{S30}. For stations with a range of V_{S30}, the mean value is plotted. Circles represent measured V_{S30} values, while squares indicate values inferred from the USGS map. The results show that f_0 values from microtremor and earthquake data differ for some stations.

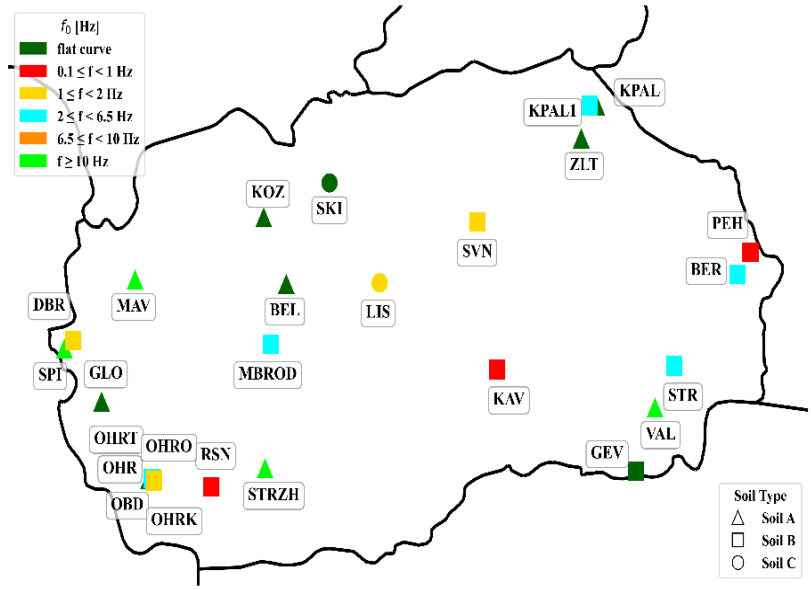

Figure 7. Fundamental frequency map, coloring of the symbols is according to the fundamental frequency value determined from earthquake data using different symbols for soil class according to EC8

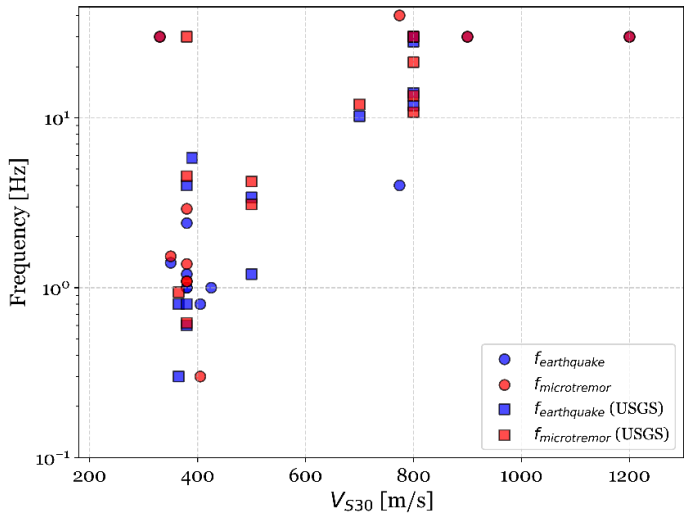

Figure 8. f_0 – V_{S30} distribution obtained from H/V spectral ratio calculations using earthquake data (blue dots) and microtremor measurements (red dots). Circle marker for V_{S30} data obtained from geophysical investigations, and squares from USGS

5. DISCUSSION

This study explored site characterization across strong motion stations in North Macedonia using H/V spectral ratio analysis based on both microtremor and earthquake data. The comparison of fundamental frequencies (f_0) obtained from these two datasets shown differences at several stations. In most cases, microtremor-derived f_0 values were slightly higher than those from earthquake recordings. This difference is likely due to surface waves being more dominant in ambient noise, while the broader frequency range of earthquake recordings allows for the identification of deeper structures and higher-mode resonance.

Figure 8 demonstrates the correlation between f_0 and V_{S30}. Lower V_{S30} values generally correspond to lower f_0 values, as expected for soft-soil sites where fundamental resonance frequencies are lower. However, the relationship is not strictly linear, especially at sites with complex stratigraphy. This suggests that V_{S30} alone may not fully capture the frequency-dependent site response, especially where higher mode resonances are observed (e.g., OHRT, OHRK).

The high-frequency decay parameter κ and its site-specific component k_0 - introduced earlier in the introduction-are key indicators of near-surface attenuation. Their values are sensitive to local damping conditions and are increasingly used in site classification and ground motion modeling. While κ and k_0 calculations are not the focus of this manuscript, the results of this study (particularly the fundamental frequencies f_0 and V_{S30} values) support a more informed selection of boundary frequencies for k estimation and help to contextualize observed k_0 variability in future studies [25]. Previous studies [26-28] have explored the relationship between the site component k_0 and the fundamental site frequency (f_0). In this study, the correlation presented in Figure 8 will be further analyzed to enhance the understanding of site effects and the relationship between k_0 and f_0 for the seizmic stations in North Macedonia.

The results of this study support the ongoing updates to Eurocode 8 (2021 draft) [29], which suggest using f_0 and other spectral indicators along with $V_{S,H}$ based measures. Our findings show that combining f_0 and V_{S30} gives a more complete picture of site response. This approach can help improve national site classification and seismic hazard models.

6. CONCLUSION AND FUTURE APPLICATION

This study presents a site characterization of twenty-six strong motion stations in North Macedonia, using data from previous geophysical and borehole geotechnical investigations, complemented by newly conducted horizontal-to-vertical spectral ratio (H/V) analyses based on both microtremor and earthquake data.

Most stations are classified as EC8 Class A or B, with only two classified as Class C, indicating that the majority of accelerometric stations are located on stiff soils or soft rock. This distribution reflects a general preference for instaling stations on sites with relatively stable ground conditions, which is common practice in seismic monitoring networks.

At locations where multiple investigation methods were available, results show strong consistency, reinforcing the reliability of H/V analysis as a supportive tool in site classification. However, exceptions at stations such as SKI and GEV highlight that relying on a single-method may lead to misleading interpretations of subsurface conditions. These cases emphasize the need for an integrated approach that combines H/V with borehole and/or geophysical methods to ensure accurate site assessment.

The findings of this study are relevant for seismic hazard assessment in the region and contribute to understanding the relationship between high-frequency attenuation (kappa) and site effects characterized by fundamental frequency. Additionally, they support efforts to refine site classification criteria in future updates of Eurocode 8.

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Research paper

THE AESTHETICS OF RURAL CULTURAL CENTRES AND THEIR IMPACT ON THE COMMUNITY: TWO CASE STUDIES FROM THE NIŠAVA DISTRICT

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Abstract

The expansion of cultural centre construction in underdeveloped areas was an integral part of the cultural policy pursued by the new political and social order in Yugoslavia following the end of the Second World War. The conceptual aim was to foster the cultural life of rural populations while simultaneously promoting the principles of collectivism and socialist ideology. These buildings were erected according to predefined schemes developed by professionals specifically engaged for this purpose. However, the actual construction process, including the final selection of materials and decoration, was largely entrusted to the local inhabitants, who actively participated in building their own cultural centres. Today, due to the dissolution of Yugoslavia and the country's entry into a transitional period, these buildings are often abandoned and in a state of disrepair, while the local communities, formerly their users, have no legal rights to continue using them. This paper analyses two case studies of rural cultural centres in the Nišava District – the cultural centre in Kamenica and the cultural centre in Gornji Matejevac. The focus of the analysis is on the aesthetic components of these buildings and the effects they generated during their active use, as well as their current aesthetic value and the impact they produce as abandoned structures. The aim of the paper is to examine the extent to which the aesthetics of these cultural centres and the symbols they embody as the only institutions of their kind in rural areas influence the local population. The expected outcomes are intended to provide a response to the hypothesis that an aesthetic imbued with specific ideological symbols, incorporated within the eclectic architectural style of cultural centres, and their subsequent devastation, affects community development and alters the identity of place.

Key words: *Rural Cultural Centres, Post-socialist Transition, Architectural Aesthetics, Community, Socialist Heritage*

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1. INTRODUCTION

Cultural centres in the territory of Serbia are closely linked to the period following the Second World War, the formation of Yugoslavia, and the introduction of the socialist political system. In accordance with the political strategies of that time, the construction of a large number of cultural centres was planned, with particular focus on the building of these facilities in less developed settlements. The reason lay in the perceived need for the existence of a central point for the development of the cultural aspect of the inhabitants' lives. Although the planned objective was not fully achieved, the construction of cultural centres with the aim of affirming the local community in both cultural and political terms represents an ambitious project of that period. With the dissolution of Yugoslavia, due to the transition and other political developments, cultural centres failed to survive as institutions because of unresolved legal issues and were gradually left to deteriorate. The subject of this research is the identification of the aesthetic characteristics of rural cultural centres as certain architectural and social phenomena of socialist Yugoslavia, as well as the analysis of the contribution of this architectural aesthetic to the formation of the identity of place and inhabitants through two selected case studies of cultural centres from the Nišava District. The methods applied in this research are analysis, synthesis, interview, descriptive and analytical research. The aim of the paper is to establish the relation between the aesthetics of socialist cultural centres and the society for which these facilities were intended, as well as to perceive the aesthetic properties of cultural centres today as abandoned institutions and their current relationship with society. By stratifying the phenomenon of the cultural centre through its aesthetic perception, the level of its significance will be observed primarily from a sociological aspect. The results should suggest that the importance of the existence of cultural centres was once considerable, even though the aesthetics and formality of the cultural centres cannot be characterised as highly valued architectural approaches. Also, today, with their closure, abandonment, and thus gradual deterioration, they form a new volume which acquires different aesthetic characteristics, and the effects of such a condition of the cultural centre on the inhabitants are entirely different compared to the active period.

2. METHODOLOGY

The research methods applied in aesthetics cannot be clearly defined, because the relationship between subject and method is causal. Therefore, the inclusion of methodological procedures from other scientific disciplines is required [1]. In this research, analysis, synthesis, case study, descriptive and analytical research will be applied, as well as interview as a method for a clearer insight into the relationship and connection between people and the cultural centres in their locality.

The selection criteria for the case studies in this research include their location in the Region of South-East Serbia, which is the least developed region; their proximity to the City of Niš, which serves as the regional hub and the centre of the Nišava District; and their inclusion in the Municipality of Pantelej, which encompasses a large rural area. Additionally, the selected villages Kamenica and Gornji Matejevac represent two different types of villages according to the Spatial Plan of the administrative territory of the City of Niš, which is important due to the size of their gravity area.

The paper will analyse the aesthetics of rural cultural centres as utilitarian architecture, their design and symbolism during the period of their construction and active operation, and subsequently the aesthetics of abandoned rural cultural centres which, through gradual devastation, form a new structure. Thus, the same buildings in different periods are interpreted as different phenomena, and their effect on society is examined. The social effects of both phenomena of cultural centres and their aesthetics are analysed theoretically and empirically, i.e., based on theoretical foundations as well as through interviews with local residents. The methodological approach can be defined as integrative-synthetic.

Aesthetics, in a general sense, can be defined as a philosophical discipline and the science of sensory perception of the world and phenomena. Contemporary tendencies in aesthetics primarily emphasise "the cultural context" [1]. In this paper, the focus will be on the aesthetics of context (environment), the aesthetics of architecture, and everyday aesthetics. The aesthetics of architecture represents an aesthetic sub-discipline. The field of everyday aesthetics is a relatively new area and is closely related to the aesthetics of architecture and the aesthetics of applied arts, whereby the observation and analysis of architecture is not conducted from the standpoint of art and technological skills, but from the standpoint of everyday life, that is, from people's everyday experiences and their aesthetic perception of architectural space. Everyday aesthetics in architecture uses coherent aesthetic analysis as the dominant method, taking into account two aspects: the everyday (routine and habitual) and the creative (different, specific) [1].

3. CASE STUDIES

Two cultural centres in the Nišava District have been selected to be used as case studies for aesthetic analysis. The cultural centres are located in the villages of Kamenica and Gornji Matejevac. The villages share a border and are located approximately 7.5 km from Niš. Basic data on these cultural centres are provided in Table 1.

Table 1. Data on cultural centres (source: author)

	Cultural Centre in Kamenica	Cultural Centre in Gornji Matejevac
Construction period	First phase of cultural centre construction (1945–1950) – unofficial data	First phase of cultural centre construction (1945–1950) – unofficial data
Legal holders of the property and land parcel	Socially-owned enterprise Agricultural and Industrial Combine "Niš"	Republic of Serbia (City of Niš), ex. Socially-owned enterprise Agricultural and Industrial Combine "Niš",
Type of rights, form of ownership and share	Ownership; social property; 1/1	Ownership; state and public property; 1/1 ex. Ownership; user rights; 1/1

Spatial position of the cultural centre within the village		
Land parcel area of the cultural centre	3368 m^2	2414 m^2
Building footprint	919 m^2	1004 m^2
Number of storeys	Basement + Ground floor + First floor	Basement + Ground floor + First floor
Subsequent interventions on the building	Sanitary facilities were added during the later socialist period	Certain ground floor rooms were adapted during the post-socialist period
Accent material	Stone	Stone
Current condition	Poor: the timber floor structure is significantly weakened, and part of the roof above the hall has collapsed	Poor: the building sustained fire damage, the consequences of which have not been remedied

3.1. Cultural Centre in Kamenica

3.1.1. Active period

Aesthetics of Context: The village of Kamenica is of unplanned origin and morphologically compact. In relation to its number of inhabitants, it belongs to the group of medium-sized villages. Due to the unplanned organisation of the settlement, there is no clearly defined centre. However, this was not achieved even with the construction of the cultural centre. The initial location for the cultural centre, which had the potential to develop into the "village centre", was at one of the main intersections, but this site was abandoned due to a tragic event involving young members of the People's Liberation Movement. The new location was established at the very entrance to the village. Although the cultural centre did not form the centre of the village, it successfully emphasises its beginning. Due to its dominant scale and the small square formed by the T-shaped base, it allows visitors to observe the most representative building of the village and, in doing so, signals their current condition and offerings in terms of cooperative products and cultural-entertainment events, thereby inviting further exploration of the village.

Aesthetics of Architecture: In terms of the functional aesthetics of the plan, the spatial units are clearly defined. The T-shaped base is divided into three parts. The frontal wing, parallel to the road, contains a decentralised entrance section accentuated by arches and columns, leading into a small hall with a bar, from which access is provided to the large hall where events were held. The hall and bar area enabled villagers to socialise before and after the events. The wing perpendicular to the road, in its ground floor volume, houses the cooperative section, positioned closest to the access road. It contained a shop also highlighted by columns and a balcony above, which belonged to the library. There was also a separate side entrance for the storage areas. The upper floor of this section comprised the administrative block and a library with a reading room. The basement level included an

additional inventory of storage and auxiliary rooms. Therefore, the clearly defined paths and movement schemes enabled villagers to comfortably use the cultural centre as a new architectural structure in the village. From the aspect of form, the volume of the building does not give the impression of massiveness, but rather of "modest grandiosity". The finish of most of the facade is in a neutral beige colour, highlighting the stone geometric articulation of the entrances to the communal and retail areas. Their form evokes a sense of approachability and seriousness. The repetition of larger windows and the accentuated geometric elements above them were not standard elements in rural environments. A further highlighted part of the building is the balcony near the road, which, together with the columns, forms the entrance to the cooperative shop. (Figure 1)

Everyday Aesthetics: The cultural centre hosted film screenings, performances, village gatherings, and associations such as folklore and marksmanship. The centre possessed a film projector, television, radio, and gramophone. Villagers emphasise that having a television was of great significance to them, as it allowed communal viewing and shared commentary on events and news. Some villagers hold very emotional memories of the cultural centre, such as seeing a film on the big screen for the first time. A particular sense of pride was associated with the activities of their centre – they highlight the recording of the first episode of the television show "Knowledge and Possession" (sr. *Znanje imanje*), and the marking of the 180th anniversary of the Battle of Čegar. Such events are remembered and often retold in the village, and the existence of the cultural centre contributed to the improvement of the cultural and social life of the residents. Through the operation of the institution and the presence of a dedicated space, new daily activities were developed or existing ones were transformed, thereby altering the aesthetics of everyday life.

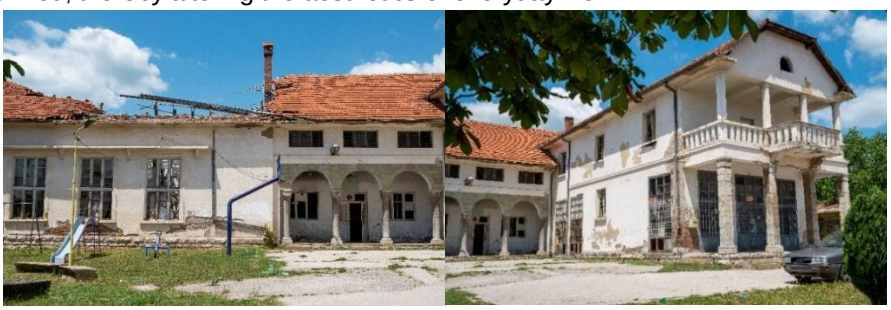

Figure 1. (a) Main entrance and roof damage above the main hall; (b) Entrance to the shop and the balcony (source: author, 2024)

3.1.2. Current period

Aesthetics of Context: The cultural centre is currently abandoned. The longest-lasting function was the village shop, which also had to be closed in the late 1990s due to unresolved legal and ownership issues. Last year, the building began to physically deteriorate. Just as its once dominant structure at the entrance to the village invited visits and signified development and activity, it now, in its devastated state, gives the impression that the village itself is in decline.

Aesthetics of Architecture: The new form of the cultural centre, shaped by partial collapse, presents a different kind of aesthetic. The previously coherent form, externally defined by minimalist architectural decoration, has been transformed with the emergence of numerous small elements — interruptions in the roof covering, protrusions of broken wooden structures behind the frontal walls, and shattered windows. In the interior, even more detailed aesthetic

traces of decay can be observed. The hall, once the central space for social interaction among villagers, has been transformed into a horizontal composition of broken roof tiles and spontaneously grown plants, which, during sunny periods, reach upwards and form a unique arrangement with diagonally positioned structural fragments. In the administrative block and library, a hint of the former "homely, cosy" atmosphere still lingers, indicated by the chandelier and crocheted curtains, while the deteriorating walls create non-repetitive patterns that speak to the centre's prolonged disuse. (Figure 2) Thus, the building does not evoke the impression of an entirely alien, menacing structure but rather, as described by residents, a sorrowful disintegration of something once cherished.

Everyday Aesthetics: Near the abandoned cultural centre stands one of the village's main shops, so residents frequently pass by the site. The small square in front of the centre is still occasionally used as a gathering place, as it contains benches, a table, and a playground added at a later stage. Inside the last-operating shop, numerous promotional posters remain, visual markers of the gradual transformation of the socio-cultural system and aesthetics of daily life during the 1990s. Since the building is not secured, certain movable furnishings have been removed. What remains includes the film projector, television, a few shelves, chairs and tables, and part of the library's book collection, which is continuously diminishing. There are currently no signs of restoration efforts, a fact well understood by the locals. The older generations, in particular, express feelings of nostalgia and disappointment, as they are confronted daily with the deterioration of the most important public building in their community, a building they are not legally permitted to restore.

Figure 2. (a) Cultural centre library; (b) One of the standard office rooms (source: author, 2024)

3.2. Cultural Centre in Gornji Milanovac

3.2.1. Active period

Aesthetics of Context: The village of Gornji Matejevac is categorised as a large rural settlement. Genetically, it is of an unplanned typology, while morphologically, it belongs to the clustered village type. The cultural centre was positioned at a busy intersection, and its T-shaped layout enabled the formation of a gathering space, allowing social life not only to take place within the interior but also to extend into the building's courtyard. The primary school and the local community office were built nearby, forming a central core within the otherwise unstructured settlement. Located at a crossroads, the cultural centre functioned as an architectural landmark of the village's central zone.

Aesthetics of Architecture: The building's plan form is shaped like the letter T. The frontal wing, containing the main entrance and hall, runs parallel to the main road. The hall, with a relatively large capacity, includes a balcony supported by columns with modestly decorated capitals and bases. The wing perpendicular to the main road accommodates a shop on the

ground floor, with its entrance facade highlighted by columns and the library's balcony above. This tract also contains storage rooms. The first floor houses administrative spaces and the library with a reading room. The building's position at the corner of the intersection provides a dominant visual presence. To further emphasise its verticality, the design of the balcony railing is echoed in the attic's decorative elements. The entrance portico of the cultural and entertainment wing is articulated with three arches supported by four circular columns with restrained decorative detailing. Above these arches, three regularly spaced windows repeat the rhythm established on the ground floor. (Figure 3) The ground floor facade is accentuated with stone finishing, while the upper storey and much of the remaining facade are rendered in ochre tones. A different type of stone defines the basement level, situated on a gently sloping terrain. As the hall extends parallel to the road, the facade features large window portals accentuated by a continuous decorative horizontal band. With its greater surface area and eclectic facade combining arched and geometric motifs, the cultural centre was readily identified as the focal point for cultural events in the village.

Everyday Aesthetics: The centre hosted film screenings, theatrical performances, village gatherings, children's shows, and other community events. All activities enjoyed high attendance. The ability to independently organise such events fostered a culture of community involvement and the improvement of village life. The main agricultural cooperative was located here, and communal gatherings in the afternoons and evenings contributed significantly to the quality of daily life.

Figure 3. (a) Main entrance to the cultural centre; (b) Entrance to the shop and the library balcony (source: author, 2024)

3.2.2. Current period

Aesthetics of Context: The cultural centre was closed following the dissolution of Yugoslavia. Today, the building is still positioned centrally within the village, and its immediate surroundings are actively used by residents for recreational purposes. On an adjacent plot, a football pitch was constructed, while the cultural centre's small square was converted into a basketball court. Various matches occasionally take place. Earlier this year, local residents organised several actions to clean up and maintain these courts. Information about these activities is often shared through the village's social media profile, which serves as a platform for updates about community initiatives. A fire that occurred several years ago severely damaged the building. Considering that, due to its volume and position, the cultural centre has retained its role as a landmark within the village, its devastated condition does not reflect the villagers' continuous efforts to maintain and adapt their settlement in line with contemporary rural development strategies. In 2022, the ownership of the cultural centre changed when it was sold at a public auction of the Socially-owned enterprise Agricultural and Industrial Combine "Niš" (PIK Niš). The City of Niš acquired the property, as well as the

neighbouring cultural centre in the adjacent village. Despite significant promises of renovation, this change in ownership has not brought any visible improvements.

Aesthetics of Architecture: The fire particularly devastated the interior of the centre, while externally, the damage is most visible in the missing window portals of the main hall. There have been attempts to repurpose parts of the building for new sports activities. This spontaneous functional adaptation led to a visually chaotic exterior, with the use of inappropriate materials, mismatched joinery, and partial repainting of sections taken back into use. One of the more absurd changes occurred inside, where the stage area behind the hall was bricked off to serve the local sports club's needs. The hall, which retains the blackened forms left by the fire, now ends in a bare, unplastered brick wall, creating a new visual identity – that of a ruin. (Figure 4) Additionally, the interior is covered in graffiti. This type of "vandalism" is uncommon in rural settings. In certain areas, such as the library, the intermediate floor is unstable, rendering entry unsafe. Nevertheless, traces of human presence suggest that people still enter the building. Despite its dilapidated condition, the original architecture remains partially legible.

Everyday Aesthetics: In the immediate vicinity of the cultural centre, a primary school and several general stores are still active, indicating that the village centre remains vibrant. Since the cultural centre is no longer in use, residents gather in these alternative locations (younger individuals in the schoolyard and older residents on benches in front of the shops). Their view often falls upon the abandoned centre. Although city authorities have announced its potential renovation, no actual plan for reactivation has materialised. In the meantime, as already noted, residents organise clean-up actions themselves, showing their own initiative to maintain the space. No original furnishings remain within the centre. The library space contains only broken shelves, now forming an unintentional geometric composition of wooden panels. Residents express disappointment that this central space has remained inactive for years. They feel the lack of a dedicated communal venue, which they believe is essential for a settlement of their size. Gatherings on benches are perceived as inadequate, contributing to a sense of monotony and prompting a growing tendency to seek cultural and entertainment opportunities in the city, which are no longer available locally.

Figure 4. (a) View of the walled-up stage in the main hall; (b) Balcony and entrance to the hall (source: author, 2024)

4. DISCUSSION – EFFECTS ON THE COMMUNITY

The cultural centre, as a phenomenological entity, reflects a specific period, a segment of history, a moment of directed rural development and an attempt to reshape the perception of cultural life among rural populations. Cultural centres represented cultural spaces in villages that developed in accordance with the needs of the local residents, yet not according to the

predetermined plan and programme, thus not fully meeting the criteria nor fitting into the context of the "ideological-theoretical matrix" [2].

Cultural centres were the result of collective labour, which was both intended to be and indeed represented a hallmark of socialism: the emphasis on community intended to stimulate "general social discourse" and highlight the importance of social benefit as a key impression and criterion by which the significance of a work is determined. The intended typicality of the cultural centre, i.e. a certain alignment of functionality, may be observed as a "sum of dominant phenomena and relations at a given time, thus representing an important characteristic of art that should reflect objective reality" (according to Georg Lukács' theory of reflection) [3]. Examples of typicality and uniformity may be noted in the cultural centres in Kamenica and Gornji Matejevac, where the same plan type was used, though the facade treatment differs in certain details. Although Kamenica was a medium-sized village at the time, it showed tendencies toward development, and thus a larger cultural centre was planned.

Ideological and political meanings are evidently present and embedded in cultural centres, as symbols of the former system can still be discerned (five-pointed stars prominently displayed on the facades). However, the residents do not consider removing these symbols, even though they no longer identify with the former system and, with historical distance, now recognise the broader context of political propaganda. Nevertheless, they believe the cultural centre brought certain benefits and significantly influenced how leisure time was spent. Architecture develops in response to specific social demands and is determined by socio-cultural conditions; it adapts to these conditions in formal, aesthetic, and ideological terms [4]. In that context, cultural centres, as a new type of building located in the village centre or, in the case of Kamenica, at the very entrance to the village, represented an ideological aspiration towards progress, even though there was later insufficient investment in their further development. The cultural centres in Kamenica and Gornji Matejevac reflect the needs of the village at the time through their massing. The layout shape defines a usable open space, and thus the T-shape offers greater possibilities for forming gathering spaces.

From the perspective of form and architectural aesthetics, there was a direction suggesting that cultural centres should possess certain visual characteristics to distinguish them and indicate their significance. However, these visual characteristics were neither predetermined nor explicitly defined [5]. Arches and columns at the main entrances stylistically reflect traits of socialist realism, as well as the traditional architecture of the region, albeit with changed materialisation. These arches and columns were intended to suggest a function different from residential use. Neutral colours dominate the facades of both cultural centres, and stone appears as a secondary dominant material. The rhythmic arrangement of large windows on elongated facades is a leading motif in both buildings. Architectural details on the cultural centres in Kamenica and Gornji Matejevac are also very similar.

The economic position of the village and social perception of the yet-to-be-formed space must also be considered. Introducing these aspects clarifies the approach to creating a rational architecture and aesthetic directed toward achieving social significance. Although seemingly simple and unimpressive in terms of the architectural innovations of the time, they fulfilled the anticipated social needs. While these buildings may not stand out for their architectural value or significance, their "symbolic charge" is more pronounced and supports the assertion that the symbolic nature of a building is not necessarily proportional to its aesthetic value. The emphasis was therefore primarily on functionality, to which residents

had to become accustomed and familiar during the construction process. The architecture of cultural centres was meant to be close and accessible to the people, that is, "socialist in content and national in form" [6].

The analysed cultural centres also exhibit programme similarity. This can be attributed to the comparable level of cultural development in the villages. The notion of everyday life encompasses routines, familiar elements, a certain continuity of action and activity, and habits [1]. According to the residents, cultural centres were quickly accepted, thereby enhancing the aesthetic of daily life. Inhabitants felt a desire and need to spend time there. The ritual of visiting the cultural centre after agricultural work or labour in the city contributed to the aesthetic dimension of daily routine, as a nearly everyday act in support of their social and cultural lives. Residents state that the atmosphere offered by the centre in terms of space, light, and the vibrancy of visitors had a direct impact on improving the quality of leisure time. The most attended events were film screenings, dances, and village gatherings. In the summer, people gathered outside the centre, although main events were held in the large hall. Among the available activities, the library was the least visited. The reason for this was that people primarily came to the cultural centre for the aesthetic atmosphere it offered. Community interaction, including passive presence (e.g., collective television watching), were favoured activities, and these experiences reveal the residents' perception and aestheticisation of using the cultural centre during its active period. It should be noted that in terms of entertainment content, these sometimes bordered on kitsch, as popular commercial music performers occasionally held events there. From a cultural perspective, such content is not entirely appropriate to the function of a cultural centre. Nonetheless, residents agree that even such content was necessary from time to time. It is evident that the cultural development process required transitional content of this kind. The period when cultural centres in Kamenica and Gornji Matejevac were active was marked by significant influence on the local community (contributing to social cohesion, development of collective identity, and the formation of personal development). Moreover, one of the intended goals was achieved: the development of political awareness among rural inhabitants, fostering a sense of "personal participation in the construction of socialism".

The dissolution of Yugoslavia led to a transition from a socialist to a capitalist social system, accompanied by a period of societal transformation. The negation of the previous system, the strengthening of nationalism, as well as the confrontation with economic crises accompanied by deindustrialisation and privatisation, directed political tendencies and strategies towards attempts to address these issues. As a result, rural development was once again sidelined and often omitted from detailed considerations [3]. Cultural centres thus remained symbols of socialist tradition and planning even after the breakup of Yugoslavia. Today, even in a state of devastation, they represent the clear end of that ideology and the abandonment of its developmental aspirations. This highlights the problem of contemporary socio-cultural values, where the village is once again marginalised, without consistent investment or planning for cultural events. What is predominantly mentioned regarding rural areas is the opportunity for rural tourism, which primarily brings economic profit and tends to commercialise rural potentials if developed rapidly and without planning. However, very little investment is made in the cultural and social aspects of village inhabitants' lives. And even when certain initiatives for renewal exist, they do not belong to a long-term strategy for rural development. In the case of these two centres, there is no plan for renovation or reactivation. They are thus left to decay over time, creating new structures and aesthetic compositions of

ruin that cannot be precisely predicted. The collapse of a prominent and frequently visited village site demotivates the residents, causing frustration, sadness, and fear of being neglected and alienated from the nearby urban city structure.

While architecture was once a direct medium for expressing socialist ideas, it is now characterised by a certain intrigue created by crumbling walls shaped primarily by the passage of time. The aesthetics of ruin may be seen as an invitation to discuss society, lifestyle, politics, and architecture itself, along with its remnants. Damage to the structure may be defined as any change that has occurred during or after its use. Depending on the type, such damage does not necessarily impact the building's functionality, but as it progresses, it may render the space unsafe and unfit for its original purpose [7]. Simultaneously, damage alters aesthetic value. Aesthetic value is still present, but in a different form and interpretation. This is evident in the cultural centres in Kamenica and Gornji Matejevac, which have undergone various forms of devastation. The initial stage involved the disappearance of inventory and furniture, which occurred more gradually in the cultural centre in Kamenica. The cultural centre in Kamenica experiences a "natural" form of devastation due to abandonment, structural weakening, weather conditions, and the passage of time. The cultural centre in Gornji Matejevac suffered a fire, followed by vandalism from unknown visitors who further damaged the interior by creating often inappropriate graffiti. These modern ruins are depictions of ephemerality; they are not permanent and will continue to transform unless such processes are halted through planned intervention. Despite symbolising transience, the ruined cultural centres now possess a new ambient and narrative value, creating a different dialogue with the community. To emphasise the aesthetic qualities of a structure, the surrounding environment also plays a key role. The deterioration of a structure once crucial to the community's cultural life may also be interpreted as a metaphor for life itself.

With the abandonment and decay of the centre, residents are deprived of their only existing platform for cultural events, forcing them to spend their leisure time in the city or adapt activities to current limitations. In Kamenica, for example, people still gather in the courtyard of the cultural centre or in front of the local shop. However, these spaces are inadequate for accommodating larger groups, indirectly forcing residents to confine their social activities to private yards, which themselves are often too small to host community-scale events. This reduction in community interaction decreases the level of socialisation, and people become more oriented towards close acquaintances, which negatively impacts inclusivity in villages that, compared to cities, have significantly smaller and simpler urban structures. To realign the cultural aspect of rural life with contemporary tendencies, it is necessary to define development goals and formulate a strategic plan. It should be noted that most village residents support the idea of renovating the existing cultural centre. They also support constructing new buildings at different locations, but due to the established emotional and spatial connection with the current cultural centre and its location, they would not support its demolition, but rather its renovation in accordance with expert recommendations.

5. CONCLUSION

Today, cultural centres predominantly serve the function of remembrance of a previous period of social organisation. The aesthetic quality of the architecture of cultural centres should primarily be interpreted as a project of a political system that aspired to economical and primarily utilitarian buildings, without, at that time, a developed and clearly defined

stylistic direction, while the aesthetic understanding of the abandoned cultural centre is in fact a sensory analysis of a dynamic structure caused by the parameter of time, as well as by other complex factors.The effects on society caused by this discontinuity in the development of cultural centres are particularly significant, and through communication with the villagers, the necessity of a cultural space is perceived, a context of a central gathering place that would communicate with its users.

Considering the aesthetics of architecture and everyday aesthetics in both the active and current period of the two case studies, which are relatively close to each other, it is observed that cultural centres, although architecturally simple structures, are in fact highly complex compositions containing aesthetic and symbolic details, utilitarian aspects, social, political and cultural nodes. Although cultural centres may be described as symbols and materialised elements of the strategic cultural policy of the socialist government, it is undeniable that they had an affirmative impact on the local community, as such a space was necessary for the village as a turning point in its development. The closure and deterioration of cultural centres in representative locations can be interpreted as a depiction of the current relationship between rural areas and state development strategies, whereby this has an impact on the degradation of the identity of place and community. Although in poor condition, the residents do not feel the need to distance themselves from the building, in which some of their ancestors participated in construction or with which they are emotionally connected through memories associated with the cultural centre. Thus, among the locals, emotions of melancholy and nostalgia prevail, as well as frustration due to their inability to help or influence restoration, and subsequently the development of new potentials that the cultural centres would likely gain through revitalisation.

Future directions of research should examine what approaches to the process of revitalisation would be appropriate for this architectural typology, in order to ensure the quality of the aesthetic atmosphere, bearing in mind that certain cultural and social patterns of the inhabitants' leisure time have changed over time.

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Review paper

PIONEERS OF PREFAB ARCHITECTURE – CRYSTAL PALACE AND MAISON CITROHAN

Danijela Đurić Mijović[1], Vuk Milošević[2], Danijela Milanović[3], Aleksandra Cilić[4], Miloš Nedeljković[5]

Abstract

Although prefabricated buildings have long been present in modern civil engineering and architectural practice, they still have strong supporters and opponents. This paper explores the achievements of prefabricated construction in the 19th century and the first half of the 20th century by presenting two significant buildings: Joseph Paxton's Crystal Palace in London from 1851, and Le Corbusier's Maison Citrohan in Stuttgart, developed between 1920 and 1927. These authors and their buildings - each in their own time - pushed the boundaries of prefabricated construction through their authenticity, ideas, visions, applied technologies, and materials, opening the door to a method still in use today.

Keywords: *Prefabrication, Technology, Joseph Paxton's Crystal Palace, Le Corbusie's Maison Citrohan.*

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1. INTRODUCTION

Prefabricated construction is a field in architecture and civil engineering that, since the inception of the very idea, has continuously gone through phases ranging from approval—even euphoria—to disappointment and abandonment. In the ups and downs of prefabrication, civil engineers have primarily focused on solving practical issues, from designing connections, producing large-scale components, and ensuring material quality to developing the machinery necessary for transporting and assembling prefabricated elements. Over time, architects and designers have oscillated between enthusiasm and disdain for this system. Visionaries eagerly await technological innovations and opportunities to break free from conventional spatial design for living and working environments. In contrast, some designers remain reserved and opportunistic, considering buildings constructed this way overly simplistic, standardised, and limited in aesthetic potential.

The concept of prefabrication is subject to various definitions and interpretations over time. At its core, prefabricated construction refers to a building method based on elements produced either in a factory or on-site, which are assembled into a whole at the construction location. As buildings can be constructed from different materials, this definition should encompass all materials, primarily wood, steel, and concrete, as the most common. However, due to the development and widespread use of concrete prefabricated elements in the second half of the 20th century, it is not uncommon for prefabrication to be associated predominantly with factory-made concrete structures.

In a broader sense, buildings that can be defined or categorised as “prefabricated” can be found across the globe throughout different stages of societal development. These structures are typically tied to locally available materials, inherited technologies, and prior advancements. The Mongolian yurt, which dates back to the 13th century, continues to be utilised in contemporary society [1]. In North America, a significant example is the wooden panelling building brought by the English to Cape Ann, Massachusetts, in parts assembled there as early as 1624 [2]. This structure served as housing for a fishing fleet. Due to the nature of the work, which required frequent relocation, these buildings were often disassembled, transported, and reassembled multiple times. It is also important to mention examples from the Western Balkans, where people were forced to move due to unstable living conditions and adapted some of their dwellings to suit a more mobile lifestyle [3].

Although the above-mentioned facilities can be compared to modern prefabricated construction in some ways, they show the importance of having a shelter and property, along with the speed of construction and the ability to relocate structures, either in whole or in part according to current needs, has always been significant. This need has consistently served, as it still does today, as a powerful motivation. This research aims to explore the origins and core principles of prefabricated buildings as we know them today. It is based on analysing relevant literature and case studies focusing on two architectural visionaries: Joseph Paxton and Le Corbusier.

2. IMPORTANT PREFAB BUILDINGS OF THE 19th AND 20th CENTURIES

"The strength of the prefabricated house lies in its popularity, its cheapness and the industrial base from which it operates. These are precisely the areas in which modern architecture is weakest. Modern architecture is unpopular, expensive and divorced from industrial production. This is why whenever it has tried to extend its field to include the territory of the prefabricated house, it has failed and been forced to retreat."
Davies, 2005 [4]

This section presents two significant buildings: Joseph Paxton's Crystal Palace, built in 1851, and Le Corbusier's Maison Citrohan, completed in 1927. Each of these structures, in its own time, pushed the existing boundaries of construction and reshaped the perception of architectural culture in terms of public spaces intended for the masses and private residential environments. Through their innovative approaches, these projects captured the interest of professionals and users alike and contributed to humanity's ongoing pursuit of improving spaces for living and working.

2.1. Crystal Palace

Inspired by the Exhibition of Industrial Achievements held in France in 1849, Prince Albert conceived and initiated, while the Royal Commission organized, the Great Exhibition of the Works of All Nations. The goal was to showcase numerous important innovations from across the globe, resulting from discoveries made during the Industrial Revolution. At a time when Britain and France were engaged in constant competition—even in terms of innovation and technological advancement—this exhibition was the first to include other nations and their inventions. It is considered a forerunner of today's world-renowned EXPO exhibitions. A design competition was announced for the exhibition building that could be located in Hyde Park, requiring a net floor area of 800,000 square feet (74,000 m²) and a maximum budget of £100,000 [5]. The structure was expected not only to impress the world and demonstrate the strength of the British nation but also to be the largest building ever constructed at the time—and cheaper per cubic foot than previously built structures of a similar type.

The time constraints were also challenging: the competition ran from March 13 to April 8, 1850, while the exhibition opening was scheduled for May 1, 1851, leaving less than 13 months for the entire project. An additional challenge was the requirement that the building be dismantled after the exhibition and that the trees in Hyde Park remain untouched. A total of 245 proposals were submitted, including 38 international entries. The Building Committee rejected them as unsuitable or too expensive (some exceeding the proposed budget by up to three times), causing dissatisfaction among several architects.

The situation grew tenser as it had already been announced that Queen Victoria would personally open the exhibition. Only then did the renowned gardener and greenhouse builder Joseph Paxton express interest. With building engineer William Barlow, Paxton quickly submitted a proposal for the exhibition hall (Figure 1a). Since their design met the key criteria—rapid construction, cost-efficiency, and the ability to be dismantled—the Building Committee approved the project on June 20, 1850.

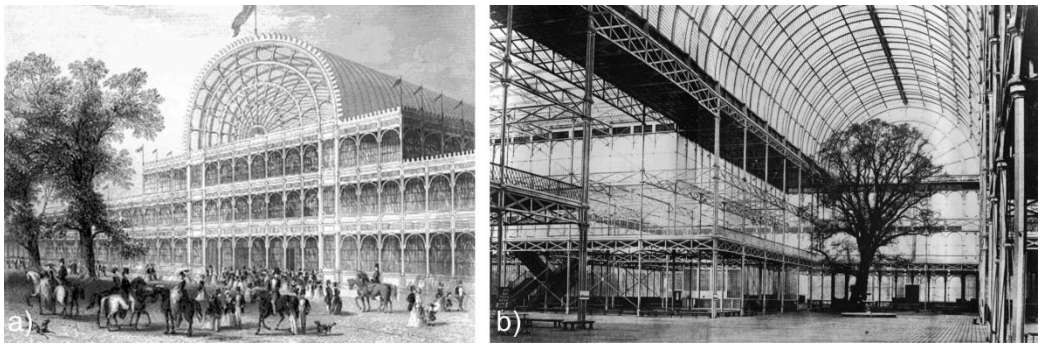

Figure 1. a) Crystal Palace 1851, b) interior with elm tree [6]

The dedication and consistency of the competition organizers is also evident in the episode when the 11th July Committee, while reviewing and approving additional sketches and drawings, requested that the height of the structure be increased by approximately 20 feet (6.1 meters) to avoid cutting down three large elm trees (Figure 1b). This request was fulfilled with the construction of a laminated timber arch system, which had been discovered and patented by J. Paxton ten years earlier. Constructed with cast iron, wood, and glass, the Crystal Palace became the largest building in the world at the time, symbolizing the pinnacle of the First Industrial Revolution's achievements.

At a time when buildings were most often built of stone and clay products, a time-consuming process requiring skilled workers, the Crystal Palace—measuring 564 x 139 x 39 (41) meters—was conceived, designed, all the necessary components manufactured, then transported to the site and assembled, so that the building was fully completed in 39 weeks [7]. Figure 2 compares the traditional construction methods used up to that time with J. Paxton's improved process, showing that the construction of the Crystal Palace was at least three times faster, which was made possible by several important factors: modular construction, industrial production of standard elements and fasteners in factories, and the possibility of continuing and combining standard elements to obtain new elements.

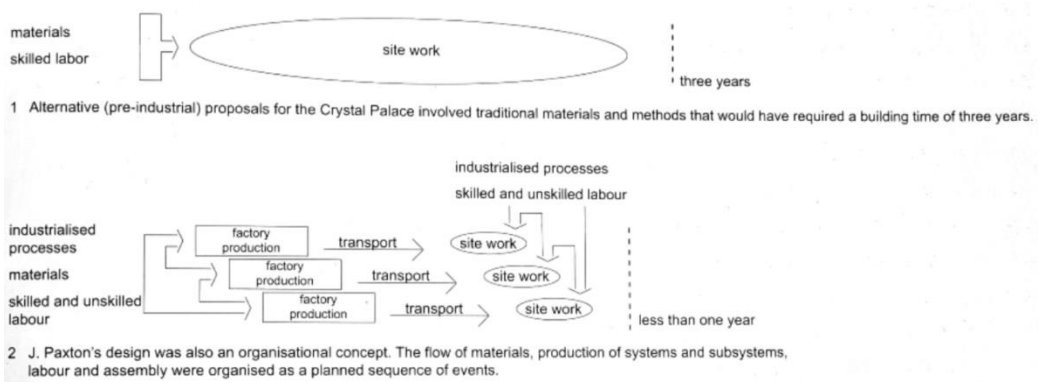

Figure 2. Comparison of pre-industrial and early-industrial production, organization, and assembly of Crystal Palace [7].

The Crystal Palace earned the reputation as the most transparent and light-filled building of its time, thanks to its glass roof and envelope. At the time, glass could only be manufactured in sheets measuring up to 1.25 meters in both dimensions, so the author took glass panes 1.25 x 0.25 meters, requiring more than 293,000 identical panes to complete the building envelope. All the glass panels used were of uniform size. Since Britain's largest glass producer, Chance Brothers (Smethwick), could not fulfil such a large order within the required timeframe, additional glassworks were hired from Saint-Gobain, France.

The glass panels were installed in wooden frames supported by cast-iron trusses and columns, while the foundations were made from concrete. All components were fully prefabricated and mass-produced. These standardized parts were combined with identical or different elements to create new forms. This approach reduced the number of manufacturing elements and increased batch production, leading to an overall cost reduction. The entire structure used just two types of columns, both with the same cross-section: one measuring 22 feet (6.7 m) for the ground floor and the other 20 feet (6.1 m) for the upper levels. Assembly was carried out independently, as all components were self-supporting and were later connected to form the complete structure.

The building featured natural lighting, ventilation, and drainage—characteristics that define sustainable architecture today. Remarkably, the construction did not disturb the existing vegetation in the park; instead, it was preserved and integrated within the building itself. The Crystal Palace was built by a workforce of 2,000 people. At that time, the total construction cost was £80,000 (equivalent to approximately £9.3 million in 2024). During the 5.5-month-long exhibition, the structure attracted six million visitors [5].

Figure 3. Crystal Palace in Sydenham 1928, Historic England Archive. Aerofilm Collection. EPWO21373 [8].

This remarkable structure is considered the true spark of prefabricated construction. After the exhibition, it was dismantled, relocated to Sydenham in southwest London (Figure 3), and reassembled, where it served various functions until it was destroyed by fire on November 30, 1936.

2.2. Maison Citrohan

"The house is a machine for living in." Le Corbusier [9]
"His vision of industrialization and its implementation in architecture is closer to the mythification of an era and his will for progress than to the reality, he leaves on the technological development not only the renovation of architecture, but the revolution of the whole society." Alfonso Diaz Segura [10]

The period after World War I posed a challenge for all areas of life and work, especially for architecture and construction, given the devastated housing stock, mass population migrations, and the urgency of solving these problems. Aware of the current situation and the necessity of new approaches, Le Corbusier emphasizes the following recommendations, considering them important for the future Modern Architecture: an unreserved acceptance of new materials, technologies and construction systems, awareness of new social realities, and he emphasizes that manufacturing had to be based on industrial dynamics with rational and efficient task management [11,12].

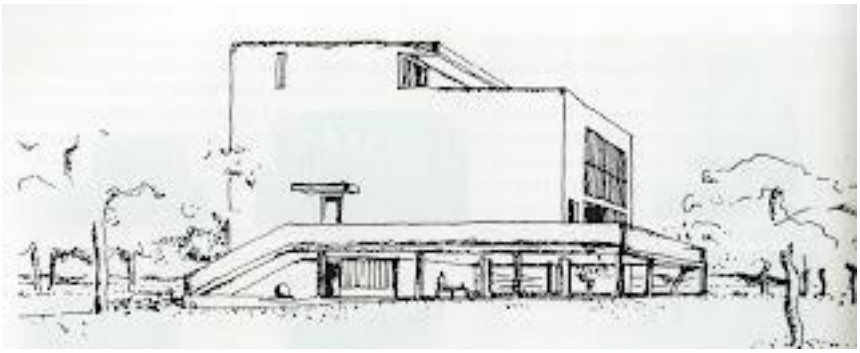

Figure 4. Sketch of Maison Citrohan [13]

As one of the possible solutions to the set requirements, prefabrication, more commonly known as prefabricated architecture, is proposed. Le Corbusier created three basic house prototypes in line with these trends: the Domino, Monol, and Citrohan (Figure 4). The name of the last prototype is provocative and intentionally reminiscent of Citroen, a popular car brand at the time, thus emphasizing the object as a "machine for living." World War I and its consequences significantly influenced the design of these models, so, in addition to aesthetics, the focus was placed on functionality and accessibility for ordinary people to enhance people's daily lives. Maison Citrohan evolved through five versions from 1920 until 1927, each representing an improvement over the previous version. The first version spans three floors and includes everything necessary for a comfortable life for a single person or a family, such as a yard and a usable roof terrace. The idea stems from Parisian painting studios, resulting in a living room with a double-height ceiling and full-height windows facing north. In 1925, for the first time, there was an opportunity to construct these buildings as living units for workers in Pessac, prompting the author to reduce the dimensions and forgo the double-height ceiling. From the foundational idea, with continuous improvements by 1927, Le Corbusier and Pierre Jeanneret designed the fifth version of Maison Citrohan, which was showcased at the famous Weissenhof exhibition in Stuttgart, where it radiated in its full glory and became synonymous with a modern and accessible building (Figure 5).

The evolution of the Maison Citrohan building through five variants in seven years, starting from an idea based on a Parisian painting studio and progressing through a series of improvements, refinements, and simplifications, culminates in the final model. Recognizing industrialism and technology as essential for societal advancement, Le Corbusier envisioned the Citrohan house as efficient and innovative, aimed at enhancing the living conditions of the working class. By creating an efficient design, the houses would be constructed from mass-produced, readily available materials such as concrete, and the factory-produced components would resemble parts on an assembly line, illustrating his concept that the Citrohan house mirrors not only the efficiency of cars but also the very method of production.

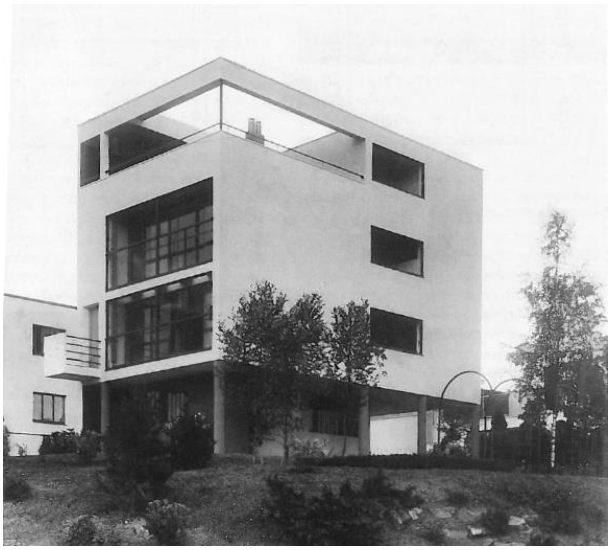

Figure 5. Le Corbusier's Maison Citrohan 1927 [14].

3. CONCLUSION

In contemporary architectural practice, opinions occasionally challenge prefabrication as a construction method regarding certain aspects. However, with the tools available today for designing, manufacturing, and installing prefabricated building elements — from the foundation to the façade systems — the characteristics of prefabrication can now be regarded solely as advantages.

The emergence of modern prefabricated construction, as we define it today, is fundamentally rooted in the Industrial Revolution. Through significant and numerous inventions, the Industrial Revolution transformed the concept of production and, consequently, the construction of buildings themselves. Therefore, prefab architecture results from new technological knowledge, improved processes, and people's willingness to explore, refine, and adapt new concepts to their environments and circumstances.

Today, we must understand prefabrication as a broader concept, especially as technical, technological, and digital innovations have introduced a variety of materials and systems into the market. An additional challenge lies ahead in controlling carbon footprints and the emerging influence of artificial intelligence in this field.

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Research paper

SPEED AND ROAD GEOMETRY EFFECTS ON ROAD SAFETY: INSIGHTS FROM THE ŠTIP–RADOVIŠ SECTION OF THE A4 IN NORTH MACEDONIA

Maja Vitanova[1], Zlatko Zafirovski[2], Slobodan Ognjenovic[3], Riste Ristov[4], Ivona Nedevska - Trajkova[5], Vasko Gacevski[6]

Abstract

The development of a country is often reflected in its road infrastructure, but true civilization is measured by how well it prioritizes the health and safety of its people. As roads expand, traffic increases, and speeds rise, ensuring human well-being must remain a key focus. Road design plays a crucial role in safety, with vehicle speed being a decisive factor. While higher speeds can save time and reduce costs, they also heighten risks, leading to accidents and casualties. This paper analyzes vehicle speeds along a specific road section, comparing them to official speed limits. Based on findings, improvements will be suggested, which may involve adjusting speed limits, modifying infrastructure, or enhancing road signage and equipment. Some changes could even impact the road's classification. Ultimately, the aim is to create a safer environment for drivers and pedestrians, minimizing risks while maintaining efficiency in transportation.

Key words: *Road, Speed, Safety, Geometrical Design Elements, Traffic*

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1. INTRODUCTION

Road safety depends on matching speed to road design. Drivers must adjust their speed to suit road geometry, weather, and traffic, while engineers must design roads that guide and support safe travel behavior [1]. Safe speeds on well-designed roads save lives.

Speed doesn't operate in isolation—how fast vehicles can safely travel depends heavily on the design of the road itself. Road safety is significantly influenced by both the velocity of vehicles and the geometric design of the roadway. Understanding this relationship is essential for designing safer transportation systems and encouraging responsible driving behavior. Key elements of road geometry that influence safety include:

- Curvature and Alignment: Sharp horizontal curves at high speeds increase the likelihood of losing vehicle control [2]. Roads must be designed with curves that match safe operating speeds.
- Sight Distance: Roads should provide adequate stopping sight distance—the length of road visible to a driver to safely stop if needed. This distance increases with speed.
- Lane Width and Shoulders: Narrow lanes or shoulders can be dangerous at high speeds, especially for larger vehicles. Wider lanes improve safety on high-speed roads.
- Grade (Slope): Steep downgrades can increase braking distance, especially in wet conditions. Speed limits must consider road slope to prevent runaway vehicles.

A road's design speed is the maximum safe speed that can be maintained under ideal conditions. Safety improves when operating speeds are consistent with this design speed. Sudden changes in road geometry without proper signage or transition can lead to driver error and crashes [3].

The aim of this paper is to compare, in a simple and straightforward way, the permitted vehicle speeds with the speeds that the geometric elements of the road can support. Based on the results of this comparison, appropriate measures will be determined or solutions proposed to improve traffic safety. The defined procedure in the methodology will allow for the assessment of any existing road and its corresponding improvement. Additionally, the methodology will be applicable to roads that are in the design phase, allowing timely implementation of necessary modifications [4].

The objective of this work is to identify the need for and locations where speed should be reduced in order to enhance safety. On the other hand, it will also assess whether there are places where speed could be increased, with the aim of creating longer road sections with consistent speeds [5].

2. METODOLOGY FOR EVALUATING SPEED'S IMPACT ON ROAD SAFETY

To examine the impact of speed on the safety of road users along a specific road, it is necessary to utilize all available theoretical and experimental knowledge. For this purpose, the paper applies a methodology that aligns the geometric elements of the road with the applicable vehicle speeds. This relationship can be illustrated through a design speed diagram [6].

To begin, an existing road alignment is selected as the basis for the study. The start and end points of the alignment are defined. Along the entire length of the road, all traffic signs

indicating speed limits are recorded based on actual field conditions. If there is other relevant vertical or horizontal traffic signage, it is also recorded. Using an indicative method, it is assessed whether there are other factors along the route that could influence the results of the analysis [7].

If there are artificial or natural objects, equipment, or obstacles on or near the road, they should be noted by type, location, and size. These may be part of the road infrastructure or independent of it, but what matters is whether or not they impact road safety. All these observations are entered into a special section of the longitudinal profile. Care must be taken to accurately record the direction in which these elements are located, which is especially important for speed limit signs [8].

Once this base layout is prepared, speed diagrams are drawn. Diagrams should be created for both directions of travel, for both the horizontal and vertical projections of the road. These are then superimposed into two summary diagrams—one for each direction. A comparison is made between the summary speed diagram and the actual speed limits on the road [9].

Based on the comparative speed diagram, the following parameters are examined:

- The lengths of the transition curves,
- The radii of the horizontal curves,
- The longitudinal gradients of the road profile,
- The vertical and horizontal traffic signage.

All these parameters define the level of driving safety [10].

If any of the listed parameters do not meet the required standards, improvement measures are proposed for those segments. These measures may include:

- Reconstruction of a horizontal curve to increase its radius,
- Reconstruction to increase the length of transition curves,
- Reconstruction of one or two consecutive vertical curves to reduce the longitudinal slope,
- Addition of a lane for certain types of heavy vehicles if they are slowing down traffic on a segment,
- Installation of traffic-technical signage for speed limitation,
- Application of specific measures for forced speed reduction, etc. [8]

The primary goal of all these measures is to enhance the safety of road users. At the same time, they contribute to greater driving comfort and improved traffic flow. By defining the maximum speeds that the road can safely and comfortably support, the road's potential is assessed, which may also justify an upgrade in its classification [9].

This detailed insight into the relationship between speed and road geometry enables the development of concrete plans, procedures, and projects aimed at enhancing road safety along the examined route [11].

3. ANALYSIS OF THE SELECTED ROAD SECTION

For the purposes of this thesis, the selected section for analysis is the Štip – Radoviš segment of the A4 main road.

The base documentation used for the examination of this road is the original design project upon which the road was constructed. From this project, the cross-sectional profile,

horizontal alignment, and vertical alignment were obtained. The consistency between the designed and constructed road was verified by comparing the alignment from the project with satellite imagery on Google Maps. The cross-sectional profile was confirmed through field inspection. Since these elements align with the original design, it is assumed that the constructed vertical profile (grade line) matches the designed one. Consequently, the longitudinal profile from the base project—containing all relevant data—was used to develop the speed diagram [12].

To assess the actual on-site conditions, a continuous video recording was made along the entire length of the road. The video was recorded from a moving passenger vehicle. From the footage, data regarding the placement of speed limit signs was extracted. During the data collection process, continuous comparison and verification were made with the project's alignment plan to avoid errors. No discrepancies between the recorded data and the design documentation were observed.

From both the video recording and a visual field inspection, it was determined that the alignment is completely "clear," meaning there are no additional objects, equipment, or obstructions of any kind that would influence vehicle speed or compromise visibility and road safety. The route includes several bridges, retaining structures, overpasses, and interchanges. All are in good condition and fully functional, without hindering the use of the road.

Along the alignment, there are no tunnels, no railway crossings, no major watercourses or reservoirs, and no parking areas, gas stations, or service facilities of any kind [13].

3.1. Speed Limit Diagram for 110 km/h

In the situational-horizontal design of the expressway, there are 37 horizontal curves. Some of them have transition curves, while others do not. The radii range from 400 m to 5,000 m. Calculations for the lengths of acceleration and deceleration were made using an Excel table. All values for the radii of the horizontal curves, as well as the values for the transition curves, were entered accordingly. The transition curves do not affect the calculations but are included in the same column for practical reasons, facilitating easier comparison with the obtained values for the lengths of acceleration and deceleration.

By inserting the appropriate formulas for calculations, all values for acceleration and deceleration lengths are obtained in a few simple steps. The calculations were based on the maximum allowed speed of 110 km/h, the maximum allowed cross slope i=7%, and the radial friction coefficient f=0.157 [13].

The results from the table show that only one curve does not meet the conditions for movement at a speed of 110 km/h, as shown in Table 1.

The curve's elements allow movement at a speed of 107.39 km/h. This curve is located between station 6+723.72 km and 6+839.80 km. If we examine the speed limit signage, it is evident that before the curve, at station 6+300.00 km, there is a 100 km/h sign—an appropriate measure to ensure safe driving.

Table 1. Calculations for the Speed Diagram, for a Speed of 110 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp" calculated [km/h]	Vp" selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
400	110	107.39	107	2.61	108.69	43.86	21.93

Similarly, in the opposite direction from Radoviš to Štip, before this curve, at station 7+100.00 km, the speed is limited to 100 km/h by a traffic sign.

The table 1 shows that the curve with a radius of 400 m has transition curves of 50 m, which satisfy the required lengths for acceleration (43.86 m) and deceleration (21.93 m) when entering and exiting the curve, respectively. This indicates that although the radius is relatively small, the curve still has acceptable geometric characteristics from a safety standpoint [14].

The speed diagrams for both directions are shown in the following diagram, in Figure 1.

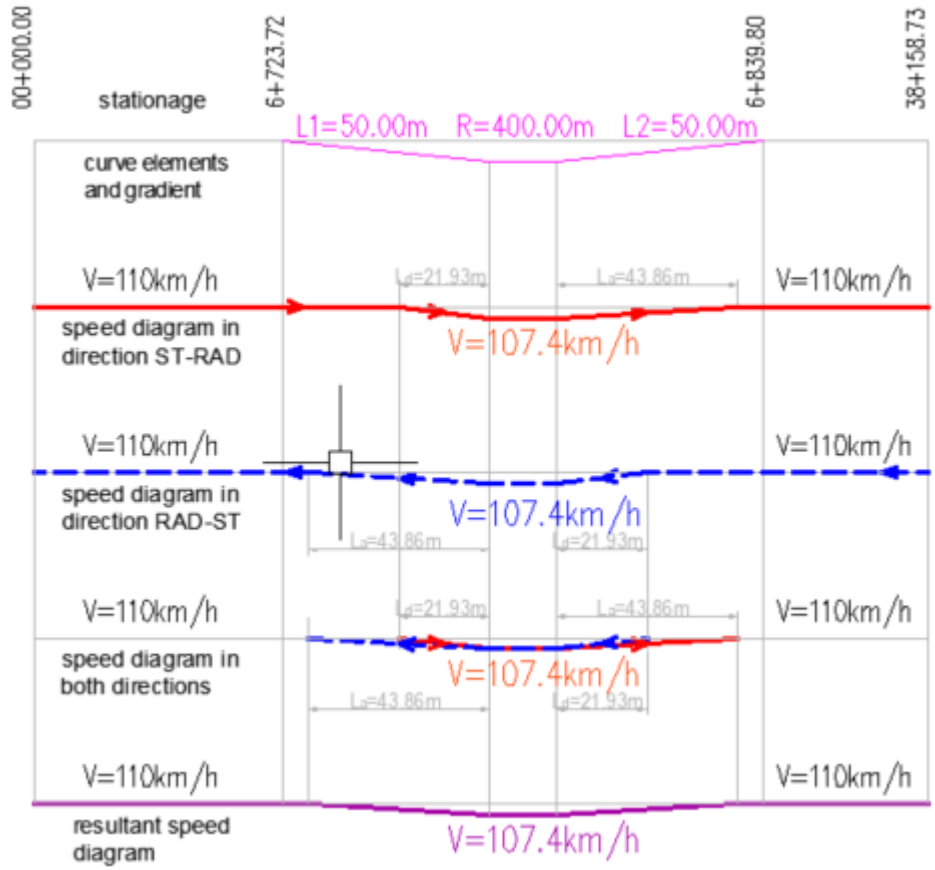

Figure 1. Speed Diagrams for the Curve with the Smallest Radius in Both Directions at V=110 km/h

When constructing the speed diagram dependent on the vertical alignment (grade line), only the longitudinal slopes within the range of i>4% for ascents and i<−5% for descents are considered.

The examined expressway has only one such section. The longitudinal slope has a value of 5.77% from station 33+665 km to 34+035 km, with a total length of 370 meters.

The diagrams for both directions are shown in the following diagram, in Figure 2.

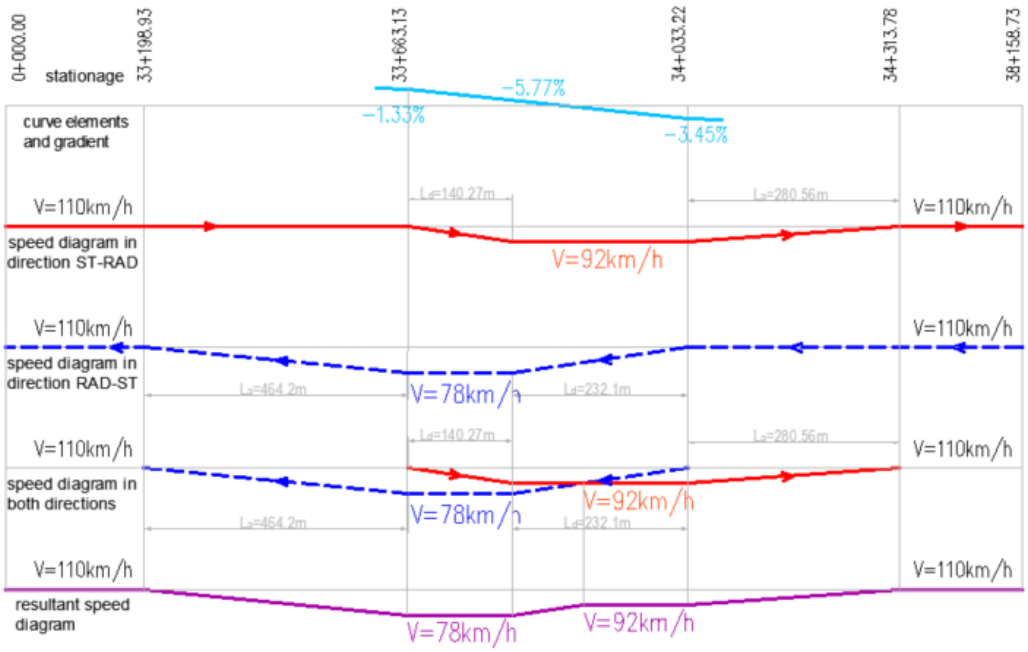

Figure 2. Speed Diagrams in Vertical Projection for Both Directions at V = 110 km/h

Based on the obtained results, speed diagrams were graphically drawn along the entire length of the analyzed route, in both directions of travel. This is presented in the diagram in Figure 3.

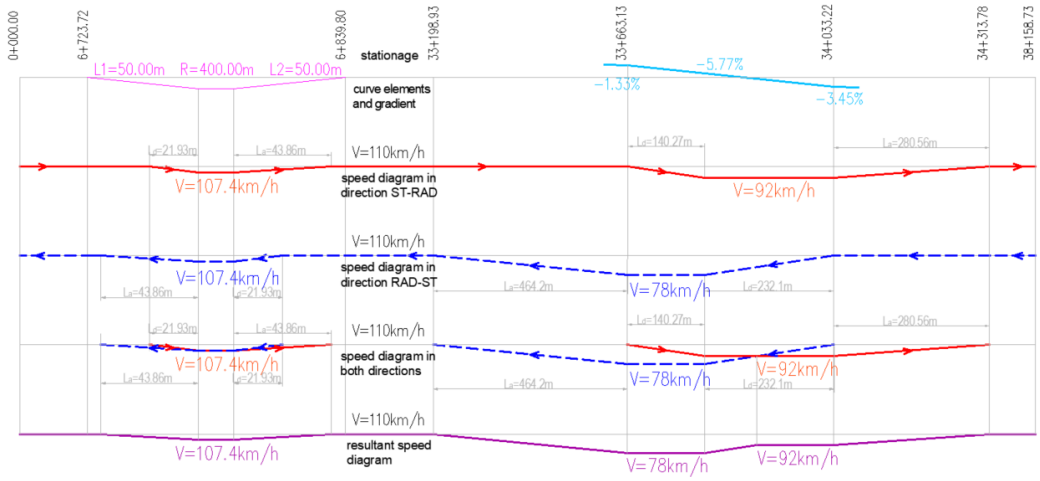

Figure 3. Resultant Speed Diagram for Both Directions at V = 110 km/h

3.2. Speed Limit Diagram for 120 km/h

A calculation was made for a design speed of 120 km/h, using the maximum allowable superelevation of *i* = 7% and the lateral friction coefficient *f* = 0.143. [14]

Table 2. Calculations for the Speed Diagram, for a Speed of 120 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp'' calculated [km/h]	Vp'' selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
400	120	104.02	104.02	15.98	112.01	276.20	138.10

From the results, it can be observed that the circular curve with the smallest radius of 400 m, although it includes transition curves of 50 m, still does not satisfy the criteria for movement at 120 km/h, as shown in Table 2 [15].

Based on the obtained results, speed diagrams were graphically drawn along the entire length of the examined road section, in both directions of travel. The resultant diagram is presented in Figure 4.

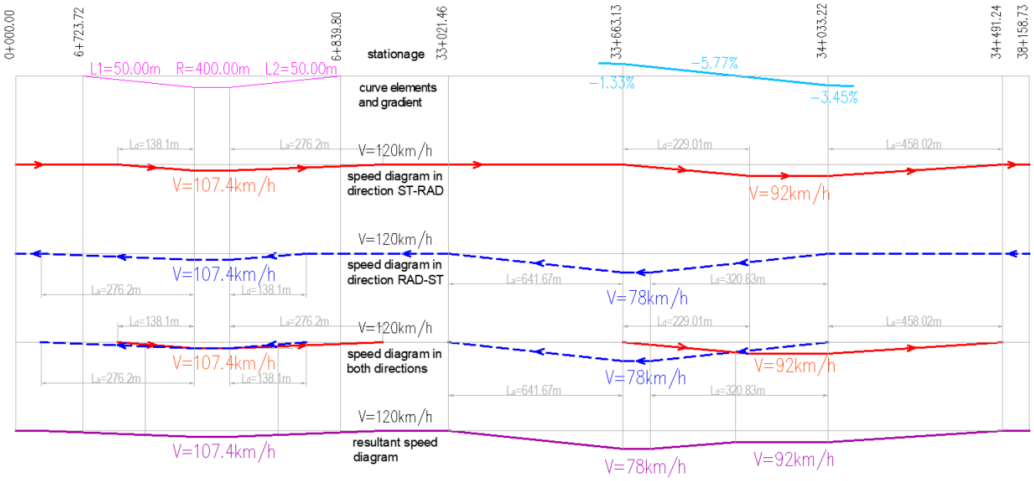

Figure 4. Resultant Speed Diagram for Both Directions at V = 120 km/h

3.3. Speed Limit Diagram for 130 km/h

A calculation was performed for a design speed of 130 km/h, using the maximum allowable superelevation of *i* = 7% and a lateral friction coefficient *f* = 0.143. [15]

All horizontal curves with radii smaller than 600 m were identified as critical points. Through analysis, it was concluded that the radii must be increased to at least 625 m in order to satisfy the conditions for travel at 130 km/h. This is presented in Table 3.

When ensuring design conditions for higher-speed travel, both the number and width of the traffic lanes must be considered. In such cases, a minimum lane width of 3.75 m should be provided, along with at least two traffic lanes in one direction. Given that the total

carriageway width is 11.4 m, it can accommodate two traffic lanes of 3.75 m each, along with a slow vehicle lane of 2.5 m. This cross-sectional profile meets the requirements for one direction of a motorway [16].

Table 3. Calculations for the Speed Diagram, for a Speed of 130 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp'' calculated [km/h]	Vp'' selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
625	130	130.03	130.00	0.00	130.00	0.00	0.00

4. CONCLUSIONS AND RECOMMENDATIONS

By addressing the problem, relevant theoretical principles, mathematical equations, and data from experimental research were identified in the professional literature[17]. Based on these, a methodology for conducting this study was defined. The entire procedure from the methodology was applied to the Štip – Radoviš expressway.

The analysis of the results led to the following conclusions:

- The locations where speed limit signs of 110 km/h are installed genuinely provide safe driving conditions.
- The placement of speed limit signs of 100 km/h at horizontal curves with a radius of R = 400 m is appropriate.
- If the horizontal curve with R = 400 m were reconstructed to achieve a radius of R = 500 m, it would then be possible to maintain a driving speed of 110 km/h on that section as well. This would result in a longer stretch of uniform speed, which is much safer and more favorable for the driver.
- On the road section with a longitudinal slope of 5.77%, speed limit signs of 90 km/h and 70 km/h should be placed in both directions, respectively.
- The locations where speed limit signs of 80 km/h are installed are justified due to the slower movement of vehicles that are merging onto or exiting the road.
- In the areas of the interchanges, the road has geometric characteristics that ensure safe driving at speeds of 120 km/h. If dedicated lanes with sufficient lengths for acceleration and deceleration are provided for vehicles entering and exiting the main road, the speed in the “transit” zone of the interchange could be increased to 120 km/h. This would result in a significantly longer segment with a uniform speed.

Considering that a motorway is planned along the same route, the application of this methodology could be used to assess whether this section meets safety conditions to be used as one direction of the future motorway. The conclusions are as follows:

- The geometric elements satisfy the requirements for driving at a speed of 120 km/h, except for the horizontal curve with R = 400 m and the longitudinal slope of 5.77%.
- By reconstructing all horizontal curves with radii smaller than 625 m, the section could support vehicle movement at a speed of 130 km/h.

Roads are linear structures of considerable length, connected to their surroundings, so any potential "realignment" during reconstruction is a highly complex process. Therefore, when designing a new road, it is essential to conduct a thorough analysis of the topography,

geological and geomechanical properties of the terrain, as well as economic indicators and the projected economic development of the regions to be served by the road. This ensures that the most technically sound and economically justified long-term solution is achieved [15].

This paper established that the examined Štip–Radoviš road section, with a length of 37 km, includes only one critical point with a small horizontal radius that necessitates a speed limit of 100 km/h. The remaining horizontal curves on the road allow safe travel at speeds of up to 120 km/h. The longitudinal grade of 5.77% requires a speed reduction on that section: 90 km/h in the Štip–Radoviš direction and 70 km/h in the Radoviš–Štip direction.

Therefore, it is recommended that this procedure be implemented during the road design phase to identify in advance the sections that require reduced speed limits. The design phase is the optimal stage to incorporate the expected operational speed into the selection of geometric road elements.

Furthermore, during the planning and design stages, it is advisable to evaluate the potential for future road reclassification. In addition to assessing current terrain conditions, the investor should consider the projected development of the region and neighboring areas served by the road. Such an analysis can influence the choice of geometric elements in a way that will reduce future financial costs and minimize construction interventions when upgrading or reconstructing the road to a higher classification.

In addition, integrating methodologies for assessing pavement quality and identifying critical black spots, as demonstrated in recent regional and international studies, can further improve the effectiveness of road safety strategies [17].

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Research paper

SYSTEMATIZATION AND QUALITY ASSESSMENT OF THE REGULATORY FRAMEWORK FOR THE PLANNING, DESIGN, AND CONSTRUCTION OF HEALTHCARE FACILITIES IN SERBIA

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Abstract

Previous studies in the field of architectural and interior design of patient rooms in secondary and tertiary healthcare institutions in the Republic of Serbia have highlighted the need for access to regulatory documents that legally define the requirements for the planning, design, and construction of such facilities. A key issue identified is the absence of a unified and comprehensive list of easily accessible legal and regulatory acts. The aim of this paper is to compile a complete inventory of the relevant legal frameworks and to evaluate both the scope and quality of their content. The research methodology combines literature review, analytical and synthetic approaches, and comparative analysis. The findings point to an urgent need for reform of the existing regulatory system governing the planning and development of healthcare institutions in the Republic of Serbia.

Key words: *Healthcare facilities, architectural design, regulatory framework, Serbia, legal acts*

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1. INTRODUCTION

The development of technology, new treatment methods, emerging knowledge, and their application in architectural practice have created the need to revise existing or adopt new norms, guidelines, regulations, and standards—in other words, a comprehensive regulatory framework. Such updates aim to reduce design errors in hospital architecture, improve user satisfaction with services and accommodation, and enhance working conditions and occupational safety for healthcare staff. The overriding challenge for commissioners, regulators and providers of both health and social care and associated physical environments in which care is delivered, is reconciling the need for patient safety, effectiveness and efficiency and the need for creating a truly therapeutic environment [1].

By adopting a research-informed design methodology - Evidence-Based Design, the international regulatory framework for healthcare facility design is continuously evolving and improving. The advancement of regulatory frameworks governing the planning, design, and construction of healthcare facilities is often driven by national standards bodies, governmental ministries, or professional associations. Regardless of the institutional origin, the overarching goal is to enhance the quality, safety, and efficiency of healthcare delivery through systemic regulatory improvement. Guidelines are published either as comprehensive standard manuals, e.g. *Planning, Design, and Construction of Health Care Facilities* [2] or as individual standards and regulations included in official regulatory lists for healthcare facility design e.g. *Complete List of Publications Related to NHS Estates* [3].

To determine the institutional actors responsible for the development of legal regulations in the field of healthcare facility planning and construction in the Republic of Serbia—and to assess whether this regulatory framework is being continuously updated and harmonized with international standards—a comprehensive list of current regulations will first be established in this study.

2. METHODOLOGY

The research methodology is structured into three phases.

The objective of the first phase is to identify the current regulatory framework for the planning and design of healthcare facilities in the Republic of Serbia through an extensive literature review. To achieve this, relevant sources will be examined, including official government and ministry websites, the website of the Republic Fund of Health Insurance, the Serbian Chamber of Engineers, the Institute for Standardization of Serbia, The Official Gazette, as well as other available literature related to the design of health centers and hospitals. This phase will also involve the systematization of collected data according to the type of regulation, the initiating institution, and the date of the most recent revision.

In the second phase, each document will be analyzed to determine the quantity of information related to the planning, design, and construction of healthcare facilities. This phase will identify whether the legal act refers entirely or partially to healthcare buildings and, if partially, which specific sections are applicable.

The third phase is focused on assessing the quality of the information content in each document. A qualitative and comparative analysis will be conducted to determine the extent to which the current Serbian regulatory framework for healthcare architecture is aligned with international standards.

3. RESULTS

Through database searches and literature review, a total of 15 regulatory acts relevant to the planning, design, and construction of healthcare facilities in Serbia were identified. These include five laws, six rulebooks, two government decrees, one technical specification, and one European standard. The results of the first and second phases of the research are presented in Table 1. The table includes the type of regulation, title, date of the most recent amendment, initiating institution, and an indication of whether the regulation applies entirely or partially to healthcare facilities.

The Law on Healthcare Protection and the Law on Fire Protection are fully applicable to healthcare buildings. The Law on Planning and Construction applies partially—specifically in Articles 2/24 and 2/44. The Law on Sanitary Surveillance is relevant in Article 8, and the Law on the Prevention of Discrimination Against Persons with Disabilities applies through Article 13.

Among the six rulebooks, only the Rulebook on Quality in the Field of Transfusion Medicine applies partially to healthcare facilities (Article 7). The remaining five rulebooks apply fully: Rulebook on the Conditions and Manner of Internal Organization of Healthcare Institutions, Rulebook on Detailed Conditions for Performing Healthcare Activities in Healthcare Institutions and Other Forms of Healthcare Services, Rulebook on General Sanitary Conditions Required for Facilities Subject to Sanitary Surveillance, Rulebook on Technical Accessibility Standards, Rulebook on Technical Norms for Fire Protection in Residential, Commercial, and Public Use Buildings, The Decree on the National Program for the Prevention, Treatment, Improvement, and Control of Renal Insufficiency and Development of Dialysis in the Republic of Serbia until 2020 applies in part, specifically Articles 11.2 and 11.3.3, which are relevant for design and construction processes.

The technical specification SRPS CEN/TS 16244:2018, Ventilation for Hospitals – Coherent Hierarchical Structure and Common Terms and Definitions for Standards Related to Hospital Ventilation, as well as the European standard SRPS EN 60598-2-25:2010 – Luminaires – Part 2-25: Particular Requirements – Luminaires for Use in Clinical Areas of Hospitals and Healthcare Facilities, are both fully applicable in the design and construction of healthcare facilities.

Table 1. Overview of Serbian Regulatory Framework for Healthcare Facility Planning and Construction

Type of Regulation	Title	Date of Last Amendment	Initiating Institution	Relevant Article(s)
Law	Law on Planning and Construction [4]	Official Gazette of RS, No. 62/2023, July 27	Ministry of Construction, Transport and Infrastructure, Government of RS	Articles 2/24 and 2/44
Law	Law on Healthcare Protection [5]	Official Gazette of RS, No. 29/2025, April 04	Ministry of Health, Government of RS	Entire document

Law	Law on Sanitary Surveillance [6]	Official Gazette of RS, No. 125/2004, November 22	Ministry of Health, Government of RS	Article 8
Law	Law on Prevention of Discrimination against Persons with Disabilities [7]	Official Gazette of RS, No. 13/2016, February 19	Ministry of Labour, Employment, Veteran and Social Affairs, Government of RS	Article 13
Law	Law on Fire Protection [8]	Official Gazette of RS, No. 87/2018, November 13	Ministry of Interior, Government of RS	Entire document
Rulebook	Rulebook on the Conditions and Manner of Internal Organization of Healthcare Institutions [9]	Official Gazette of RS, No. 126/2014, November 19	Ministry of Health, Government of RS	Entire document
Rulebook	Rulebook on Detailed Conditions for Performing Healthcare Activities in Healthcare Institutions and Other Forms of Healthcare Services [10]	Official Gazette of RS, No. 16/2018, March 5	Ministry of Health, Government of RS	Entire document
Rulebook	Rulebook on General Sanitary Conditions Required for Facilities Subject to Sanitary Surveillance [11]	Official Gazette of RS, No. 47/2006, June 10	Ministry of Health, Government of RS	Entire document
Rulebook	Rulebook on Technical Accessibility Standards [12]	Official Gazette of RS, No. 22/2015, February 27	Ministry of Labour, Employment, Veteran and Social Affairs, Government of RS	Entire document
Rulebook	Rulebook on Technical Fire Protection Norms for Residential, Commercial and	Official Gazette of RS, No. 22/2019, March 28	Ministry of Interior, Government of RS	Entire document

	Public Use Buildings [13]			
Rulebook	Rulebook on Quality in the Field of Transfusion Medicine [14]	Official Gazette of RS, No. 6/2019, February 1	Ministry of Health, Government of RS	Article 7
Government Decree	Decree on the Plan of the Network of Healthcare Institutions [15]	Official Gazette of RS, No. 101/2024, December 20	Ministry of Health, Government of RS	Entire document
Government Decree	Decree on the National Program for the Prevention, Treatment, Improvement and Control of Renal Insufficiency and the Development of Dialysis in the Republic of Serbia until 2020 [16]	Official Gazette of RS, No. 11/2011, February 22	Government of RS	Articles 11.2 and 11.3.3
Technical Specification	SRPS CEN/TS 16244:2018 Ventilation for Hospitals – Coherent Hierarchical Structure and Common Terms and Definitions for Hospital Ventilation Standards [17]	August 31, 2018	Institute for Standardization of Serbia	Entire document
European Standard	SRPS EN 60598-2-25:2010 Luminaires – Part 2-25: Particular Requirements – Luminaires for Use in Clinical Areas of Hospitals and Healthcare Facilities [18]	June 30, 2010	Institute for Standardization of Serbia	Entire document

In order to assess the quality of information contained in the regulatory acts of the Republic of Serbia related to the planning, design and construction of hospitals, a comparative analysis was conducted in the third phase of the research, starting with a review of relevant international and national regulations. The design regulations analyzed were: International Guidelines for Healthcare Facilities – iHFG [19], FGI Guidelines for Hospital Design and Construction 2018 [20], as well as the Complete List of Guidelines of the National Health Service (NHS) for the United Kingdom [3] and the Russian regulation SP 158.13330.2014 - Buildings and Premises for Healthcare Facilities [21]. The analysis found that these regulations are systematically organized and, within the framework of design guidelines, address a wide range of areas including structural flexibility, modularity, building construction, interior finishes and equipment, accessibility and mobility, environmental design and ergonomics, occupational health and safety, infection control, engineering services, feasibility planning and cost estimation, functional planning units with technical annexes, and standard room components.

The former republics of the Socialist Federal Republic of Yugoslavia, now independent states in the Balkan region, once shared a common system of JUS standardization as well as unified laws and regulations governing the planning, design, and construction of healthcare facilities. For the purposes of this research and documentation, the regulatory frameworks of Montenegro, North Macedonia, Bosnia and Herzegovina, as well as Croatia and Slovenia were examined. A higher level of regulatory development was anticipated in the cases of Croatia and Slovenia, given their membership in the European Union. The most significant progress in regulatory development was achieved solely by Slovenia, whose Ministry of Health adopted a comprehensive regulatory document for healthcare facilities in December 2021, titled *Tehnična smernica za graditev TSG-12640-002:2021 (Technical guideline for construction TSG-12640-002:2021)* [22]. These guidelines are fully harmonized with European Union regulations and may serve as a valid and practical model of successfully implemented regulation for other countries in the region.

A comparison between Serbian regulations and both international standards and those of regional countries such as Slovenia reveals that domestic regulations are not unified. Depending on the specific area, regulatory initiatives originate from various entities, including different ministries, the Government of the Republic of Serbia, and private companies engaged in standardization. As a result, the regulatory framework does not comprehensively cover the full spatial configurations of healthcare facilities, including all structural and functional requirements necessary to ensure a pleasant and humane environment for all users of the space—both patients and healthcare professionals. Furthermore, the regulations are not aligned with contemporary minimum technical standards.

4. DISCUSSION

A comparative analysis aimed at assessing the quality of regulatory content was conducted using the standards related to patient rooms. In the Republic of Serbia, these are defined through the minimum spatial dimensions stipulated in the Rulebook on Detailed Conditions for the Provision of Healthcare Services in Healthcare Institutions and Other Forms of Healthcare Service, specifically in Article 45, item 5, which states: Patient room: 5.5 m² per adult bed; 3.5 m² per bed for children under two years of age; 4 m² per bed for children up to six years of age; and in intensive care and emergency rooms, 6.5

m² per bed. The spacing between beds should be 60 cm, in intensive care 100 cm, and the distance from beds to the wall should be 20 cm in regular patient rooms and 60 cm in intensive care and emergency rooms [10]. These specified areas and spatial clearances are in fact lower than the standards applied during the former Yugoslavia and should instead be expanded and harmonized with contemporary European or international regulations. According to the *Manual of Hygiene* from 1966, the planning and design guidelines for general hospitals stipulated that multi-bed patient rooms should provide 6.5 m² per bed, while single-bed rooms should offer 9 m². The room height was fixed at 3.2 meters. The required spacing between beds was 75 cm, and the distance from the wall to the bed ranged from 75 to 125 cm [23].

It is noteworthy that this Rulebook does not define even the minimum floor-to-ceiling heights of patient rooms. In fact, this parameter was removed in the most recent amendment to the Rulebook, effectively enabling the establishment of private hospitals and clinics in residential buildings with insufficient floor heights. Additionally, the regulation fails to define the necessary furniture and equipment, as well as the positioning of required utility installations. The comparative overview of the selected parameters for various countries is shown in Table 2.

Table 2. National Regulatory Standards for Multi-Bed Patient Room Design

Country	Source	Min. area per bed in multi-bed adult room (m²)	Min. bed-to-bed distance (cm)	Min. bed-to-wall distance (cm)	Min. clear ceiling height (m)
SFRY (former)	Manual of Hygiene [23]	6.5	75	75–125	3.20
Serbia	Rulebook [10]	5.5	60	20	not specified
Montenegro	Rulebook [24]	5.5	60	20	not specified
Croatia	Rulebook [25]	6.0	75	75	2.60
Bosnia and Herzegovina	Rulebook [26]	5.0	100	60	2.60
North Macedonia	Rulebook [27]	6.0	80	75	2.50
Slovenia	Rulebook [22]	16.0	not specified	not specified	4.50 (floor-to-floor height)
Russia	SP 158.13330.2014 [21]	10.0	80	120	2.60

In contrast, the 2018 International FGI Rulebook recommends designing only single-bed rooms. The maximum number of beds per room in medical/surgical patient care units will be one. Two beds per room are permitted when approved by the competent authority. This rulebook also requires the design of all four functional zones - for the patient, employees, family and hygiene. The minimum area and dimensions of the rooms are also defined. The minimum area of a unit with a family zone must be at least 23.22m2, and if possible, an

additional 2.79m2 should be provided per family member. Newly built single-bed rooms should be at least 3.66 m wide and 3.96 m deep, or 14.86m2, excluding the toilet, closet, cabinets, anteroom and niche [28]. The Slovenian Rulebook also defines the design of only single-bed and double-bed rooms.

The International Health Facility Code (iHFG) in the chapter Standard Components provides detailed information on the most common rooms and spaces in health facilities. Each component consists of a Room Data List (RDS) and a Room Drawing List (RLS). Single rooms have an area of 15, 16.5 and 18 m2 and are rooms with two clearly defined zones (patient and hygiene). Single units of 28m2, 30 or 50m2 contain a family zone for the permanent stay of a family member. This code contains codes for double rooms of 28 and 30m2, which, like single rooms, do not have a zone for employees and family, but only for visitors. Four-bed units have an area of 42, 49 and 60m2, in addition to the patient area and two hygiene areas and a space for visitors. Six-bed units are units with the maximum number of beds according to this nomenclature, and can have an area of 44 and 75m2.

The aforementioned Rulebook on Detailed Conditions for Performing Healthcare Activities in Healthcare Institutions and Other Forms of Healthcare Services [10], in Article 44, paragraphs 5 and 6, addresses sanitary facilities as follows: 5) Cold and hot running water shall be available in work areas, patient rooms, and sanitary units; 6) A sanitary facility with an anteroom must be provided adjacent to the waiting area, and in hospitals, one sanitary facility and a shower with a bathtub shall be provided per every 10 beds. The critical importance of having dedicated sanitary facilities within each patient room for effective infection control has long been acknowledged.

Comparable national regulations from Slovenia, Croatia, Russia, England, as well as relevant international standards, explicitly prescribe the inclusion of sanitary facilities and bathrooms within patient accommodation units. In contrast, the regulations of other countries from the former SFRY region, as well as Serbia, require the presence of a shared sanitary facility and bathroom at the hospital ward level. Consequently, the existing regulatory framework warrants thorough revision and enhancement to align with best practices in healthcare facility design.

5. CONCLUSION

Based on the presented research findings regarding regulations in the field of planning, design, and construction of healthcare facilities in Serbia, the following conclusions can be drawn:

The regulatory framework in this domain is neither systematized nor available through a centralized, publicly accessible governmental portal. It has been structured only through this research, and it is recommended that such a systematization be formally published.

The existing regulations do not comprehensively address the entire hospital complex. There are no guidelines regarding structural systems with optimal spans that would enable modularity and flexible spatial organization. There is also a lack of recommendations for the selection and use of construction materials, or for interior finishes across different functional zones in a manner consistent with infection control principles. Where they do exist, such guidelines are often overly general, such as those found in the Regulation on General Sanitary Conditions.

The regulations do not encompass all engineering disciplines involved in the design and construction of healthcare facilities. Norms for the minimum dimensions of rooms are not aligned with international standards. Additionally, the provisions regarding the organization, surface area, and minimum equipment of patient rooms are outdated. Sanitary regulations and infection prevention measures are not in line with current global recommendations. Moreover, the regulations do not incorporate knowledge and principles stemming from the Evidence-Based Design (EBD) approach.

The current standard for lighting in healthcare facilities is obsolete, as it only accounts for incandescent, fluorescent, and discharge lamps, without considering modern LED lighting technologies.

Building upon the present study's systematization and evaluation of the regulatory framework for healthcare facility planning, design, and construction in Serbia, future investigations could focus on empirical assessments of how identified regulatory gaps affect the quality, safety, and operational efficiency of healthcare environments. Such work may include post-occupancy evaluations of newly built or renovated healthcare facilities, examining the relationship between design compliance and measurable outcomes such as patient recovery rates, staff satisfaction, and operational performance.

Further research could explore comparative policy analyses between Serbia and countries with advanced regulatory systems that have successfully integrated Evidence-Based Design principles. This would provide deeper insights into effective pathways for regulatory reform, with particular attention to adapting international guidelines to the Serbian socio-economic and healthcare context, ensuring proposed standards are both aspirational and feasible.

Another important avenue involves interdisciplinary studies on the integration of emerging technologies—such as smart building systems, advanced infection control measures, and sustainable design strategies—into regulatory frameworks. These approaches can contribute to creating resilient healthcare environments that adapt to evolving medical practices, demographic shifts, and public health challenges.

In addition, examining governance structures, institutional capacities, and stakeholder engagement mechanisms needed for the continuous update and harmonization of regulations could support the establishment of a dynamic, participatory regulatory model. Such a model would help ensure that healthcare facility design standards remain current, evidence-based, and responsive to both user needs and global best practices.

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Research paper

GROUNDWATER LEVEL ESTIMATION USING GMS SOFTWARE

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Abstract

The primary goal of this paper is to develop a mathematical model that describes groundwater flow within a porous medium. By employing mathematical modelling techniques for fluid flow analysis, valuable insights can be gained into complex flow conditions that are often difficult to assess using conventional analytical methods. Given that the spatial and temporal variations of parameters relevant to the system can be expressed through specific mathematical formulations (typically in the form of complex partial differential equations) it is advisable to apply appropriate numerical methods, as they provide a strong strategy for effectively addressing the challenges associated with the system.vOne of the significant challenges encountered in groundwater research is the lowering of groundwater levels (GWL) during the construction of buildings. Before the construction begins, it is required to lower the GWL in the foundation pit to ensure dry working conditions. The most requested data for this purpose are groundwater flow and GWL. This paper focuses on the process of lowering the GWL for a specific object while ensuring that the stability of surrounding buildings remains unaffected. To achieve this objective, it is crucial to design and implement a drainage system with adequate capacity, considering the characteristics of the aquifer. Additionally, it is important to assess filtration stability, particularly to prevent suffusion, by carefully selecting an appropriate protective filter course. The analysis of groundwater flow at the specified location was conducted using a 3D model to simulate the flow regime within a porous medium. Both conceptual and numerical groundwater modeling were performed using the GMS 10.7 software. Based on the adopted filtration coefficient from the geotechnical study, several solutions were developed. In each case, it was necessary to ensure that the GWL was lowered to the required elevation and to prevent suffusion by controlling the maximum velocities at the entrance of the filter structure.

Key words: *Groundwater Flow Model, GMS, Filtration Coefficient*

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1. INTRODUCTION

Creating a comprehensive mathematical model that considers all factors affecting the groundwater flow would require a vast amount of input data and significant computing power. Given the extensive effort and investment involved, such modeling may ultimately become impractical and lose its significance. Effective models acknowledge the primary laws and factors affecting the phenomenon while simplifying or excluding less significant parameters. Therefore, every model is based on specific assumptions and simplifications, meaning that each one has limited applicability, defined by the assumptions and conditions established during its development. Consequently, a model serves, at best, as a conditional representation of real-world conditions and processes.

When initial and boundary conditions are too complex for analytical solutions to be achievable, numerical computational models become valuable due to their flexibility. The advancement and widespread accessibility of computers have enabled numerical models to become the most used tools for solving practical problems posed by both nature and human activities.

A groundwater flow model refers to a tool used to describe the flow dynamics in a hydrogeological system. Once calibrated, it can be used to predict how an aquifer will respond to natural processes and changes due to human activities, and subsequently, for managing water resources. The primary objective of this modeling is to determine the piezometric level at a specific point within the aquifer and, indirectly, to assess the distribution of flow velocities in the current field. The first step in the modeling process is creating a conceptual model. Once this is established, the conceptual model is converted into appropriate mathematical expressions, which are then combined with boundary conditions to form a mathematical model. One of the most widely used numerical modeling software packages is GMS, based on MODFLOW 2005, developed by Aquaveo, LLC in Provo, Utah, USA. Many researchers have utilized MODFLOW in groundwater modeling for various purposes, and some have integrated it with other models and software to enhance the reliability of their research findings [1-4].

Within this paper, the lowering of the groundwater level at the site of interest was examined without compromising the stability of nearby buildings. To achieve this, the drainage system needs to be designed and executed with sufficient capacity, considering the characteristics of the aquifer from which the water is drawn. It is also important to prevent suffusion by appropriately selecting the protective filter course. When developing a groundwater flow model, it is essential to have an accurate soil profile for the specific location, which can only be obtained through geotechnical boreholes. Furthermore, correctly estimating the filtration coefficient is crucial for establishing the model and ensuring its accuracy. Considering two static groundwater levels — the level identified through exploratory drilling at an elevation of 71.85 meters above sea level and the maximum expected level determined through hydrological analyses, which was 74 meters above sea level — it can be concluded that the necessary lowering of the groundwater level at the location of interest was approximately 4.85 meters for the first case and 7 meters for the maximum expected level. Since a significant lowering of the groundwater level was required, a groundwater flow analysis was conducted using a 3D model to simulate the flow regime in a porous medium.

2. HYDRAULIC CALCULATION

2.1. Establishment of the GMS model

The initial step in establishing the model involves defining the dimensions of the area being modeled, using data from the available measuring wells. When determining this area, the dimensions of the object are crucial, as they indicate where lowering the groundwater level is necessary. In other words, defining the model's boundaries depends on the object's dimensions, requiring the boundary line to be placed in a zone beyond the well's influence. This means that the boundary line must be set where the influence of the depression cone is not felt. Since the dimensions of this cone are undefined at the beginning of the calculation, determining the boundary line along which the boundary conditions will be implemented is an iterative process that involves testing different model dimensions depending on the configuration of the wells. After defining the model's dimensions, a computational grid was created. Given that this area is significantly larger than the location of interest, primarily due to the boundary line positions, a different grid resolution approach was chosen for the grid formation. Namely, as the object and its immediate surroundings require a higher level of detail, a denser grid was used in these zones, while a higher-resolution grid was applied in the remaining areas. In this way, the model is optimized in terms of required computing resources while maintaining the required accuracy and detail at the location of interest. Thus, a grid cell size of 7.5 × 7.5 m was used for the wider area, while within the narrow zone around the object itself, at the wells' location, grid cells of 0.25 × 0.25 m were used.

To define the vertical stratification, data on soil stratification at the location in question, obtained from one exploratory well, were used. Thus, in the vertical direction, one layer (the soil layer from which the water is drawn) with a total length of about 19 m was adopted for simulation purposes. Additionally, the impermeable floor level was set at 52 masl. To complete the mathematical model, the filtration coefficient of this layer of soil was determined based on a geotechnical study. Figure 1 shows a 3D view of the adopted computational grid.

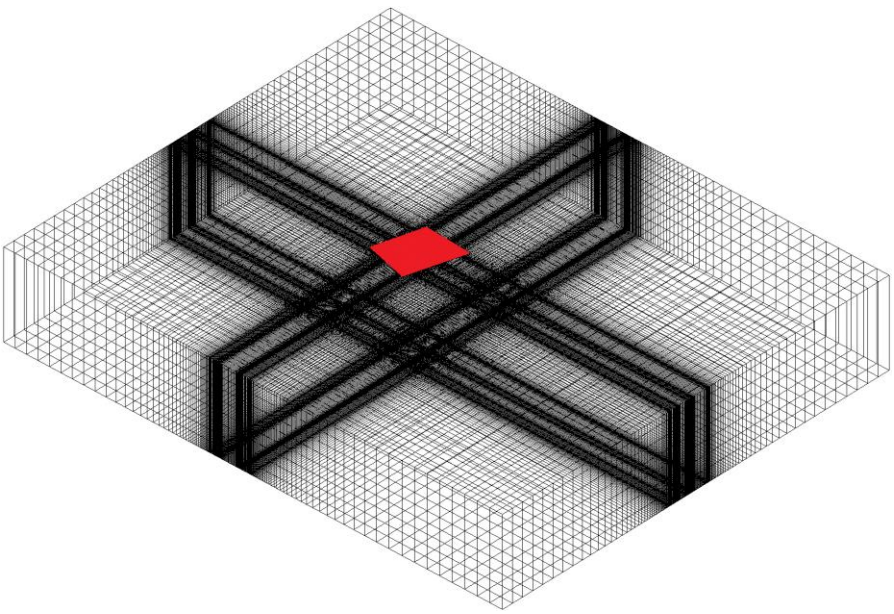

Figure 1. 3D view of the adopted computational grid

2.2. Modeling of groundwater level lowering

For the previously defined model, the next step was to determine the arrangement of the wells around the foundation pit in order to lower the groundwater level to the required elevation. Although the foundation level was estimated at 68.00 m, the request was to lower the groundwater level to 67.0 m. In addition to achieving this elevation, in order to select the optimal number of wells, it was necessary to check the filtration stability. Filtration stability was evaluated by estimating the velocity at the entrance of the well's filter and comparing it to the limit value (critical speed) adopted according to Abramov. Therefore, the configuration of wells and their flow rates were defined not only based on the required lowering level but also on the critical gradients at the contact between the soil and the well strainer. The center point of the foundation pit served as the reference point for monitoring the groundwater level lowering. However, to determine the velocity at the well's strainer, the maximum velocity value recorded at the nearest calculation point to the well was compared with the critical value.

After defining the model boundaries and the filtration coefficient, to carry out further calculations, it was necessary to define the initial level, the disposition of the wells, and the flow rates for each well. Considering the two estimates of the initial water level (71.85 meters above sea level and 74 meters above sea level), analyzes were conducted for both levels. In one set of simulations, a value of 71.85 m was adopted for the initial level, while for the second set of simulations, an elevation of 74 m was used. During the modeling process, several different well configurations and nominal flow rates were tested. For each set configuration, predefined conditions were checked after the simulation regarding the required groundwater level and maximum velocity at the well's entrance. If the configuration did not meet both criteria, the arrangement of wells was changed, and additional wells were added. Since three different values of the filtration coefficient (10^{-2} cm/s, 10^{-3} cm/s and 10^{-4} cm/s) were suggested in the geotechnical study, several iterations were conducted, resulting in one or two solutions for each of the three values of the filtration coefficient. All tested configurations are listed in Table 1.

Table 1. Tabular representation of the tested configurations.

Initial level	71.85 masl			74.00 masl		
filtration coefficient [cm/s]	1.0 x 10^{-2}	1.0 x 10^{-3}	1.0 x 10^{-4}	1.0 x 10^{-2}	1.0 x 10^{-3}	1.0 x 10^{-4}
Variant 1	4 wells Q = 6.8 l/s	4 wells Q = 0.7 l/s	6 wells Q = 0.05 l/s	8 wells Q = 5.4 l/s	8 wells Q = 0.53 l/s	8 wells Q = 0.0463 l/s
Variant 2	**6 wells Q = 5.0 l/s**	6 wells Q = 0.5 l/s	8 wells Q = 0.04 l/s	/	/	/

Several variants for lowering the groundwater level were evaluated. The most practical solution was the configuration of six wells, each with a flow rate of Q = 5.0 l/s. The values of soil and well parameters for the adopted case are presented in Table 2. The groundwater levels of the foundation pit after pumping are shown in Figures 2 and 3.

Table 2. Adopted values of soil and well parameters (k = 10^{-2} cm/s, Q = 5.0 l/s, 6 wells)

Parameters	Values
terrain elevation at the object's location	~76.55 m.a.s.l.
static groundwater level	71.85 m.a.s.l.
excavation level of the foundation pit	68.00 m.a.s.l.
min lowering level at the well site	61.69 m.a.s.l.
max elevation at the object's area (foundation pit)	66.76 m.a.s.l.
aquifer capacity (sand)	~19 m
filtration coefficient, K, of the aquifer	1.0 x 10^{-2} cm/s
required lowering of the GWL at the level of excavation of the pit	67.00 m.a.s.l.
maximum permittable depression in the well up to an elevation	61.50 m.a.s.l.
well depth to elevation	52.00 m.a.s.l.
filter length L = 6 m	55.00 – 61.00 m.a.s.l.
diameter of the well	0.25 m
the maximum capacity of the well without the occurrence of suffusion	5.0 l/s

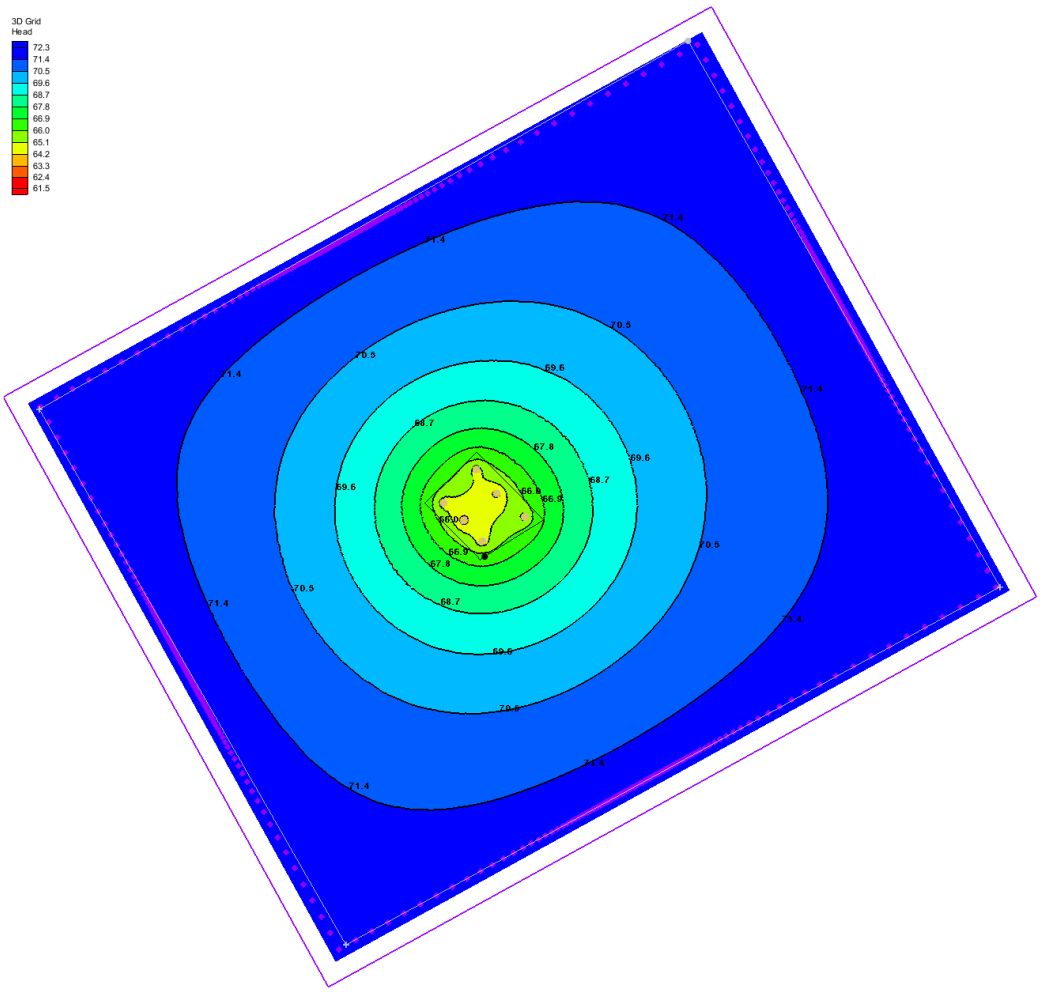

Figure 2. Display of the depression cone in the area of the foundation pit for the adopted well configuration (k = 10^{-2} cm/s, Q = 5.0 l/s, 6 wells)

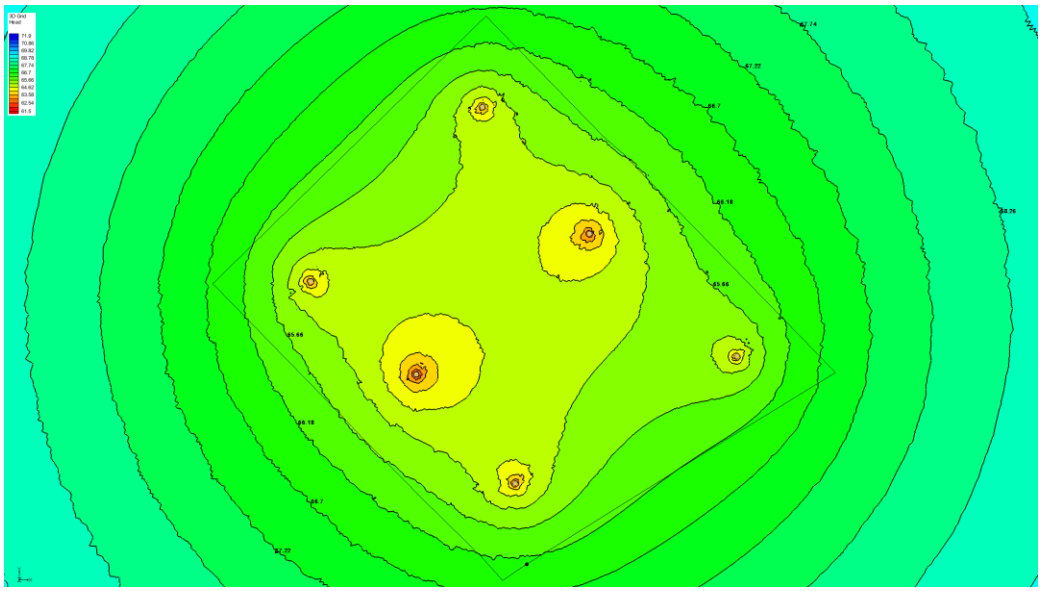

Figure 3. Detail of the depression cone in the area of the foundation pit for the adopted well configuration (k = 10^{-2} cm/s, Q = 5.0 l/s, 6 wells)

The images indicate that the required water level has been reached in the foundation pit area. After stopping the pumping process, the water level rises due to the formation of a depression cone. Therefore, the pumps are turned back on once the maximum permittable water level is reached, and this process continues cyclically. Since this is a cyclical process of periodic switching pumps on and off, it is managed by installing pumps with frequency regulation. It should be noted that the selection of the well configuration and the nominal flow was made according to the required lowering level and the critical velocity, calculated according to the Abramov criterion.

Additionally, the accuracy of flow calculations in the porous medium largely depends on the filtration coefficient. This coefficient can be determined through various methods, with the trial pumping method being the most accurate. In contrast, the least reliable method involves using formulas based on the material's granulometry. It is important to emphasize that for the hydraulic calculation of groundwater level lowering in this study, recommendations from the geotechnical analysis were used. The values obtained were based on empirical expressions; therefore, there may be discrepancies between the actual site conditions and the results obtained in this study.

3. CONCLUSION

This paper presents a mathematical modeling of the groundwater level using the GMS software package, specifically for the construction of a residential building in Novi Sad. The execution of works at the site requires lowering the groundwater level from the initial static groundwater level to an elevation of 67.00 m above sea level. Since there were two estimates of the initial water level: 71.85 meters above sea level (determined through exploratory drilling) and 74 meters above sea level (the maximum expected level based on hydrological analyses), analyses were performed for both static groundwater levels. The analysis of groundwater flow at the given location was carried out with a 3D model for simulating the flow

regime in a porous medium using GMS 10.7 software. The model incorporates soil type data and groundwater levels determined from geotechnical wells to reconstruct the soil profile at the location accurately.

Two scenarios were analyzed for each of the three selected values of the filtration coefficient and the initial groundwater level of 71.85 m. For a filtration coefficient of 10^{-2} cm/s, one scenario included four wells, each with a flow rate of 6.8 l/s, while the other scenario featured six wells with a flow rate of 5.0 l/s per well. In the case of a filtration coefficient of 10^{-3} cm/s, one scenario consisted of four wells, each with a flow rate of 0.7 l/s, while the alternative involved six wells with a flow rate of 0.5 l/s each. For a filtration coefficient value of 10^{-4} cm/s, one solution consisted of six wells, each with a flow rate of 0.05 l/s, while the other solution included eight wells with a flow rate of 0.04 l/s per well. Then the analysis was carried out with the initial level of 74 m and all three values of the filtration coefficients. The resulting configurations are: eight wells with a flow rate of 5.4 l/s per well (for a filtration coefficient of 10^{-2} cm/s), eight wells with a flow rate of 0.53 l/s per well (for a filtration coefficient of 10^{-3} cm/s) and eight wells with a flow rate of 0.0463 l/s per well (for a filtration coefficient of 10^{-4} cm/s).

In addition to lowering the groundwater level to the desired elevation, the filtration stability process was also controlled. The criterion for permissible velocities at the entrance of the well's filter is crucial for ensuring filtration stability and practically determines the capacity of the designed well. Given that this situation involves wells with limited exploitation time, the Abramov criterion (based on the relation between the maximum velocities at the entrance to the filter construction and the filtration coefficient of the aquifer) was used to determine the maximum permittable velocity. Although all solutions meet the established conditions, the configuration with six wells and a flow rate of 5.0 l/s per well (for the initial groundwater level of 71.85 m and the filtration coefficient of 10^{-2} cm/s) is recommended as the most realistic solution. This recommendation is based on the optimal pumping flows typically observed in this local area.

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Research paper

ANALYSIS OF THE NATURAL FREQUENCY OF COMPOSITE PLATES MADE OF CROSS-LAMINATED TIMBER AND CONCRETE

Nikola Janković[1], Andrija Zorić[2], Radovan Cvetković[3], Lazar Živković [4], Ivan Nešović[5]

Abstract

This paper investigates the natural frequencies of square and rectangular cross-laminated timber–concrete composite plates using the approximate analytical Rayleigh method and finite element analysis in Abaqus/Standard. Determining the natural frequency, as dynamic characteristic, is important for verifying the serviceability limit state regarding the vibration criteria of such composite plates. The Rayleigh method, as an approximate method, allows for quick result acquisition, while modeling in Abaqus provides more detailed and accurate information about the plates dynamic characteristics. By comparing the results of both approaches, this paper examines the advantages and disadvantages of each method, offering guidelines for practical engineering applications. The conclusion of this study is that the Rayleigh method provides results for plates of characteristic dimensions that are in good agreement with those obtained using the Abaqus/Standard software package, which was used as a benchmark.

Key words: *composite plates, cross-laminated timber, concrete, natural frequency, Rayleigh method, finite element method*

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1. INTRODUCTION

For the design of floor plates, it is necessary to verify both the ultimate limit state and the serviceability limit state. Within the serviceability limit state, the vibration criterion, which is particularly relevant for composite plates, requires the determination of the natural frequency. According to the current Eurocode 5 regulations, in order to avoid more detailed dynamic analyses, the natural frequency of vibration of residential building timber floor systems must exceed 8 Hz [1]. In the case of composite timber-concrete floors, which represent an attractive alternative to conventional reinforced concrete plates due to their favorable properties, there is no explicit limit value for the natural frequency [2]. However, the same recommendations as for timber floors can be adopted. This is because a frequency below 8 Hz can cause discomfort to occupants and potentially coincide with the walking frequency of residents, which could lead to resonance effect and compromise the stability of the floor system.

Reinforced concrete plates have larger stiffness and mass, and typically exhibit higher natural frequencies compared to timber–concrete composite plates, making this condition generally insignificant. However, in the case of timber composite floor systems, which are relatively lightweight, the serviceability limit state with respect to vibrations may become the governing criterion for design.

Various models have been developed to determine the dynamic behavior of structures. Depending on the approach, these models may include analytical, numerical, or semi-numerical methods, which can be either exact or approximate. The most well-known among them are the Rayleigh method, Rayleigh-Ritz method, Galerkin method, Frobenius method, differential quadrature method, differential transformation method, finite difference method, and many others [3].

This paper analyzes the vibration frequencies of square and rectangular composite plates made of cross-laminated timber and concrete, obtained using two approaches: the Rayleigh method and finite element modeling in the software package "Abaqus" [4].

For the approximate analysis of the plate, the Kirchhoff plate theory (Classical Plate Theory, CPT) is used, which assumes that plane sections normal to the mid-surface before deformation remain plane and normal after deformation and neglects transverse shear deformation.

In this study an ideal bonding condition between the layers of the composite plate is imposed: perfect adhesion is assumed and no slip occurs at the interfaces. This idealisation simplifies the model and permits direct application of the Rayleigh method to estimate the natural frequencies. It should be noted that this assumption represents an upper bound on the structural stiffness and therefore may slightly overestimate the natural frequencies compared to real assemblies where some interlayer slip occurs. Experimental investigations have shown that interface behaviour and connector stiffness influence the effective bending stiffness and can shift the natural frequencies of timber–concrete composite plates and beams [5, 6]. In particular, differences between fully composite and partially composite beams can reach about 10% in natural frequency [5].

The results obtained using both methods are compared, and conclusions are drawn regarding the validity of the Rayleigh method for calculating the vibration frequency of timber-concrete composite plates.

2. GEOMETRIC AND MATERIAL PROPERTIES OF THE ANALYZED COMPOSITE PLATE

The analyzed plate consists of five layers of cross-laminated timber, each 3 cm thick, with a concrete plate of 8 cm thickness placed above them, resulting in a total plate thickness of 23 cm as shown in the Figure 1. Square plates with side lengths ranging from 4 m to 8 m in 1 m increments, and rectangular plates with a fixed span of 3 m and widths varying from 4 m to 8 m, were analyzed. All plates were simply supported along all four edges to investigate the influence of side length and width on their natural frequencies.

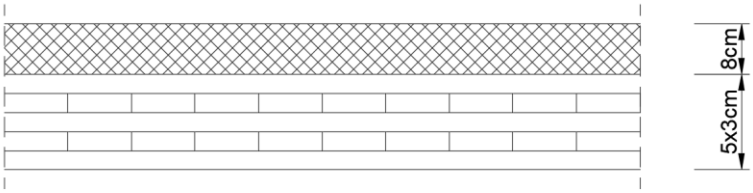

Figure 1. Cross section of composite plate

The timber used for the laminates is of grade C24, and the corresponding mechanical properties are provided in the Table 1 [7].

Table 1. Mechanical Properties of C24 Grade Timber

E_1 [MPa]	E_2 [MPa]	G_{12} [MPa]	G_{23} [MPa]	v_{12}	v_{21}	ρ [kg/m]
11000	370	690	50	0.38	0.01278	420

In the Table 1, E_1 and E_2 represent the Young's modulus in the principal directions, G_{12} and G_{23} are the shear modulus v_{12} and v_{21} are the Poisson's ratios, while ρ represents the material density.

The concrete used is of grade C25/30, and the corresponding mechanical properties are provided in Table 2.

Table 2. Mechanical Properties of C25/30 concrete

E [MPa]	G [MPa]	v	ρ [kg/m]
31000	1292	0.20	2400

3. RAYLEIGH'S METHOD

Rayleigh's method is an approximate analytical method used in structural dynamics to determine the natural frequencies of a system. It is based on the law of conservation of energy, which states that the sum of kinetic and potential energy remains constant. At the natural frequency, the ratio of maximum kinetic to potential energy is constant as follows:

$$\frac{T_{max}}{U_{max}} = \text{const} \tag{1}$$

where U_{max} represents maximum potential energy and T_{max} maximum kinetic energy.

For the composite plate, the maximum potential energy, depending on the transverse deflection of the plate w and the bending stiffness, D_{ij}, is defined as [8]:

$$U_{max} = \frac{1}{2}\int\int\left(D_{11}\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + 2D_{12}\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + D_{22}\left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 4D_{66}\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2\right)dxdy \quad (2)$$

while the maximum kinetic energy is represented in the form:

$$T_{max} = \frac{1}{2}\rho h\omega^2 \int\int w^2 dxdy \quad (3)$$

In the previous equation ω represents the natural frequency, while h denotes the total thickness of the composite plate.

In laminate theory, D_{ij} represents the bending stiffness matrix and can be calculated as:

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}\left[\overline{Q}_{ij}\right]_k \left(h_k^3 - h_{k-1}^3\right) \quad (4)$$

where h_k represents the distance between the geometric midpoint of the composite plate and the edge of each layer, as shown in Figure 2.

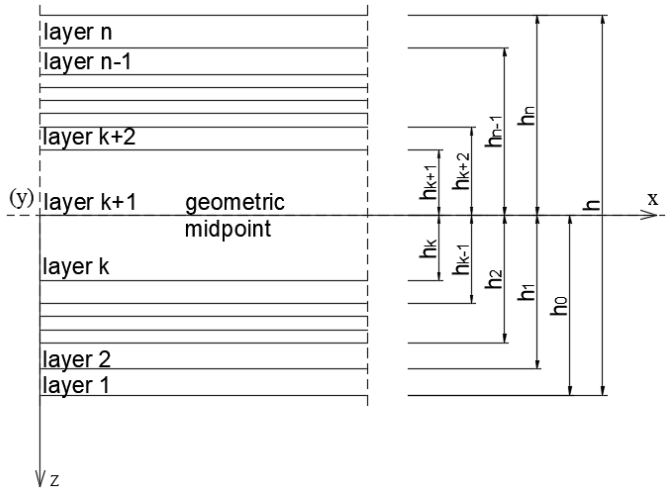

Figure 2. Layer designations in the composite

We define $\bar{z}_k$ as:

$$\frac{(h_k + h_{k+1})}{2} = \bar{z}_k \quad (5)$$

Thus, the bending stiffness matrix is now given as [8]:

$$D_{ij} = \sum_{k=1}^{n}\left[\overline{Q}_{ij}\right]_k \left(\frac{t_k^3}{12} + t_k \cdot \bar{z}_k^2\right) \quad (6)$$

where t_k represents thickness of k-th layer.

The matrix $\overline{Q_{ij}}$ is the reduced stiffness matrix, obtained as:

$$\overline{Q_{ij}} = [T]^{-1}[Q][R][T][R]^{-1} \tag{7}$$

where $[T]$ represents the transformation matrix, $[R]$ is the Reuter's matrix and $[Q]$ is the stiffness matrix, and the matrices are given as:

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\cos\theta\sin\theta \\ \sin^2\theta & \cos^2\theta & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \tag{8}$$

$$[R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix} \tag{9}$$

$$[Q] = \begin{bmatrix} \frac{E_1}{(1-\upsilon_{12}\cdot\upsilon_{21})} & \frac{E_2\cdot\upsilon_{12}}{(1-\upsilon_{12}\cdot\upsilon_{21})} & 0 \\ \frac{E_1\cdot\upsilon_{12}}{(1-\upsilon_{12}\cdot\upsilon_{21})} & \frac{E_2}{(1-\upsilon_{12}\cdot\upsilon_{21})} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \tag{10}$$

The approximation of the transverse deflection function using Rayleigh method is given by [9]:

$$w(x,y) = A\cdot X(x)\cdot Y(y) \tag{11}$$

where X and Y are the admissible functions that form the functional basis. They must satisfy the boundary conditions along the plate's contour. A represents the amplitude coefficients that need to be determined.

For the simply supported edges the characteristic function X and Y that satisfy the boundary conditions can be chosen as:

$$\begin{aligned} X(x) &= \cosh\lambda\frac{x}{a} - \cos\lambda\frac{x}{a} - \gamma(\sinh\lambda\frac{x}{a} - \sin\lambda\frac{x}{a}) \\ Y(y) &= \cosh\lambda\frac{y}{b} - \cos\lambda\frac{y}{b} - \gamma(\sinh\lambda\frac{y}{b} - \sin\lambda\frac{y}{b}) \end{aligned} \tag{12}$$

The coefficients λ (lambda) and γ (gamma) are determined using boundary conditions, requiring zero deflection along all edges of the plate and zero moment, where a and b represent the dimensions of the plate. [10]

In order to obtain the natural frequency one can apply the law of conservation of energy [9]:

$$\frac{\partial U}{\partial A}-\frac{\omega^2 \rho h}{2}\frac{\partial}{\partial A}\iint w^2 dxdy=0 \tag{13}$$

For the analysis using the presented approximate analytical method, a MATLAB program code was developed, and the results are shown in Table 2 and Table 3.

Table 2. Natural frequencies of square plates vibrations obtained using the Rayleigh method

Dimensions of a square plate [m]	lambda (λ)	gamma (ϒ)	f (Hz)
4x4	1.676E-04	1.239E+00	28.48
5x5	1.661E-04	1.219E+00	18.22
6x6	1.655E-04	1.211E+00	12.66
7x7	1.652E-04	1.208E+00	9.30
8x8	1.651E-04	1.206E+00	7.12

Table 3. Natural frequencies of rectangular plates vibrations obtained using the Rayleigh method

Dimensions of a rectangular plate [m]	lambda (λ)	gamma (ϒ)	f (Hz)
3x4	1.701E-04	1.277E+00	39.40
3x5	1.694E-04	1.267E+00	33.81
3x6	1.692E-04	1.263E+00	30.60
3x7	1.691E-04	1.261E+00	28.58
3x8	1.691E-04	1.261E+00	27.23

4. MODELING IN ABAQUS SOFTWARE

To compare the results obtained using the approximate Rayleigh method, a plate model was created in the „Abaqus" software package [4] and material properties specified for each layer were defined using the "Lamina" option. The plate was modeled as a 2D composite with six layers, each with its corresponding material properties. Along the plate edges, pinned boundary conditions were applied: displacements in all three translational directions (U1, U2, U3) were restrained, while rotations were left free (Figure 3).

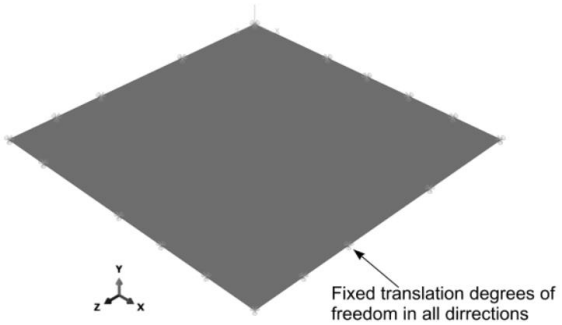

Figure 3. Plate model

The model is meshed using linear quadrilateral shell elements with four nodes, linear interpolation and reduced integration (S4R). A mesh convergence study was performed by varying the global seed size from 0.05 m to 0.15 m. The resulting values of natural frequencies exhibited a minimal variation of only 0.22 %, proving that the model yields reliable results. Therefore, a global seed size of 0.15 m was adopted in this study to facilitate more efficient computation.

The shape of the first natural mode for square plate 4x4m is shown in Figure 4. The corresponding mode shapes for rest square and rectangular plates exhibits a similar pattern and is therefore omitted for brevity. The vibration frequencies obtained for square plates of various dimensions are presented in Table 4, while those for rectangular plates are given in Table 5.

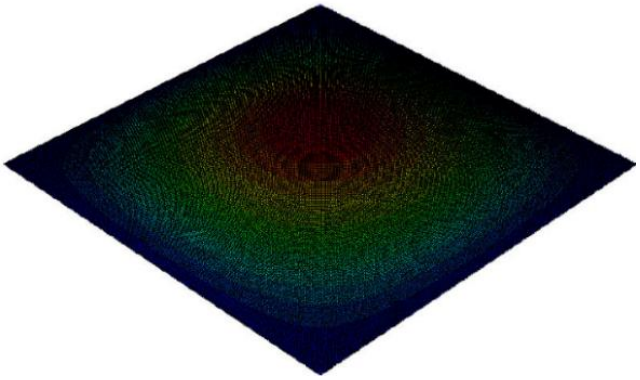

Figure 4. First natural mode of square plate 4x4m

Table 4. Natural frequencies obtained in Abaqus

Dimensions of a square plate [m]	f (Hz)
4x4	30.15
5x5	20.59
6x6	14.66
7x7	11.04
8x8	8.59

Table 5. Natural frequencies obtained in Abaqus

Dimensions of a rectangular plate [m]	f (Hz)
3x4	39.39
3x5	35.03
3x6	32.94
3x7	31.82
3x8	31.16

5. RESULTS DISCUSSION

The obtained results of frequencies for square and rectangular plates simply supported on all four edges were compared between the aproximate analytical analysis using the Rayleigh method of energy conservation in MATLAB and the finite element method using Abaqus software [4].

The data analysis shows that the frequencies obtained using the Rayleigh method are slightly lower compared to the values obtained in Abaqus. The difference is more pronounced for larger plate dimensions, while the deviations decrease as the dimensions decrease as shown in Table 6 and Table 7.

Table 6. Comparison of the obtained results for square plates

Dimensions of a square plates [m]	Rayleigh f [Hz]	Abaqus f [Hz]	Deviations [%]
4x4	28.48	30.15	5.54
5x5	18.22	20.59	11.51
6x6	12.66	14.66	13.64
7x7	9.30	11.04	15.76
8x8	7.12	8.59	17.11

Table 7. Comparison of the obtained results for rectangular plates

Dimensions of a rectangular plates [m]	Rayleigh f [Hz]	Abaqus f [Hz]	Deviations [%]
3x4	39.40	39.39	0.02
3x5	33.81	35.03	3.61
3x6	30.60	32.94	7.65
3x7	28.58	31.82	11.34
3x8	27.23	31.16	14.43

These differences can be attributed to the assumptions used in the Rayleigh method, which involve approximations in the expressions for potential and kinetic energy and the differences are graphically shown in Figure 5. and Figure 6.

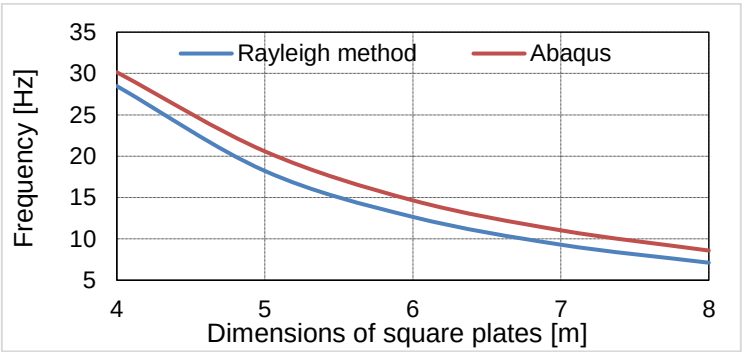

Figure 5. Comparative results of the dependence between natural frequency and plate dimensions for square plates

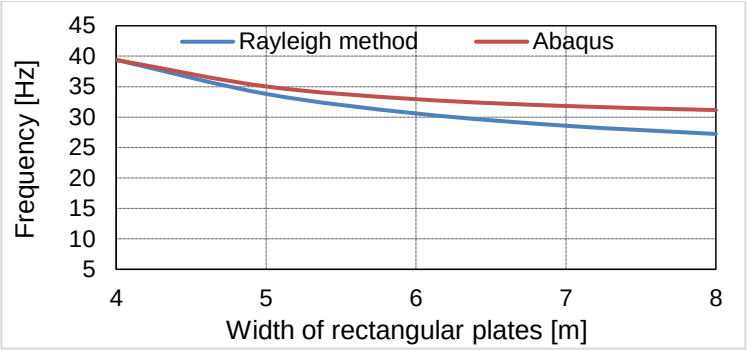

Figure 6. Comparative results of the dependence between natural frequency width of rectangular plates (constant span of 3 m)

In general, it can be concluded that the analytical (Rayleigh) method shows good agreement with the finite element analysis results for plates with characteristic dimensions. Both approaches exhibit the same trend of frequency reduction with increasing plate size, confirming the consistency of the models. However, due to the more conservative kinematic description of the plate in the Rayleigh method, the calculated natural frequencies are slightly lower than those obtained with the Abaqus software.

6. CONCLUSION

This paper presents two methods for determining the natural frequency of composite plates made of laminated timber and concrete using the Rayleigh method and modeling in Abaqus software. Based on the presented results, it can be concluded that the methods are in good agreement, with small deviations observed for plates with shorter spans and increasing deviations as the plate dimensions become larger. The results indicate that the natural frequency of composite plates can be reliably calculated using the Rayleigh method, making it suitable for use in engineering practice.

In addition to the assumption of ideal bonding between timber and concrete, which affects the results, only a single term was used in the Rayleigh method, which limited the accuracy in predicting the natural frequencies. To further improve the accuracy and expand the validity of the results, it would be beneficial to implement an extended model with two or more terms in the deflection function approximation, which would represent the Rayleigh-Ritz method. This approach would allow for a more detailed analysis of the plate vibrations and could lead to more accurate results, especially in more complex cases.

Additionally, in this study, only the self-weight of the composite plate was considered as the load, which represents a simplified approach. To more accurately simulate actual conditions, it would be beneficial to include an additional dead load that influences the plate's vibrations. This can be achieved by increasing the material density in the analytical Rayleigh method.

Additionally, it could be considered to expand the research to include different types of plates (varying layer thicknesses, or different materials) in order to analyze the generalizability of the methods in a broader context. Also selection of different trial functions for X and Y could represent a further step toward a more accurate application of the Rayleigh method for analyzing the behavior of plates under various conditions.

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Review paper

CONTEMPORARY ARCHITECTURE AND ITS IMPACT ON THE ENVIRONMENT – MODERN SUSTAINABLE BUILDING SYSTEMS

Vukašin Stefanović[1], Anđela Stevčić[2]

Abstract

Rethinking contemporary construction goes beyond conventional building techniques and is conditioned by the context of technological progress. The aim of this paper is to analyze the transformation of the city, the impact of contemporary design solutions, and the assessment of their effectiveness after implementation in modern projects. Transformations experienced by cities in underdeveloped countries indicate a loss of the human character, which was the fundamental idea of architects of the modernist movement. Such change can be interpreted in various ways, but in the context of cities, it can be reduced to certain aspects such as comfort, infrastructural equipment, aesthetics, content, and other elements that must meet contemporary needs. Their interconnection is crucial for the creation of high-quality physical spaces. This paper calls for further research and re-examination of construction techniques with the aim of reducing negative environmental impacts.

Key words: *modern construction, sustainable construction, ecological principles, green materials, technological progress, development, Masdar City.*

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1. INTRODUCTION

The environment as we know it today is the result of established economic, political, social, and ecological processes. Fundamentally, it is a natural space, but it can be said that under the influence of the mentioned processes, it has become a social product, shaped according to the needs of the people living in that space. The transformation of natural space into physical space is the task of urban planners and architects. This space can be defined through the relation of space-time-activities and depends on the relationship between the actors of that space. Creating the living environment for people is essentially the study of the relationship between humans and the environment in which they live, that is, understanding the complexity and changes of those relationships that occur over time [1]. The fate of the environment depends on people, and its development will look the way humans define it. Problems affecting its development require a responsible approach in order to eliminate the consequences of inadequate human behavior towards nature. Historically, viewed as a conscious being, humans have from the beginning used nature and its resources for their own benefit. Although we are not the only living beings on the planet, we have shaped nature exclusively according to our needs. The question arises whether nature or humans come first, and whether nature is necessary for humans. All actions so far indicate an anthropocentric view that nature exists because of humans. If we talk about sustainable development, it is necessary to change the anthropocentric attitude and establish a framework of equality for all living beings to whom nature also belongs [2].

If we accept that the living environment of modern humans is a product of their activities and that architecture is the most visible result of their work, then cities can be seen as a personification of that product. The problems of modern cities primarily stem from the increase in the number of people on Earth. This problem brings with it more built-up areas, pollution, increased resource consumption, traffic, and climate change. The growing number of people on Earth and the anthropocentric view leave little room for sustainable urban development unless there is a change in the ethical principles by which people currently live. If sustainability is defined as development that solves the problems of the present generation without preventing future generations from performing the same activity, then in order to establish such a model of operation, changes in thinking must be made. Sustainable development will have a future when humans overcome their primitive instinct to place personal needs and interests above the needs and interests of others. Without a sense of responsibility for the people and nature around them, a healthy future cannot be discussed [2]. In this regard, the paper explores the impact of contemporary architecture on the modern living environment of people, or in other words, the relationship between contemporary construction and the city. Sustainability is no longer an academic aspiration but a necessary way of life and thinking. Examples of such functioning should be sought in many European countries. There is no rational reason preventing this, especially when sustainable technologies are present and ideas and strategies are implemented.

"Contemporary architecture is a real product and reflection of new times," is part of the thoughts of Prof. Nikola Dobrović [3]. The development of architecture and technological progress run in parallel, and their separation has never been possible. Therefore, we speak of buildings that use and will use innovative systems to be adequate for their users and environmentally friendly for their surroundings and nature.

2. THE IMPACT OF CONTEMPORARY ARCHITECTURE ON THE ENVIRONMENT

2.1. About contemporary cities

The environment is an integrated system that includes natural ecosystems, social values, and economic aspects, but viewed through the prism of architecture, it is a physical space shaped to fulfill human needs. Its variability is the product of different geographical, social, and economic parameters, and architecture is their articulation (concretization) in physical space. The scope of the environment is defined by the number of inhabitants and the facilities it provides. It is certain that the environment experiences certain pressures caused by population growth, construction, climate change, and other current negative phenomena, whose impact is most visible in cities.

The city represents a civilizational achievement, a symbol of progress in every sense. We define it as a complex organism composed of systems of buildings, infrastructural flows, and public spaces. To live, it needs people who use these spaces to establish social interaction. Utopians see the city as an ideal place to live, but its sustainability depends on thorough changes based on sustainable development and ecological design.
The dualism of human action is reflected in his power to create but at the same time to destroy. Humans build but simultaneously disrupt natural ecosystems and the natural balance. The result of their activities is rapid resource consumption, fewer forested and green areas, pollution, climate change, and the disappearance of many species of plants and animals, which are also inhabitants of the Earth. Environmentalists define these phenomena as the Sixth Extinction, viewing humans as the cause of such occurrences. Sustainable architecture is the construction industry's response to rapid negative changes in the Earth's environment and its ecosystems [4].

2.2. Tendencies of the contemporary construction industry

The construction industry is also attempting to improve sustainable building techniques due to the increased needs of certain countries for natural resources. Their production and economy are based on increased consumption of fossil fuels, which causes shortages and rising prices of certain materials and agricultural products. China is a good example of a country facing problems of overpopulation and resource scarcity. Their appetite for materials is growing due to increased production volume. Leadership in all branches of global trade and production has been based on constant construction and expansion, which significantly reduces free physical space and leads to other negative phenomena such as the expansion of the Gobi Desert due to frequent droughts and water shortages. The solution to the problems of overpopulation and limited available space is being sought through sustainable construction and the introduction of new typologies in residential and social architecture. The construction industry is heavily reliant on the consumption of these resources (fossil fuels), and in order to remain healthy and solvent, it must change.

2.3. High-performance buildings

Contemporary buildings are designed to meet high standards in terms of energy efficiency, comfort, durability, and sustainability. They stand out for the use of advanced

materials that reduce environmental impact, and their efficiency and impact assessments are continuously reviewed during the design phase through advanced software technologies. To better understand the aspirations of modern construction, the design strategies that achieve these standards will be explained below [4].

• *Transparency regarding energy efficiency and materials*

Awareness of human health requires architects to use quality materials that do not negatively affect the condition and health of space users. In this regard, it is very important that green architecture adopts a transparent approach to design and provides information about product composition, potential toxicity, and the energy efficiency of buildings themselves. When discussing building performance, it is important that data about it be accessible to facilitate monitoring of their performance and environmental impact. Such data allow modernization and optimization of systems that do not meet required conditions [4].

• *Application of BIM technology (Building Information Modeling)*

The use of BIM-based software significantly improves the design process and allows easier tracking of construction phases and processes. Its implementation provides an integrated solution for the entire building. Thanks to this, multiple users can work simultaneously, which leads to faster work, better overview of solutions, and reduced risks of errors. BIM can be understood as a comprehensive methodology for more efficient management of construction and infrastructure projects. The difference from CAD design lies in the software's intuitiveness, which simultaneously develops a three-dimensional model while working on 2D drawings, enabling spatial visualization of solutions during all design phases. In other words, the solution is generated based on a model consisting of real elements. All changes to it are simultaneously reflected in all relevant technical drawings [4].

• *Life Cycle Assessment (LCA)*

LCA is a methodology and analysis of the life cycle that is gaining increasing importance because it enables quantification of the ecological impacts of design decisions throughout the entire project lifespan [4]. What this assessment provides before building construction is the comparison of certain systems, materials, constructions, or other aspects of solutions relevant to the building's effect on specific natural phenomena (such as the greenhouse effect, global warming, etc.) or simply its impact on the environment where it will be built. This allows the selection of solutions for which the assessment determines the least possible negative impact on the environment and phenomena, or solutions that will be completely neutral to the environment [4].

• *Zero energy consumption*

A pressing problem of modern architecture is the high energy consumption of buildings, which increases the amount of emitted carbon dioxide resulting from the burning of fossil fuels, which remain the most common energy sources. Zero-energy buildings are considered carbon neutral precisely because of their use of renewable energy sources, predominantly solar energy. An example of such a building in Serbia is an urban villa in Belgrade called Zero Energy, designed by architect Vladimir Lojanica. This building is formed as a photovoltaic monolith, whose envelope consists of a total of 405 panels providing 90% of the building's total energy needs, together with panels on the roof. All other systems are connected as a

smart system, enabling automation of ventilation, cooling, and heating processes [5]. The goal of such buildings is to achieve a net-zero energy balance, meaning that energy consumption for maintenance, heating, and cooling is minimized. This implies that the amount of renewable energy the building produces is equal to the total amount it consumes annually. Of course, to achieve zero energy consumption, it is not only necessary to use renewable energy sources but also to synchronize the influences of construction, materials, and other systems in such buildings [4].

- *Carbon Footprint Calculation*

The increase in population requires a greater number of buildings for various purposes, which entails occupying areas that were once green spaces. This leads to an increase in the amount of emitted CO2, one of the causes of climate change. Global warming causes droughts that lead to the dying of trees, which further increases CO2 levels. Carbon footprint calculation is done per capita, and high values are characteristic of developed countries (countries with large populations and developed industries). The previously mentioned strategies and their implementation can help reduce it. In other words, the goal must be the gradual phasing out of pollutants from everyday use in order to restore climatic balance [4].

3. SOME CURRENT SUSTAINABLE SOLUTIONS

3.1. Green roofs

Although greening of roof surfaces is not a new concept, given technological advancements, their application should by now be standard in the design and construction of buildings in urban areas. However, in practice, the situation is different; for example, in Serbia, there is no significant use of this system, even though its implementation would significantly improve parameters indicating the level of urban pollution. Green vegetative roofs, as one of the methods of greening building envelopes, are an innovative technology that largely compensates for losses in the urban environment caused by the construction of new buildings. Like other modern methods, designing green roof coverings is applicable to existing buildings with flat roofs. Their use is even recommended for buildings undergoing redesign to increase their energy efficiency.

For roof greening, a mixture of sedum plants is used, chosen according to the climatic conditions of the area. These plants are drought-resistant, and their maintenance involves annual feeding and care. The effectiveness of green roofs depends on various factors such as soil layer thickness (a thicker soil layer means better interior cooling and greater possibilities for planting various plant species), greenery and its planting density (greenery creates shade that positively affects cooling), and climatic elements (precipitation, solar exposure, relative humidity, etc.). Green roofs are categorized into three types: extensive (requires minimal maintenance), simple intensive (requires occasional maintenance), and intensive (requires intensive maintenance) [6].

3.2. Green facade walls

Another method to address pressing urban issues related to the lack of greenery in cities is the greening of building facade walls. This is also a modern method of urban design and architectural planning of buildings. Such walls help improve the energy performance of

structures, promote the restoration and development of biodiversity, and contribute to the reduction of air pollution [7]. By greening the facade wall structure, an interaction between the environment and the interior space is established, resulting in certain indoor comforts, energy harmony, as well as enhancing the exterior appearance of the building. To enrich the walls with greenery, mainly vines and climbing plants are used, which require three to five years for full development. The formation of a vertical garden on walls can be achieved by installing ready-made panels or modules with already planted vegetation on a substructure. The use of such systems is more common in areas with intensely warm climates where overheating is a frequent problem. In regions with a Mediterranean climate, the effect of green walls can reduce solar heat load by up to 20%, especially when the green facade is designed on the east side of the building [8]. The longevity of such walls is ensured through regular maintenance and feeding of the vegetation. Designing green walls does not have to be a characteristic only of newly designed buildings; the existing urban fabric can also be energetically renovated by applying this system, simultaneously redesigning the urban tissue [6].

3.3. Photovoltaic Facades

Designing photovoltaic facades represents yet another innovative method for improving buildings with the goal of achieving energy efficiency. This refers to a glass envelope made of vertical photovoltaic panels mounted on a substructure attached to the building's primary structure. These systems are also known as BIPV – Building Integrated Photovoltaics. Their efficiency depends on several factors, including the number of sunny days, the building's surface area coverage, shading, the angle of installation, and the technology used in manufacturing the panels. There is no single definition of such systems, but the term generally encompasses the technical, functional, and aesthetic integration of solar modules into buildings. Differences between systems arise from the degree of integration of photovoltaic modules into the building structure. The most commonly used systems are semi-integrated, which do not involve embedding solar cells into building materials or structural elements of the building. In contrast, there are also fully integrated systems [9].

3.4. Modern wood-based constructions (GLT, CLT)

Wood is still used as a construction material due to its natural origin, relatively low cost (especially for "light" structures), fire resistance, weight, and its constructive capabilities. Naturally, the environmental impact of wooden structures is significantly lower compared to reinforced concrete, which is most commonly used for structural assemblies. However, for the needs of demanding modern architecture and construction, wood-based materials/constructions are used, namely GLT – glued laminated timber and CLT – cross laminated timber. The characteristics of these systems include the improvement of the natural basic properties of wood while minimizing or completely eliminating the negative impacts.The goal of lamella bonding is to use a relatively small volume of wood while simultaneously increasing load-bearing capacity and strength under compression and tension. Their application covers various uses and typologies, and compared to reinforced concrete, construction proceeds significantly faster. Structural elements are produced in specialized factories, meaning that the structure is assembled on site by joining prefabricated elements.CLT (Cross Laminated Timber) technology is used for panel production, where

lamellas – boards – are arranged in two directions at a 90° angle. These panels are used for walls, floor structures, and roofs. To achieve the desired load capacity and quality, the pressure intensity is precisely determined.

The importance of these constructions also lies in the renewability of wood as a resource used for their production, as well as the fact that during its growth period, wood binds large amounts of carbon dioxide, which has been repeatedly mentioned as a major current pollutant [10, 11].

4. ANALYSIS OF THE MASDAR CITY PROJECT – THE MOST SUSTAINABLE CITY IN THE WORLD (UAE)

Masdar City is conceived as an urban hub — a desert community designed and built to be carbon-neutral and zero-waste. The project was initiated by the Abu Dhabi government with the goal of advancing renewable energy and technology development, aiming to create a model for sustainable cities in the post-fossil fuel era. Masdar covers an area of 640 hectares, located adjacent to Abu Dhabi, leveraging its transport infrastructure while connecting with neighboring communities and the international airport.

The purpose of Masdar City is to integrate various innovative fields to pool knowledge that will result in technologically advanced yet truly sustainable settlements. Although situated in a desert, the city is designed to offer optimal living conditions while surrounding land is allocated for wind farms, solar farms, research activities, and plantations, ensuring energy self-sufficiency and independence. The project was designed by architect Norman Foster and is considered the first sustainable eco-city in the Arab world. It explores the feasibility of future cities based on three pillars of sustainability: social, environmental, and economic.

Masdar City is designed to be free of carbon dioxide emissions, cars, and waste. It relies solely on renewable energy, with 80% coming from solar power, and the rest from wind turbines and waste processing. Cutting-edge infrastructure and construction technologies reduce energy and water consumption by about 70%. For transportation, Masdar uses electric vehicles and is connected to a light rail public transit system [12, 13]. To further sustainable development, Masdar is developing a university (Masdar Institute of Science and Technology) in cooperation with MIT, focusing exclusively on sustainability research [13].

Figure 1. Masdar city, source: www.archdaily.com

The urban design of Masdar is inspired by traditional Arab architecture and urbanism, featuring narrow streets, low-rise buildings, public spaces with high density, mixed uses, and walkability — all aimed at overcoming harsh desert climate challenges. The city is oriented southeast-northwest to create shade during the day and to align with prevailing winds, aiding natural cooling. The landscape design, called the “three fingers” park system, channels airflows through linear parks. Both public and private spaces are designed to maximize fresh air and cooling, including water features that provide evaporative cooling. The vegetation consists mostly of drought-resistant local plants that require minimal irrigation, enhancing the city’s green feel.

Figure 2. Streets of Masdar city, source: www.archdaily.com

Figure 3. Streets of Masdar city, source: www.rethinkingthefuture.com

Masdar has succeeded in reducing water use by 54% compared to other UAE cities. About 75% of its hot water is produced by solar collectors installed on rooftops, which also provide additional shading. The city is exploring geothermal potentials with deep wells (2,500 m) providing water for cooling and sanitation — crucial for desert living. Irrigation efficiency is increased by 60% using special nozzles and by using 100% recycled wastewater, preserving potable water supplies.

Sustainability is also reflected in material choices, with extensive recycling of steel, wood, and concrete waste. Materials are sourced locally to reduce costs and environmental impact from production and transportation. Masdar has a dedicated recycling center divided into sectors for wood, metal, concrete, and other materials. Non-recyclable waste is incinerated to generate additional energy [14].

Figure 4. Masdar city landscape, source: www.rethinkingthefuture.com

The city's power supply comes primarily from a solar farm covering 22 hectares with 87,777 photovoltaic panels, the largest in the Middle East. The farm is expected to generate 17,500 megawatts and reduce CO2 emissions by 15,000 tons annually, equivalent to removing 33,000 cars from the road. A major challenge is dust and sand accumulation on the panels, requiring frequent cleaning that increases maintenance costs. Photovoltaic panels are also installed on building rooftops, supplying 30% of the campus's energy needs [14].

4. DISCUSSION

Although contemporary architecture offers innovative solutions that address many of today's problems, their application in our practice is often not rational. First and foremost, there is a lack of understanding and interest in society to introduce changes that would enhance the environment. If we return to the example of Masdar, we can conclude that it is easier to implement sustainable development strategies when an entire city is rebuilt from scratch, with the investor's goal being sustainability and a green future. Cities that already have an established urban fabric respond differently to implementation, both from the perspective of the physical and built environment, and from the psychological perspective of users. A problem also arises with project investors; private individuals are generally not interested in investing in innovative systems that are often not affordable. In this case, government projects offer greater possibilities, so some projects have been developed using some of the mentioned systems. Viewed this way, projects developed in the Middle East become exemplary models of good practice for solutions we try to apply in our environment. Their innovation often sets precedents even for the European community, which leads the way toward a green future.

Specifically in Serbia, problems also include the lack of infrastructure for recycling construction waste, which is often dumped in unsanitary landfills, high initial costs, and a lack of incentives such as government subsidies, tax relief, and favorable loans. Legal and regulatory frameworks represent another barrier discouraging the implementation of energy-sustainable solutions (the lack of clear and binding regulations complicates the adoption of sustainable standards). Furthermore, the centralization of capital affects the localization of positive examples mainly to Belgrade. Finally, technical challenges in the use of recycled materials require testing and adaptations to ensure the materials are used adequately. This refers to the fact that recycled materials do not possess the properties of the originals, so their rational reuse is necessary.

5. CONCLUSION

As mentioned in the introduction, this paper calls for further research into the needs, development, and function of contemporary cities. In the context of sustainability, awareness of its necessity is essential to understand the solutions that lead to it. Without this, projects aimed at a green future will lack understanding and acceptance from the community. In such cases, everything boils down to a small number of projects whose effectiveness is not at a satisfactory level unless the entire system functions cohesively. The problems mentioned in the previous section can be overcome if the government initiates a few measures to improve

legislation through clear and binding regulations, launches subsidies for the application of energy-efficient materials, systems, and other solutions, and decentralizes financial distribution across various regions to expand the network of positive project examples. Along with these proposals, education is an indispensable factor—both in educating space users and training professionals who will participate in related projects in the future.

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Research paper

STUDY OF THE TRANSFORMABILITY OFARCHITECTURAL FORM UNDER THE INFLUENCE OF LIGHT AND SHADOW

Jasmina Tamburić[1], Olivera Nikolić[2]

Abstract

The paper presents a study on the transformability of architectural form under the influence of light and shadow as key elements of visual perception, experience, art, and architecture. Through the analysis of examples where these factors are the primary determinants of the appearance of architectural form, the study demonstrates the principle of shaping ambiance and evoking specific emotions. The study of the transformability of form perception is illustrated through a series of photographs of the same architectural structures (or their segments) taken at different times of the day. These photographs served as the primary means of expression in the research on the influence of light and shadow on architectural form. Visual perception, as a complex process of experiencing shape and space, although primarily linked to the sense of sight, does not function in isolation from other senses, previously acquired knowledge, experiences, and emotions. It consists of a set of impressions and understandings of the observed object, which change depending on the movement of the observer. Among the numerous factors that influence the visual perception of architectural form, light and shadow stand out as dominant, playing a crucial role in its transformability and experiential quality.

Key words: *Visual perception, Transformability, Architectural form, Light, Shadow, Photography*

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1. INTRODUCTION

This paper presents a method for examining the visual characteristics of architectural form and its transformation under the influence of light and shadow. The study of the transformability of architectural form refers to the emergence of newly perceived shapes created by the interaction of light with form. Such dynamic change occurring in the natural environment on static physical forms is constant and represents one of the most important features of spatial form. The perception of form in humans is, to a large extent, an automatic cognitive process, explored within a specific branch of perceptual psychology. For the purpose of this research, the human eye as the center of visual perception is represented through the camera lens and photography, which serve as visual documentation in which the formal transformations of spatial form are identified. This research builds upon established theoretical approaches in visual perception, such as those presented by Stanisavljević [1], Arnheim [2,3], Norberg-Schulz [4,5], and Pallasmaa [6], providing a perceptual framework for understanding the dynamic interaction between light, shadow, and form based on visual perception by Ognjanović [7].The photographs used in this study originate from the author's archive [8,9], as well as from student projects developed within the course *Visual Research* in 2024 at the Faculty of Civil Engineering and Architecture, University of Niš.

1.1. Method

The method of examining the transformability of architectural form is presented through a series of monochromatic photographs. These photographs depict architectural forms and the changes in their perception caused by the influence of sunlight at different times of day. Monochromatic photographs are particularly suitable for studying form transformability, as they more clearly reveal the geometry of shadows, as well as the features of the form such as lines, volumes, tonal values, and shapes. The study of form transformability through photography was conducted within practical exercises by first-year students as part of the Visual research course.

2. SUBJECTIVE ASSESSMENT OF VISUAL PERCEPTION

Visual perception is an integral part of human cognition; it enables the understanding of the world around us through mental analysis and organization [10]. It occurs largely automatically, but also consciously. The root of the word “perception” comes from the Latin *perceptio*, meaning “reception, observation and understanding”. Visual perception refers to the process by which the human brain interprets information primarily gathered through the sense of sight. However, the interpretation of visual information is not merely a physiological function of the eye. The scientific study of perception challenges the idea that the world we encounter in everyday life is solely physical rather, it is largely experiential. Our contact with the physical world is indirect, and what we experience in daily life is a representation constructed by our senses and central nervous system.

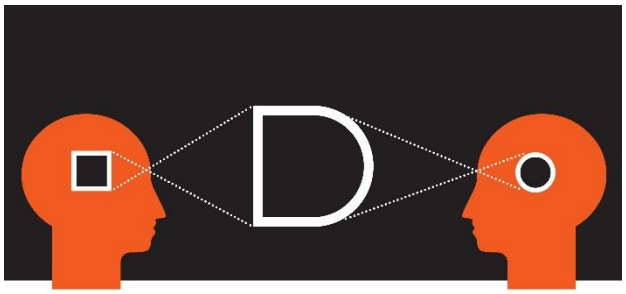

Figure 1. Graphical representation of visual perception

Visual perception does not function in isolation from other human senses, nor from previously acquired knowledge, experiences, and emotions. Although primarily related to vision, all other senses actively contribute and play a significant role in enriching and complementing it. Information from the external environment is received through our primary senses, which operate in a systemic manner, enabling the brain to build a comprehensive image of the world. The integration of all sensory information provides a more complete and precise representation of the visual world.The perspective from which we observe the visual world is located in our eye, which can occupy only one position at a time. As we move, our eye carries the visual world with it. This world is both real and imaginary—a physical world of shapes and spatial relationships that create a highly complex system of perception. Visual perception is an individual and unique understanding of the visual world, arising from the subjective experience of the senses.The initial stage of visual perception begins with sensory input processed by the visual system. The eye detects light, colors, shapes, and motion. The information gathered by the eyes is processed by the brain to create an image of the context or environment. The visual system collects data, identifies objects, and determines their spatial relationships.

Visual experience is a subjective process that involves a combination of physiological observation (through the eye) and cognitive processing of what is seen (through the brain). It represents the way in which the human mind and senses perceive and interpret visual information from the environment. Cognitive processing, in fact, determines how we experience the visual world.

3. OBJECT OF VISUAL PERCEPTION

Form, in the context of a solid spatial structure, possesses perceptual, sensory, and dynamic properties [11]. This research focuses on the perceptual and dynamic attributes of spatial form. The perceptual properties include its size, shape, color, and texture [12], while the dynamic ones pertain to its change or visual transformation. Visual perception shapes the perceptual experience, and spatial form is its primary object.

Spatial form is not merely a static object, but a dynamic visual entity that continuously changes depending on lighting conditions. Light and shadow act as key factors in its visual articulation, modeling surfaces, revealing volume, and emphasizing structure. Through changes in intensity, direction, and quality of light, the same form can acquire different visual characters, thus becoming transformable in a perceptual sense. In this way, form is not observed solely as a geometric whole, but as a perceptual phenomenon that emerges through the interaction between lighting conditions and the observer’s sensory experience.

Figure 2. Forms, light and shadows [13]

4. LIGHT AND SHADOW

Light and shadow are integral elements of form and space, contributing to their dynamic qualities in terms of appearance and relativity. They are key components of visual perception—on one hand, defining shape, texture, and color, and on the other, conveying depth and atmosphere within a space. Form and space can only be perceived when illuminated, even by a minimal light source. Visual perception of space and form depends on the intensity, direction, and color of illumination.

There are natural and artificial sources of light. Sunlight is white and composed of six clearly defined colors and all transitional shades (yellow, red, blue, orange, violet, and green—the spectrum of the rainbow). The quality of white sunlight shifts depending on various natural influences, thereby creating the color of the atmosphere. As the seasons change, the angle of sunlight and the shades of electromagnetic radiation change as well, producing altered perceptions of the same forms. Sunrises and sunsets change the color of the atmosphere because light travels a longer path, making red and orange wavelengths more visible. Thus, the same space or object may be experienced differently at various times of day or during different seasons.

Light is not only a physical phenomenon that allows us to perceive color, shape, and texture; it also has the capacity to transform structure into a dynamic entity. Whether from natural or artificial sources, light is essential for defining space, evoking emotion, and enhancing the overall aesthetic experience. For example, soft, diffuse sunlight can create a calm ambiance, while a focused beam of light can draw attention to a specific architectural detail or artwork. Deliberate manipulation of light and shadow can profoundly alter the way space is perceived. Light and form are primary elements of architectural composition, and both are prone to dynamic transformation depending on the time of day, the season, or the intensity of natural light.

Artificial lighting plays a particularly important role in shaping and redefining spatial perception. Unlike natural light, which depends on external conditions, artificial light allows for constant and intentional control—it can be precisely directed and modulated in line with the author's vision. Its intensity, direction, color temperature, and degree of diffusion directly influence how a form is visually perceived. Light effects shape the relationships between surfaces, emphasize textures, structures, and material qualities, while shadows become active components of visual dynamics. In this way, light projects a new geometry by forming shadows as spatial drawings, creating a sense of ongoing visual transformation. Artificial light allows for multiple interpretations of the same form. It can be categorized by character—diffuse (soft) or direct (hard)—as well as by direction, the shape of the source, and the type of light fixture used.

A shadow is a phenomenon that occurs when an opaque object obstructs the path of light. The characteristics of light directly affect the appearance of the shadow. A shadow has its own shape, dynamics, and visual features. Its form always depends on the light source, the position and shape of the object casting the shadow, and the surface onto which the shadow is projected. A small or point light source will produce sharp and well-defined shadows, while diffuse light creates lower contrast and softer edges. The closer the light source is to the object, the larger and more widespread the shadow will be; conversely, if the source is farther away, the shadow becomes smaller and more precise. Besides distance and angle, shadows are shaped by surface textures and light reflection. When multiple light sources are present, overlapping shadows may occur. Shadows can also be categorized based on the degree to which light penetrates the object.In architecture, shadows play a crucial role in shaping space and atmosphere and in evoking different emotional responses. They emphasize form and volume. Particularly important are the dynamic qualities of shadows—their ability to create rhythm or harmony within space.

5. STUDY OF FORM THROUGH PHOTOGRAPHY

The photographic study of form occupies a key role, serving as a bridge between visual perception, analysis, and visualization. It is presented through black-and-white photography, as this medium is more suitable for the exploration of form. Using achromatic black, gray, and white tonal values, the visual qualities of form, such as shape, contrast, and proportional relationships among structural elements, are more clearly revealed under the influence of light and shadow.Its use functions as an analytical tool, enabling a deeper investigation and understanding of formal and other dynamic relationships. Form studies through photography can be conducted under controlled studio conditions, where relationships between elements are examined using artificial lighting and a neutral background. Through careful selection of framing, angle, perspective, lighting conditions, and the relationship between foreground and background, attention is directed toward key formal characteristics [14].The position and variation of the light source, its intensity, and the shape of the light beam further remodel the form, while shadows reveal its structure and dynamics. In this sense, light becomes not only a means of visibility, but also a carrier of meaning.

The illustrations present a series of examples of formal transformations of a single solid form, shown from a frontal view against a neutral background. The resulting photographs were taken under strictly controlled studio conditions, using artificial lighting. In all examples, the position of the camera, the object of perception (the subject) and the background remained identical. The only variable was the number, position, and intensity of the light sources.

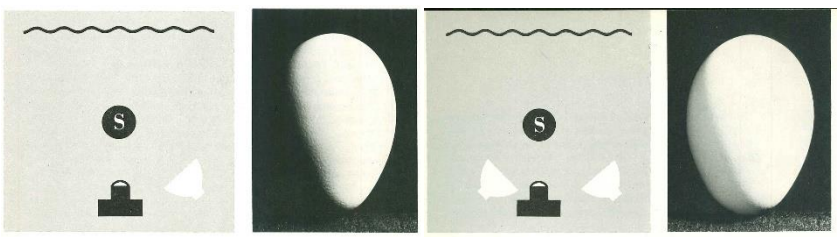

Figure 3. a) Example with one light source
b) Example with two light sources of different intensity

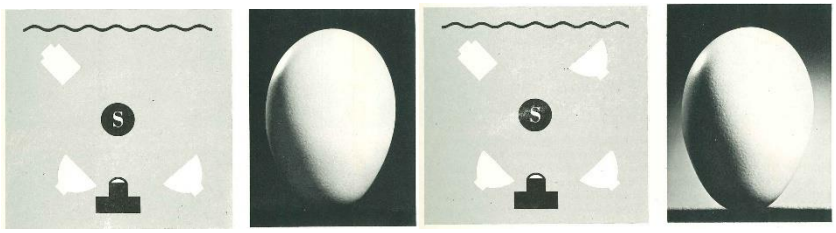

Figure 4. a) Example with three light sources of different intensities and positions
b) Example with four light sources of different intensities and positions

The presented examples illustrate the formal transformations of shape caused by variations in the number and intensity of light sources. The light sources differ in terms of diffusion and direction and are oriented toward the subject of perception. In the final example, one light source is directed toward the background, resulting in a perception of spatial context, while in the others, the focus remains exclusively on the subject. A single light source creates a simpler visual impression, in which the fully shaded portion merely hints at the subject's form. Introducing a second light source reveals the form through a transparent shadow cast by the stronger light. With the addition of a third light source aimed at the subject, a new shadow emerges and its intensity increases. *(Figure 3,4.)*

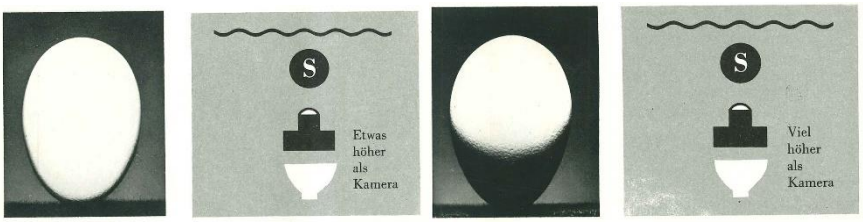

Figure 5. a) Example with a light source larger than the camera
b) *Example with a light source positioned above the camera*

When the light source is larger than the camera lens and located behind the point of perception, the form is displayed as a shape defined by a prominent edge shadow, also illuminating the background. When the light source is moved vertically, the shadow changes shape relative to the extent of the movement. This example demonstrates greater contrast in terms of light intensity and source positioning. *(Figure5.)*

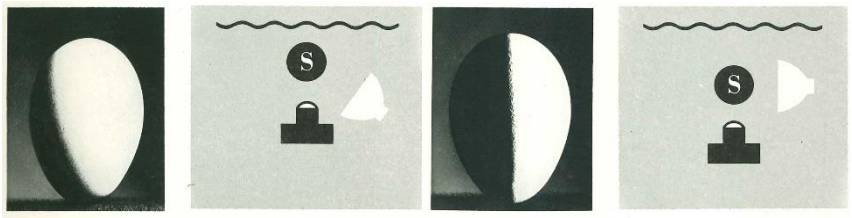

Figure 6. Examples of a direct light source and its positional change

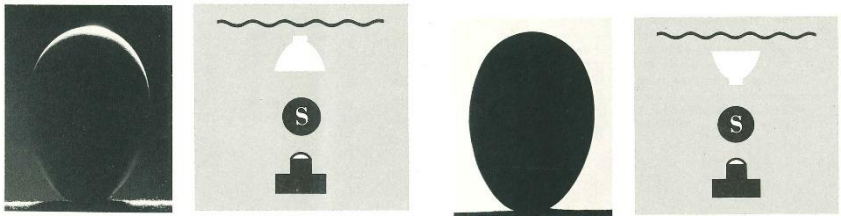

Figure 7. a) Example with the light source positioned behind the subject and directed toward the camera, b)*Light source positioned behind the subject and directed toward the background*

As the light source is brought closer to the subject, sharp shadows are formed that match the contours of the perceived form. If the same high-intensity light is directed laterally toward the subject, it creates a visual geometric plane that evenly divides the subject between light and complete shadow *(Figure 6,7).*

The study of form outside of controlled studio conditions can be conducted in unpredictable and spontaneous natural environments. In such cases, observation and analysis include the interaction between the form and its immediate surroundings, or the form as an independent entity. A reduced number of details in the photograph results in fewer visual cues, which in turn directs focus toward the visual analysis of the studied subject. In this visual investigation, the photographs were produced by students as part of a semester assignment for the course of the same name. The task required them to identify suitable positions and frames of selected architectural structures within an urban context. All observations were made from the same position, angle, and framing of selected details, but at different times of the day. Since the angle of natural sunlight shifts throughout the day, the study required documentation at various times, resulting in four photographs per subject. In this way, the transformation of the visual characteristics of architectural form under the influence of light and shadow quality was documented and interpreted.

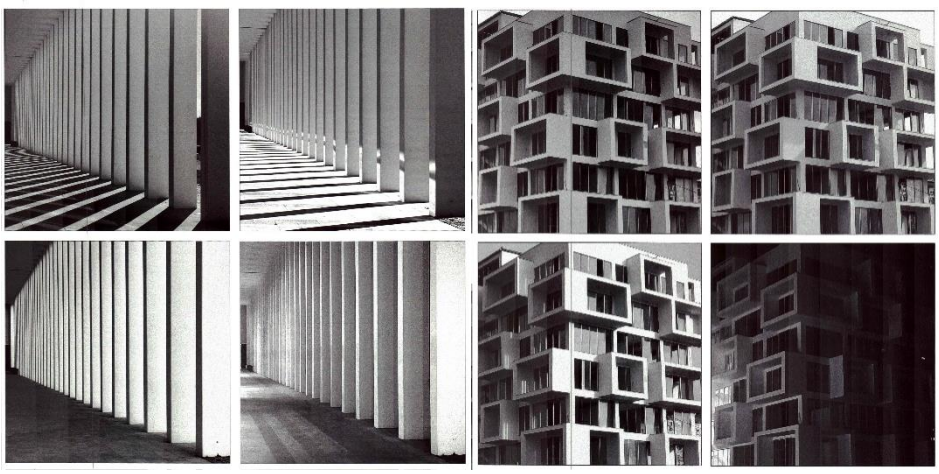

Figure 8. Student works from Visual Research course 2024- Faculty of Civil Engineering and Architecture, University of Niš a) Aleksandra Peulić b) Milica Đorđević

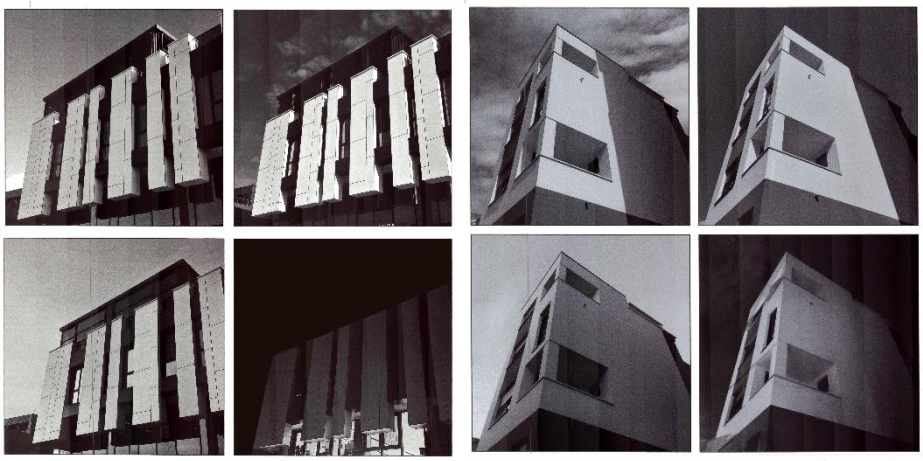

Figure 9. Student works from Visual Research course 2024- Faculty of Civil Engineering and Architecture, University of Niš a) Sanja Ranković b) Ivona Đelić

Elaboration

The presented student works demonstrate how variations in natural lighting throughout the day significantly affect the visual perception of architectural elements. The shadows become sharper or softer, highlighting different parts of the form and shifting the viewer's focus. For instance, in Figure 8b, the light from the late afternoon sun accentuates the relief and depth of the façade, while the morning light in Figure 8a results in a more uniform and flattened appearance. These shifts in perception confirm that light and shadow not only reveal geometry but also redefine the emotional and spatial experience of the observed object. Such insights provide valuable recommendations for architectural lighting design—emphasizing the need for dynamic light studies in early design phases to enhance form expression and spatial atmosphere.

6. CONCLUSION

The study has shown that light and shadow, as fundamental elements of visual perception, play a crucial role in transforming the experience of architectural form. Their ability to model space, shape shadows, and emphasize structural characteristics makes them not only visual phenomena but also instruments of expression and meaning. Analysis conducted through controlled photographic experiments and student projects in real urban environments confirmed that the visual identity of form is not static but dynamically shifts depending on the light source—its direction, intensity, and number. Photography, as a methodological tool, proved to be an effective mediator between perception and visual analysis, enabling precise articulation of form transformability. These insights highlight the importance of understanding lighting conditions in architectural design processes, especially in the context of education, where awareness of visual sensitivity and the perceptual complexity ofspace is cultivated.

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Review paper

VISUAL ELEMENTS OF ARCHITECTURAL FORM

Sanja Spasić Đorđević[1], Vladan Nikolić[2], Sanja Janković Rakić[3], Olivera Nikolić[4], Jasmina Tamburić[5]

Abstract

Visual elements in the design of architectural forms are crucial in shaping space and creating the final architectural composition. The shape and proportion of the object determine how the architectural form will fit into the environment and how users will perceive the space. The colors and materials used in construction can significantly influence the visual dynamics, creating contrasts or harmony within the space. Lighting and the shadows that are created have an important role in highlighting details, creating visual depth and atmosphere within the object. Good architectural design not only meets technical requirements but also carefully balances these elements to create a space that satisfies aesthetic needs. The aim of this paper is to explore the impact of each of these elements on the form of the built object. By examining these elements, the paper will provide a deeper understanding of their interrelationship and how they all contribute to the final appearance and functionality of the object.

Key words: *architectural form, design, visual elements, architectural composition, shape*

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1. INTRODUCTION

Architectural form is an important element in the analysis of an architectural object and is often the subject of various theoretical and practical researches. Even in the ancient period, Vitruvius in his book Ten Books on Architecture points out that architecture rests on the principles of order (táxis), arrangement (diathesis), eurythmy, symmetry, propriety and distribution [1]. These principles do not only apply to the construction of the building, but also to the way in which the shape of the building reflects the harmony of the elements, thus creating a recognizable visual expression. Vitruvius' principles still have significant theoretical value today because they show that the relationship between the form and the meaning of an object has been present since the earliest thinking about architecture. As one of the key elements of the visual experience of architecture, form never acts independently. Rob Krierer [2] says that the three elements of architecture are function, form and construction and that all three have equal significance in designing. However, through the understanding of the form, it is possible to see the way in which the object communicates with the space and the observer. The statement that "shaping is nothing but the creation of tangible and visible forms of a building"[3] speaks of form as the visual language of an architectural idea. Designing an object can be understood as the process of transforming abstract spatial ideas into concrete forms. Through shaping the form, architecture not only becomes accessible to the observer, but also invites him to a deeper experience and understanding of the object. According to Ching [4], form is "the configuration of mass and space, which results from the organization of lines, surfaces and volumes in three-dimensional space", and as such represents the basis for further perception of the built object. The visual elements of the architectural form represent the basic components of the architectural expression through which communication between the space and the observer is achieved.

This paper focuses on the analysis of the visual elements of architectural form, exploring how they contribute to shaping the building's appearance, identity, and the impression it leaves on observers. Special emphasis is placed on how the form communicates with its environment and users, as well as how it contributes to the recognizability of the architectural work.

2. VISUAL ELEMENTS IN THE DESIGN OF ARCHITECTURAL FORM

Architectural form represents the visible shape of a building, resulting from the relationship between space, structure, and function, while also taking into account the context in which the building is created. [4]. Most often, we describe the form of an object as either regular or irregular [2]. However, for a deeper analysis, it is necessary to examine each of the visual elements of the applied form more specifically. Visual elements are crucial for understanding the designed architecture, as they shape the way users perceive the space, its structure, atmosphere, and aesthetic qualities. The basic visual elements of architectural form include [5]: **shape, size, color, light, and texture** (Figure 1). Each of these elements plays a specific role in creating the general impression of the object and significantly influences the way the space communicates with its environment and users. Bacon [6] states that these elements relate not only to the exterior appearance and perception of the object but also apply to the interior. Additionally, he mentions **shadow**

along with light, which will also be taken into account during the analysis of each individual element.

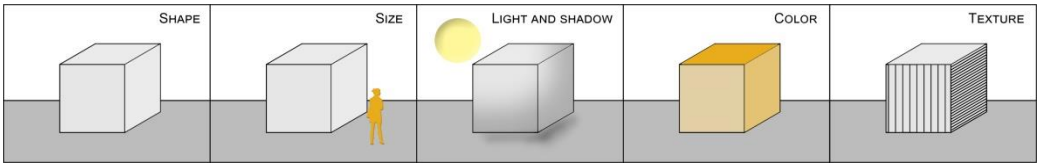

Figure 1. Visual elements of Architectural form

Shape represents the fundamental visual element through which architectural form is identified and recognized in space [4]. In the process of interpreting the shape of a building, we often first identify basic geometric forms such as the circle, rectangle, or triangle. These forms serve as the foundation of architectural composition, but their transformation through bending, multiplication, rotation, or interpenetration leads to the creation of more complex, intricate shapes. The interpretation of more complex architecturally shaped parts or entire objects used in the creation of form requires knowledge of geometric surfaces and their classification in order to recognize the specific shape of a building. In some more complex forms, segments or sections of surfaces are used, and through multiplication and merging, they create a complex spatial structure [7]. In contemporary architecture, especially with the development of digital tools and parametric design, fluid, organically shaped forms have emerged, which, through the analysis of form, can be classified as abstract forms.

When analyzing shape, it is important to recognize its symbolic aspect. In the architecture of memorials, museums or certain public buildings, the form often carries a deeper meaning, the architect then uses a metaphor, or awakens an emotion in us by creating a certain form. The shape is then not only an aesthetic choice, but a means of communication and transmission of the message that the object presents to the observers.

Size is one of the fundamental visual elements of architectural form and refers to the dimensioning of an object. By defining size, it is possible to emphasize important elements both of the object itself and by creating landmarks in relation to other objects. Therefore, the perception of size should always be considered in relation to other forms, space, and above all, the observer. It is also important to highlight that when we talk about size, we are not always referring to massiveness, but rather to the emphasis of certain parts by defining smaller or larger sections, or the entire object. For example, if we want to emphasize how magnificent or powerful something is, we increase the dimension of the element. However, we also talk about size when we want to highlight the intimacy of a place by creating a more harmonious, smaller element**.** Size is closely related to scale [5], because it only becomes legible in relation to the person or the environment.

Color is the attribute that most clearly separates a form from its surroundings [4]. The use of different colors allows for the emphasis of certain parts of an object, creating a dominant element in space, but also connecting it to the context in which it is located. The choice of colors must be carefully considered in order to achieve harmony and balance. Color is closely related to light and the texture of materials, and therefore significantly affects the perception of the shape and atmosphere of a space. When we talk about color, we do not always think of bright colors such as red and blue, but we can also talk about the value of white and black and their shades. The choice of colors has a strong psychological effect because it affects the mood of the user or observer.

Light. "Architecture is a knowledgeable, correct, and magnificent play of forms assembled in light. Our eyes are made to see forms in light; shadows and bright spots reveal forms" [8]. When we talk about light as a visual element, we must observe two directions. Natural light, the position of the object in relation to the sun, the shading in relation to neighboring objects, the creation of a natural shadow from the object itself and the surroundings contribute to the experience and affect the appearance of the object itself. Through the play of light and shadow, the volumes and textures of the material are emphasized. Natural light changes the appearance of the architecture during the day, creating a dynamic ambience. Another thing is the application of artificial lighting, which can be used to emphasize some parts of the object, it gives the architects additional control, which enables them to emphasize certain elements of the form. Light can affect the emotional response of the user, creating a feeling of warmth, drama or calmness, that's why light is one of the important visual elements of the form that shapes the entire visual identity of the space.

Texture represents the surface structure of the material from which the object is made. The texture directly depends on the selection of the material used to build the object or the finishing coating used to cover the element itself. "The texture of an object is perceived by sight and touch, it can be rough or smooth, matte or shiny, etc. The texture affects the way light is reflected and the perception of the object's color, the experience of objects that have the same color but a different texture is completely different." [9]. Through different textures, the object gets a specific visual identity, which significantly influences the way we observe and experience it in space.

1.1 Interaction of visual elements in the development of the final design

When observing all these elements, we can notice that they never act independently and that only through the combination of these elements does the designed form **achieve** beauty and harmony. In The Dynamics of Architectural Form, Arheim [3] states: "Just as no machine, orchestra, or sports team can perform without the integrated cooperation of all its parts, neither can a work of art or architecture fulfill its function and convey its message if it does not represent an organized structure." According to Ching [4], all these elements contribute to achieving a harmonious form, which he presents through the following principles: axis, symmetry, hierarchy, rhythm, datum, and transformation. Through these principles, the architect shapes the form according to their vision and the functional requirements of the space.

Each of the visual elements presented in the previous chapter plays a crucial role in creating composition and balance within a space. A well-designed combination of shape and size can establish a harmonious relationship between an object and its environment, while the interplay of light and shadow, along with the careful selection of materials, colors, and textures, contributes to the form’s dynamism. These elements are always used in interaction, achieving a balance between the aesthetic values and the functionality of the space. The harmonious integration of these factors, like pieces of a puzzle, contributes to the overall perception of the object, making it visually appealing to the observer.

2.1. Analysis of Visual Elements on the Selected Object

Since we will not now deal with the influence of function on form, or the construction of the element itself, but only with the relationship of the elements used to the applied form, the most famous work of Bogdan Bogdanović was chosen for the analysis. The Stone Flower monument (Figure 2), built in 1966 in Jasenovac, is dedicated to the victims who died in the concentration camp located at the same location. Despite the time in which it was built, the analyzed monument has an attractive design and attracts attention even today [10].

The stone flower represents one of the most famous features of Yugoslav architecture, and it is recognizable precisely by its form. Based on the previous chapter, we will analyze each of the visual elements.

Figure 2. Jasenovac monument, source: https://www.spomenikdatabase

The shape of the analyzed monumental object is recognizable by its shape imitating a flower (Figure2). In this case, the shape came from the symbolic idea of the architect, where the flower is shown as a new life, but also as a memory of suffering. The shape of the flower is achieved by the formation of 5 petals, which are placed radially around the central pillar of a cylindrical shape. The petals have a more complex geometric shape, each petal is shaped like a curved surface. By transforming and refining the surface, balance was created in the design and simplicity in proportion.

If we look at the monument itself, we will see that **its size** represents a clear central landmark in relation to the rest of the area, a symmetrical structure with a dominant flower attracts attention from whichever direction you look at it. With a height of 24m and a length of 36m, it stands out in relation to the natural environment in which it is located [11] (Figure 3). The plain that surrounds it and the hill on which it is located contribute to its magnificence. With the appropriate size, a balance was achieved in relation to the environment. In the picture shown, you can see how magnificent it is in relation to the observer. With this kind of presentation, its greatness stands out even more (Figure 4).

The absence of color is not accidental, but represents a choice that strongly contributes to the overall expression of the work through the absence of decorativeness. On some of the architect's sketches, attempts at colored shading can be seen, but the building is made of concrete, which is a characteristic material for memorials from that period of construction. Color was avoided in this case, so as not to demean the seriousness of the subject of suffering. The gray shade of concrete additionally enhances the atmosphere of sadness, the neutral, cold surface of the material directs the viewer's attention to the form itself, the play of light and shadow and the message the object sends.

Figure 3 Showing the size of the object in relation to the height of people, source: https://www.spomenikdatabase

Figure 4 View of the object in relation to the natural context in which it is located, source: https://www.jusp-jasenovac.hr/

Some of B. Bogdanovic's first sketches show that he thought deeply about the position of the planned building in relation to **sunlight**, (Figure 5a). The place where the monument was placed was chosen thoughtfully, precisely through the analysis of the shadow and reflection that will be created in the water that is next to it. Also, the shadows created by the flower itself and the openings in the petals contribute to the impression that the flower is rooted in the ground because a dark shadow is created by the upper element. The openings on the petals allow light to penetrate into the interior of the flower, further highlighting its shape.

Figure 5a, 5b Bogdan Bogdanovic's sketches, source: https://www.jusp-jasenovac.hr/

Even during the planning of the building, horizontal hatching is clearly visible on the sketches (Figure 5b), which was later implemented. **The texture** was achieved by choosing concrete as the material, and the flower column itself is additionally emphasized with a relief

that imitates the stem of the flower. Visually, its rough surface reflects light in an irregular manner, creating a play of shadows that further emphasizes the drama of the form.

3. VISUAL ELEMENTS IN THE FUNCTION OF CREATING ARCHITECTURAL IDENTITY

The form of the monument “Stone Flower” cannot be viewed in isolation from the broader architectural and cultural context in which it was created. “Memorial architecture played an important role in establishing the newly created Yugoslav identity” [12]. In this sense, the analyzed monument is not an isolated phenomenon, but rather part of a broader visual system that characterizes the architectural production of that period.

Specific visual elements such as geometric abstract shapes, dramatic contrasts of light and shadow, the absence of color, emphasized sizes, and expressive surfaces of rough texture were not exclusively formal choices of individual authors. In fact, they became characteristic elements of the language that shaped the visual identity of the space of socialist Yugoslavia. This aesthetics of brutalism and late modernism is recognizable not only in monuments, but also in cultural centers, public institutions, schools, residential architecture, and even in the design of urban furniture.

What connects the buildings of that period is the rejection of historical stylization in favor of a new modernist paradigm in which form, through shape, size, material, texture, and light, become the main elements of the complete architectural expression. It is precisely through the repetition and variation of these visual elements that a recognizable visual identity of the state was built, which also had an ideological dimension — it symbolized collectivity, progress, resistance, and memory.

In this broader context, the “Stone Flower” can be interpreted as an archetype of the entire era in which it was built. Its brutalist aesthetic is not only a stylistic designation, but a visual medium through which the values of resistance, suffering, but also unity and permanence are articulated.

4. CONCLUSION

Analyzing the visual elements on the example of the Stone Flower monument clearly shows how carefully and thoughtfully the architect uses shape, size, color, light, shadow and texture to create a strong spatial experience and emotional reaction of the viewer. The form in this case is not only an aesthetic choice, but carries a deep symbolic meaning. Through the careful integration of all visual elements, Bogdanović managed to shape an architectural work that becomes a powerful symbol of collective memory and remembrance of the victims of suffering. This analysis confirms that the architectural form cannot be viewed separately from the elements that build it, but as a result of their complex interrelationship. That is why it is important to consider visual elements in the earliest stages of design, already at the level of the first sketches, as we had the opportunity to see through the analysis of this work. Today, there are also 3D tools with which we can experiment and try several versions through modeling before the final selection of the form, which facilitates the selection and creation of the final form of an object. Through understanding the relationship of the analyzed elements, the architect can direct the further development of

the form towards achieving the desired expression and atmosphere. Visual elements are not only a means of design, but also a tool for conveying ideas and emotions that the object should evoke. Their thoughtful use enables the establishment of a connection between the space, the user and the wider context. Only through a comprehensive analysis and careful balancing of these elements is it possible to create architecture that leaves a lasting and powerful impression.

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Research paper

INDOOR ENVIRONMENTAL QUALITY IN SCHOOLS THROUGH THERMO TECHNICAL SYSTEM UPGRADES

Milija Radović[1], Mirjana Miletić[2], Rada Radulović[3], Ružica Božović[4]

Abstract

Recent studies emphasize the importance of energy efficiency in public buildings, with particular attention to school facilities. While much research focuses on enhancing the thermal performance of building envelopes, it is equally crucial to analyze the indoor environment, especially thermal comfort. Since classrooms are designed for younger populations, ensuring optimal thermal conditions is essential for both well-being and productivity. Numerous studies indicate a strong correlation between thermal comfort and students' cognitive performance. This study examines the thermal comfort conditions in schools built in the first half of the 20th century. Representative model of these buildings is analyzed using energy simulations in DesignBuilder software. The research assesses thermal comfort levels and energy efficiency before and after the modernization of heating systems. Specifically, the study evaluates the replacement of traditional heating systems with heat pumps, which offer greater energy efficiency and lower environmental impact. Findings suggest that upgrading heating systems has a moderate impact on thermal comfort but significantly reduces energy consumption. The results also highlight the necessity of integrating energy-efficient solutions in school renovations to enhance indoor conditions and sustainability. Future research should further explore the interplay between modern HVAC systems, air quality, and overall indoor comfort in educational spaces. By implementing sustainable heating solutions, school buildings can provide healthier learning environments while contributing to broader energy conservation goals.

Key words: *schools, indoor environment, thermo-technical systems*

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1. INTRODUCTION

High energy consumption is one of the most serious problems facing global society today. Globally speaking, buildings are responsible for 50% of total energy consumption, which is mainly used for heating and cooling. The energy-efficient renovation of buildings is of great economic and environmental importance. If existing buildings, identified through analysis as requiring renovation, are properly retrofitted, energy consumption can be reduced by up to 90 % [1]. This involves improving the thermal characteristics of the building envelope and thermo technical systems. In this way, the so-called *Factor 10* can be achieved, which represents the enhancement of buildings with a resulting energy savings of 90 % [2].

The building's thermo technical system is a technical subsystem that includes installations, equipment, and devices for air conditioning, heating and cooling, as well as the domestic hot water (DHW) system [3].

There are many studies investigating the energy efficiency of school buildings [1], [4–9]. They mostly focus on seven key aspects of improving energy efficiency: improving the thermal envelope, HVAC systems, automation of heating, cooling, and lighting systems, maximizing the use of daylight, lighting control, use of geothermal water, and use of solar panels [10].

In 2017, the Republic of Serbia, in cooperation with the Republic of Germany, implemented an energy renovation initiative for public buildings, aiming to improve the energy efficiency of 30 to 40 school buildings. Besides reducing energy consumption, the project also aimed to improve comfort conditions in student spaces [11].

The main objective is to highlight the importance of energy renovation of a specific type of school buildings, focusing on improving thermo technical systems in existing buildings through the lens of thermal comfort in student spaces. From this main objective, the following tasks arise:

Analysis of renovation results for school buildings through dynamic simulations;

Identification, analysis, and calculation of possible interventions in thermo technical systems, particularly heating systems, to be applied to a specific type of school building in the Šumadija District.

The initial hypotheses were formed after a thorough examination of the research subject and an analysis of potential heating systems applicable to primary schools in the Šumadija District.

The main research hypothesis is:

By improving thermo technical systems and selecting appropriate heating systems, without addressing the thermal envelope of the building, it is possible to improve thermal comfort conditions in schools.

Additionally, the research is based on the following auxiliary hypotheses:

By using air-to-water heat pumps as improved systems compared to existing ones, it is possible to achieve energy savings of 20%.

The methodology established in this study and the proposed heating system improvement measures enable the identification of school types most suitable for implementing the proposed heating system in terms of energy savings and improved thermal comfort.

2. METHODOLOGY

This study is designed to proceed in three interconnected directions. The first involves a theoretical consideration of the issues related to the energy efficiency of school buildings, climatic characteristics, legislation, comfort conditions—with a particular focus on thermal comfort—and previous research concerning thermo technical systems and heating systems in school buildings in Serbia. The second direction consists of data collection and analysis of the existing condition of selected representative sample of school buildings in the Šumadija District. This building undergoes defined improvements of thermo-technical systems, specifically heating systems, without taking into account any enhancement of the building's thermal envelope. In order to achieve results and compare the existing condition of school building with the condition after the implementation of improved thermo technical systems, the third direction of the research is conducted. The comfort conditions of both the existing and improved states, as well as the energy consumption for heating, are examined.

The results are analyzed and calculated using dynamic simulations. Energy modeling and dynamic simulations of the buildings carried out by software package DesignBuilder, version 5.0.3.007.

2.1. Comfort conditions for school buildings

Comfort includes thermal conditions, visual perception, air quality, and appropriate noise levels. The concept of comfort encompasses thermal, visual (i.e., lighting), air quality, spatial, and acoustic aspects.

"Thermal comfort represents a psychological state that corresponds to a pleasant sensation of thermal conditions in the space, that is, when thermal equilibrium of the human body is achieved. The objective parameters of thermal comfort are: air temperature, mean radiant temperature of surfaces, air velocity, and air humidity" [3].

The main indicator of indoor environmental quality is the Predicted Percentage of Dissatisfied (PPD), which is determined for each category of comfort individually.

Certain standards define criteria and parameters for achieving optimal indoor environmental conditions. For each individual comfort aspect, specific standards were used during dynamic simulations:

Thermal comfort is addressed by three international standards:

SRPS EN ISO 7730 – *Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local thermal criteria* [12],

ASHRAE Standard 55 [13],

CEN EN 15251 [14].

The CIBSE Guide A is a concise reference covering environmental conditions, energy efficiency, and methods of improving various types of spaces in terms of energy performance and achieving energy efficiency [15].

In Section 1.4 of the CIBSE Guide, Table 1.5 provides basic guidelines for all types of comfort as initial parameters for the design of thermotechnical systems in student spaces. Table 1 represents an excerpt from Table 1.5 of the CIBSE Guide A.

Table 1. Indoor environment for school buildings, Source: CIBSE Guide A [15]

Thermal space	Winter operational temperature and clothing level			Summer operational temperature and clothing level			Air level / Ls^{-1} per person	Light lux	Acoustic level dB
	Temp. °C	Activity met	Clothing clo	Temp °C	Activity met	Clothing clo			
School building									
amphi-theatre	19-21	1.4.	1.0.	21-23	1.4.	0.65	10	500	25-35
semminars	19-21	1.4.	1.0.	21-23	1.4.	0.65	10	300	25-35
classrooms	19-21	1.4.	1.0.	21-23	1.4.	0.65	10	300	25-35

3. REPRESENTATIVE MODELS OF SCHOOL BUILDINGS

The school building analyzed in terms of energy efficiency and potential measures for improving the heating system are full (eight-grade) primary schools in the Šumadija District, constructed in the first half of the 20th century. The analysis of the thermal envelope in both the existing and improved states, as well as the analysis of HVAC systems and comfort conditions in both states, was conducted through dynamic simulations. It should be noted that the thermal envelope is not treated as one of the measures for improving energy efficiency, but its analysis is essential in dynamic simulations.

The building analyzed in the study, both in their existing and improved states, belong to the type of facilities with compact layouts. This school is Category B school – buildings intended for primary education, Type I – facilities built before 1945 [16].

3.1. Dynamic Simulations

Modeling of the building in both existing and improved states in terms of thermo technical systems, as well as dynamic simulations—i.e., the analysis of thermal comfort conditions and energy consumption for heating, cooling, and lighting—was carried out using the DesignBuilder software package, version 5.03.007, with EnergyPlus 8.5, The Activity module defines the activity present within the building, based on which the number of hours or time spent in the space is determined. For both buildings, the selected module was *Teaching areas – student spaces*, with an occupancy rate of 0.55 per/m² (D1 Edu ClassRm:Occ).

The HVAC module represents the thermotechnical systems present in the building. As previously mentioned, this mainly refers to lighting and heating. In the existing state, this corresponds to the *Low Standard* module. There is no cooling system, and coal is used as the primary heating fuel. The Heating system seasonal CoP is 0.4.

3.1.1. Model S1- existing conditions

The primary school "Vuk Karadžić" in Knić, model S1, municipality of Knić, was built in 1938. The gross developed area of the school is 907.62 m². The surface area of the façade wall is 877.37 m², while the area of the openings is 244.22 m² (Figure 1).

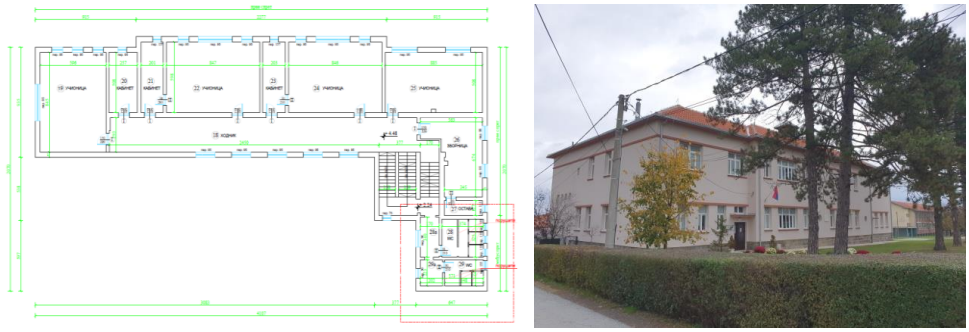

Figure 1. Model S1 School in Knić, Authors

The thermal envelope of building S1 and the maximum allowed values of the heat transfer coefficient U (W/m²K) according to the Regulation on Energy Efficiency of Buildings are presented in Table 2.

Table 2. Thermal envelope of S1

Thermal layers	Layers , δ (m)	U (W/m2K)	Umax (W/m2K)
External wall	Cement plaster 0,013 Polystirene 0,8 Brick 0,22 Gypsum plaster 0,013	0,309	0,9
Glass	Wooden frame Double glass	1,96	1,5
Ground floor	Urea formaldehid foam 0.13 Concrete 0.1 Screed 0.07 Wooden floor 0.03	0,25	0,4
Roof	Tile 0,025 Air 0,02 Wooden layer 0,005	2,9	0.2

Air conditioning, ventilation systems, and the domestic hot water preparation system are not present in the building. The original heating system consisted of wood and coal stoves. Through reconstruction and renovation of the building, a radiator heating system and an air-to-water heat pump were installed.

Simulations have shown that the annual energy consumption for heating is Qhnd 24.18 [kWh/m²a], indicating that the school, in its existing state, belongs to energy class B. The good thermal performance of the walls results in low heat losses, and the use of local stoves for heating as needed also demonstrates efficient energy consumption. Supplemental heating ensures that the school already meets the requirements for an appropriate energy class in its current state.

The heating design, including radiant and operative temperatures, as well as air and surrounding surface temperatures, is shown in Figure 2.

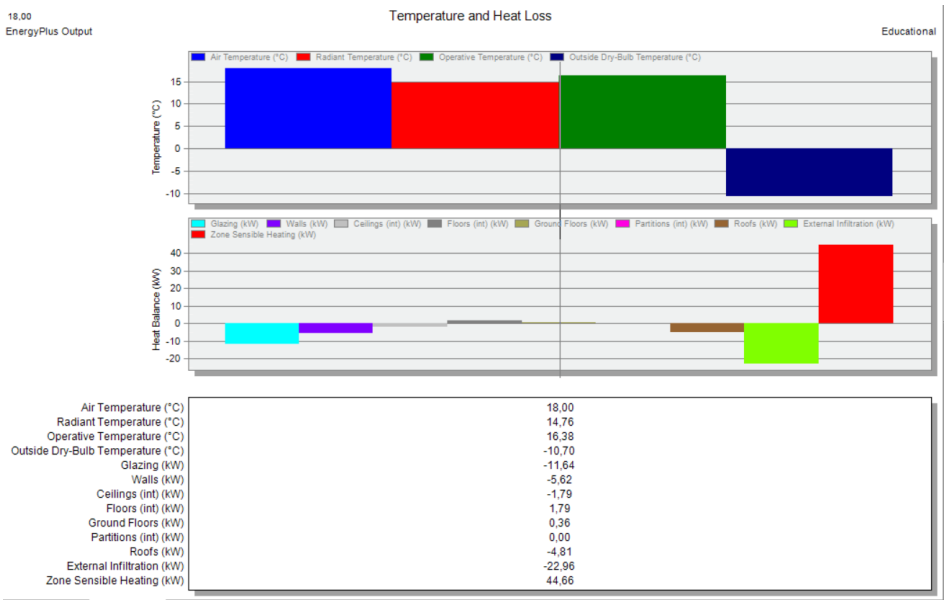

Figure 2. Heating design of S1, Design builder software

When calculating the thermal comfort values, the following comfort parameter values for student spaces were taken into account (Fig. 11). (ASHRAE 90.1)

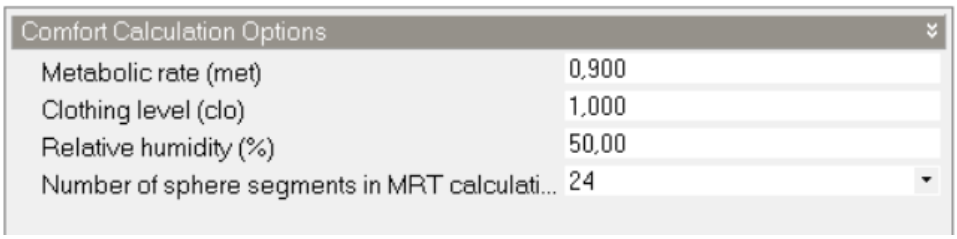

Figure 3. Comfort calculations, Design Builder, CFD Modul

In the classrooms, based on the results obtained from the simulations, the conditions for thermal comfort are met. The average radiant (comfort) temperature with the installed systems is in the range of 18.77ºC to 19.60ºC, which is considered very favorable (Fig. 4).

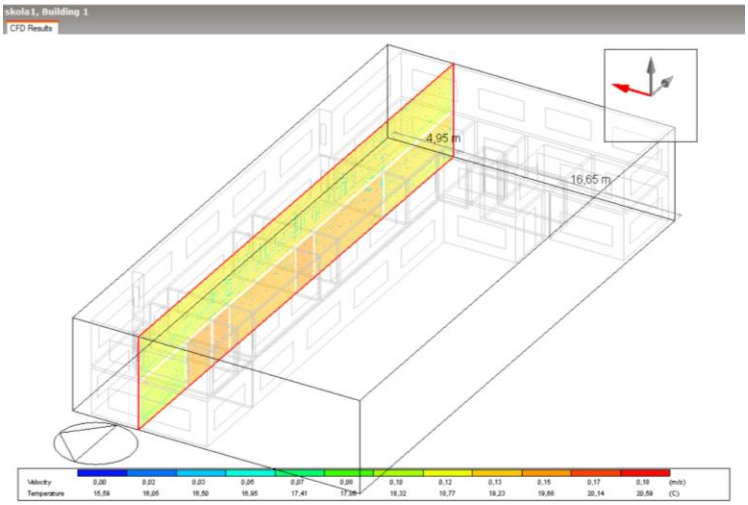

Figure 4. Comfort conditions in the classrooms of the S1, Authors

4. COMFORT CONDITIONS AFTER THERMOTECHNICAL SYSTEM UPGRADE

The building analyzed as case studies, S1 have a thermal envelope that fully complies with the parameters prescribed by the Regulation on Energy Efficiency of Buildings 61/2011 [17]. The thermal envelope was not altered in the improved state. The improvement was made by changing the heating system. In their existing state, the buildings used solid fuel stoves, burning coal and wood. The improved state involves replacing the heating system and installing air-to-water heat pumps. The modified state is represented through models S1N-

The model S1N (model S1 with improved systems) consumes Qhnd = 19.20 kWh/m²a annually, which places it in energy class A. The annual energy consumption for cooling is 94.20 kWh/m²a, which is not regulated by the Energy Efficiency Regulation of the Republic of Serbia and is considered irrelevant given the limited use of student spaces during the summer period, i.e., the summer break. The heating design is shown in Figure 5.

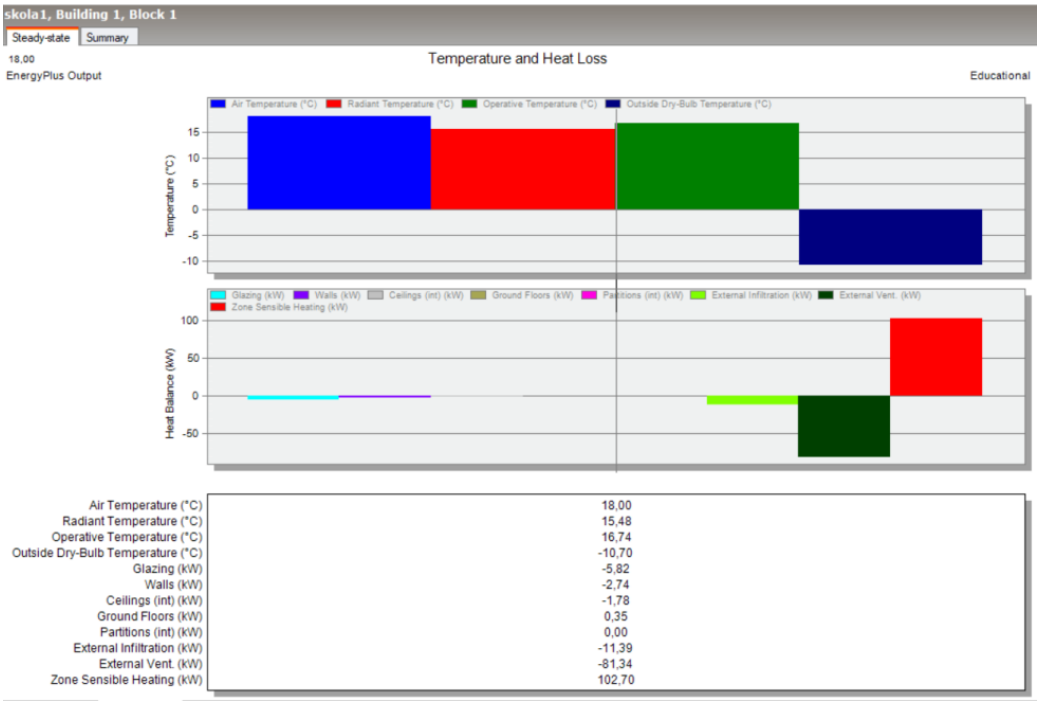

Figure 5. Design heating for S1H, Authors

4.1. Thermal comfort

PPD values for the model S1H for student spaces range from 46.17% to 98.18%. The working conditions during the winter period are acceptable, with an emphasis on colder conditions. PMV for the same spaces and the same time period ranges from -2.96 to -1.41. Additional heating is necessary for the children's workspaces. Electric heating is planned (Figure 6).

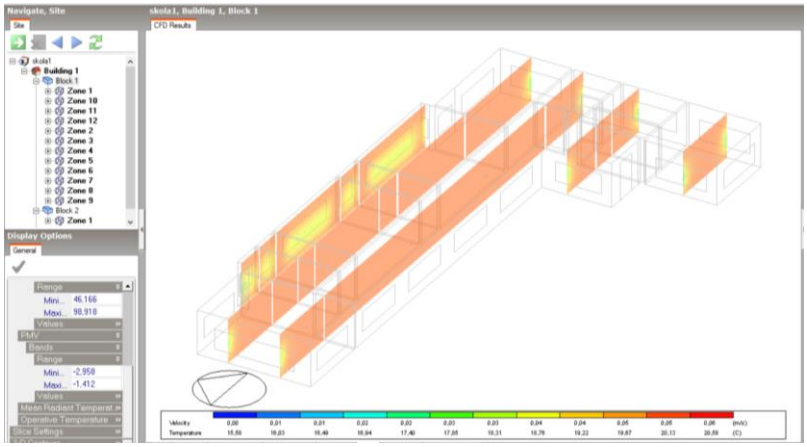

Figure 6. Thermal comfort for S1H model, Authors

4.1.1. Comparison of existing and upgraded model concerning thermal comfort

A comparative analysis of the obtained results regarding energy consumption for heating in the existing (S1) and improved states (S1N) of the school is presented in the table 3.

Table 3. Comparison of results for model S1 and S1H

Model	Heating energy Q_{hnd}[kWh/m^{2}a]
S1	24,18
S1H	19,20

Building S1, the "Vuk Karadžić" school, consumes 24.18 kWh/m²a annually for space heating, which places it in energy class B. By improving the existing heating system and installing air-to-water heat pumps, simulation results show a 20% improvement for model S1. As a result, the energy class of model S1 was improved by one level, which justifies the energy retrofit. A comparative analysis of the obtained results regarding thermal comfort for the existing and improved states of the model, S1 and S1N respectively, is presented in Table 4.

Table 4. Comfort for S1 and S1H model

Model	Comfort			
	PMV	PPD %	Radiant temperature T (ºC)	Operational temperature T (ºC)
S1	-1,96-1,47	49,03-74,95	20,00-20,00	18,83-19,96
S1H	-2,96-1,41	46,17- 98,92	13,93-20,00	14,82-20,00

Through analysis and dynamic simulations using the DesignBuilder software, specifically the CFD (Computational Fluid Dynamics) module, the results shown in Table 4 were obtained. According to SRPS EN 15251, such high PPD % values are permitted only for a limited period of time. Additional heating is required in all classrooms in the existing state According to the ASHRAE 55 standard, the acceptable PMV range is between -0.5

and +0.5, corresponding to a PPD of 10% (Table 4). Based on the results, there was no instance in which the conditions were suitable for children's occupancy. According to data from CIBSE Guide A, the operative temperature in classrooms should be in the range of 19–21 ºC. Simulations showed that the improved state leads to a less favorable indoor temperature. In the existing state, with local stoves and supplemental electric heating, the level of comfort is significantly better compared to the improved state. If we exclude the summer period and comfort conditions during the hottest months—due to the school break and adjusted activity (i.e., inactivity) in student spaces—comfort parameters were only slightly changed, with a 1% improvement resulting from the installation of the new heating systems.

8. CONCLUSION

Energy efficiency in buildings refers to the energy consumed during their lifecycle in relation to the useful output achieved, aiming to improve this ratio. Benefits of energy efficiency include improved indoor quality, reduced pollution, greater energy security, reduced emissions, and positive effects on climate change. It is especially important to evaluate comfort conditions in schools, as indoor air quality and temperature directly impact students' productivity and concentration.

This paper presents an analysis of thermal comfort conditions in student areas following improvements to the heating system. Simulations were conducted using DesignBuilder software (EnergyPlus 8.5), focusing on heating energy consumption and comfort conditions without altering the building envelope. The study analyzes representative school model (S1 and S1N) located in the Šumadija region, built before World War II. Improvement was made by replacing traditional coal/wood stoves with air-to-water heat pumps during reconstruction, and these changes were simulated without accounting for architectural upgrades to the thermal envelope.

The simulations show a 20 % improvement in heating energy consumption (from 24.18 to 19.20 kWh/m²a), upgrading the building from energy class B to A. However, thermal comfort conditions were only slightly improved (around 1%), and some classrooms still require supplementary heating.

The study concludes that while improvements in HVAC systems significantly reduce energy consumption, they offer limited enhancement of thermal comfort unless combined with improvements to the thermal envelope. Further real-world measurements and analysis of air movement and exchange are needed for a comprehensive assessment.

ACKNOWLEDGMENTS

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Research paper

NUMERICAL SIMULATIONS OF LABORATORY TESTS FOR TRIAXIAL APPARATUS

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Abstract

Numerical simulations of laboratory tests in triaxial apparatus are very important for modeling soil behavior in geotechnical earthquake engineering. Constitutive models in numerical simulations play essential role representing critical aspects of soil response under varying stress conditions and loading paths. Understanding the inherent limitations and applicability ranges of these models is crucial for selecting appropriate models for specific applications and interpreting results. This study presents comprehensive comparative analyses of several triaxial tests simulated using different constitutive material models, with soil modeled as a multiphase medium to better represent its true physical state. The triaxial monotonic drained and undrained tests have been performed at the Laboratory for Soil Dynamics and Foundation Engineering at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) in Skopje, N. Macedonia, in cooperation with colleagues from the Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of Niš, Serbia. The collaborative nature of this research enhances the validity and reliability of the experimental results. The numerical analyses were performed using the finite element software PLAXIS, which offers a comprehensive suite of constitutive models, and the comparisons are discussed in detail.

Key words: *Triaxial tests, numerical simulations, PLAXIS, finite element*

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1. INTRODUCTION

Constitutive models provide essential mathematical descriptions of the mechanical behavior of materials and are fundamental to representing the most important aspects of soil behavior in geotechnical engineering applications. These models serve as the mathematical framework that connects stress and strain relationships, facilitating the numerical simulation of complex soil response under various loading conditions. Despite significant advances in computational geomechanics over recent decades, no single material model exists that can successfully simulate all soil behaviors encountered in practice.

The limitations of elastic material models in soil behavior simulation are well-documented. Although computationally efficient and straightforward to implement, purely elastic models play a minimal role in accurately simulating soil behavior, because soils fundamentally do not behave as elastic materials except within an extremely limited strain range typically less than 0.001%. Beyond this threshold, soils exhibit complex non-linear, stress-path dependent behavior that requires more sophisticated modeling approaches.

The theory based on decomposition of strain into elastic and plastic components represents a powerful tool to describe the irreversible deformations characteristic of sandy structures. This elasto-plastic approach has become a cornerstone in geotechnical modeling, allowing engineers to predict not only failure conditions, but also pre-failure deformations that are often critical in design considerations. When the investigation is limited to failure mechanisms, a simple failure criterion such as the Mohr–Coulomb model is used [1].

For more comprehensive analysis requirements, strain hardening models [2-4] offer significantly more realistic displacement patterns than the basic Mohr–Coulomb criterion. The Hardening Soil model, a prominent example of advanced strain hardening models implemented in commercial software like PLAXIS, incorporates stress-dependent stiffness according to a power law and accounts for both shear and volumetric hardening. The strain hardening models incorporate the evolution of soil strength and stiffness with plastic straining, thereby capturing key aspects of soil behavior that simpler models neglect.

As generally observed by researchers, the inelastic behavior for sands is described within the yield surface framework, which provides a more realistic representation of soil response to loading. Hypoplastic models [5] represent another advanced class of constitutive relationships that capture realistically the influence of both mean pressure and relative density on soil behavior. These models offer substantial advantages in simulating the non-linear response of granular materials without requiring an explicit yield surface definition. The nonlinear constitutive relation is particularly reliable when coupled with volumetric behavior calculations, including the critical effects of pore pressure development during loading. This capability makes hypoplastic models especially valuable for earthquake engineering applications where pore pressure evolution significantly influences soil strength and stiffness.

Recent advances in computational capabilities have enabled increasingly sophisticated implementations of these theoretical frameworks, allowing for more realistic simulations of soil behavior under both static and dynamic loading conditions. The selection of an appropriate constitutive model for a specific geotechnical problem remains a critical engineering decision that requires careful consideration of the model's capabilities, limitations, and parameter identification requirements. This comparative study aims to provide practical guidance for this selection process by systematically evaluating the

performance of different constitutive models in simulating triaxial test results under controlled laboratory conditions.

2. SAMPLE PREPARATION IN TRIAXIAL APPARATUS

Cylindrical specimens of sandy soil, originating from the city of Skopje (hereinafter called Skopje sand), with dimensions of 140 mm in height and 70 mm in diameter were used for all test series, maintaining a height-to-diameter ratio (H/D) between 2 as recommended by standard for soil testing [6]. Due to the difficulty in preserving undisturbed samples of the investigated material and the requirement for numerous tests, all experiments were conducted on reconstituted specimens.

Various methods for reconstituting sand specimens are documented in the literature. Research has established that different reconstitution methods produce specimens with distinct structures and behavioral characteristics [7]. Therefore, it is crucial to consistently reproduce specimens with identical density and soil fabric to ensure reliable research outcomes. Previous studies have demonstrated that the method used to prepare sand to a specific density can significantly influence its settlement characteristics.

The Laboratory for Soil Dynamics and Foundation Engineering at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS-Skopje) has extensive experience with the moist tamping technique for preparing samples of different materials. This technique has been successfully employed, as documented in the works of authors [8-12]. A key advantage of this method is the ability to prepare multiple samples at nearly identical densities.

All tests within this research framework were conducted on fully saturated samples for several reasons. First, soil typically exists below the groundwater level in field conditions and is therefore naturally saturated. Second, volume change measurements are considerably more straightforward in fully saturated samples during consolidation and drained cyclic loading compared to dry or partially saturated samples. In saturated conditions, volume changes can be directly measured by monitoring pore water entering or leaving the sample, whereas in dry or partially saturated conditions, volume changes are complicated by simultaneous changes in air volume within the soil voids.

The specimen is prepared by tamping the soil material in several layers considering the same density of soil layers (Figure 1). After the specimen preparation is finished, the triaxial cell top is placed onto the base. The ram clamp is used to support the ram, so that when the cell top is placed the ram does not make contact with the sample. The cell top is tightened by clamping screws and the ram is moved down towards the sample until it just touches the rubber suction ring. The actuator should be at about mid travel or just above. Using the load machine the triaxial cell is brought down to make contact with the sample. The displacement transducer fitted to the triaxial cell ram is arranged to be close to zero on the levels screen. Triaxial test consists of cylindrical soil specimen fenced within a rubber membrane inside a pressure cell. The lower and upper loading platens have porous disks connected to the drainage system for saturating and/or draining the soil specimen. The confining pressure is applied by adjusting the chamber pressure and the axial stress is applied by pushing the piston. The triaxial cell is filled with water, when water escapes from the air bleed close the cell valve to stop water entering. The system and specimen are ready to test as can be seen in Figure 2.

Figure 1. Triaxial apparatus - preparation of a sample for testing

Figure 2. Triaxial apparatus with soil specimen ready for testing

3. CONSTITUTIVE MODELING OF SOIL IN PLAXIS SOFTWARE

The PLAXIS finite element software incorporates several constitutive models of varying complexity to address challenges in geotechnical modeling. The software offers a range of models from simple linear elastic and Mohr–Coulomb models to more advanced formulations such as the Hardening Soil model and implementations of hypoplastic constitutive relationships. Each model represents different advantages between computational complexity, parameter requirements and capability to capture specific aspects of soil behavior. When selecting an appropriate constitutive model in PLAXIS for a particular geotechnical application, specific features of soil behavior are most relevant to the problem at hand. For problems involving small strains within a limited stress range, simpler models may provide sufficient accuracy.

A particular class of these models considering small deformations, which have received special attention in recent times, is provided by the theory of hypoplasticity. The material model of hypoplasticity defines the change of stress rate of the cohesionless granular materials as a function of initial stress σ, strain-rate Δε and initial void ratio e:

$$\Delta\sigma = f\left(\sigma, \Delta\varepsilon, e\right) \tag{1}$$

This formulation is of rate type which guarantees the load paths to be very similar to reality [13]. Since initial stress and density have impact on the overall deformation of the granular soils, this formulation has in it the stress state and the void ratio as input parameters. In this work the hypoplastic formulation according to Wolffersdorf [14] is used. In tensorial way it is written in equation (2) as

$$\Delta\sigma_{ii}^{'} = L_{ijkl}\Delta\varepsilon_{kl} + N_{ij}\sqrt{\Delta\varepsilon_{kl}\Delta\varepsilon_{kl}} \tag{2}$$

It is to be mentioned that for the simulation of hypoplastic modeling there are couple of parameters which should be defined at the laboratory. In this work, the parameters for the Skopje sand used can be summarized as follows:

Table 1. Hypoplastic parameters of the tested Skopje sand

Description of parameter	Value
Angle of internal friction φc	35°
Granulate hardness hs	2650 MPa
Exponent n	0.26
Minimum void ratio ed0	0.61
Critical void ratio ec0	0.98
Maximum void ratio ei0	1.09
Numerical parameter α	0.07
Numerical parameter β	2.0

On the other hand, the models of Mohr–Coulomb and Hardening Soil make an important part in order to simulate the behavior of the soil. The Mohr–Coulomb model presented by equation (3), despite its simplicity, remains widely used in geotechnical practice and serves as a reference for more advanced constitutive models in PLAXIS:

$$\tau_f = c' + \sigma'_f \tan\varphi' \tag{3}$$

This model is characterized by a fixed yield surface defined by cohesion (c) and friction angle (φ), elastic behavior within the yield surface described by Young's modulus (E) and Poisson's ratio (ν), and a non-associated flow rule governed by the dilatancy angle (ψ).

The Hardening Soil model, on the other hand, represents a significant advancement over the basic Mohr–Coulomb formulation and was also implemented in this numerical simulations using PLAXIS. This advanced constitutive model incorporates stress-dependent stiffness according to a power law (controlled by parameter m), distinguishes between primary loading and unloading-reloading stiffness (E_{50}, E_{oed} and E_{urr}), and accounts for both shear and volumetric hardening. The determination of Hardening Soil parameters requires more comprehensive laboratory testing, including multiple triaxial tests at different confining pressures with precise strain measurements, particularly in the small strain range.

4. IMPLEMENTATION IN PLAXIS SOFTWARE

The implementation in the PLAXIS software is composed of remote scripting in which Python language is used to enable the input of the material parameters. The remote scripting functionality represents a significant advancement over traditional manual GUI-based model creation, allowing for parametric studies, automated verification and reproducible simulation workflows. The implementation process begins with establishing a connection to the PLAXIS remote scripting server as given in Figure 3.

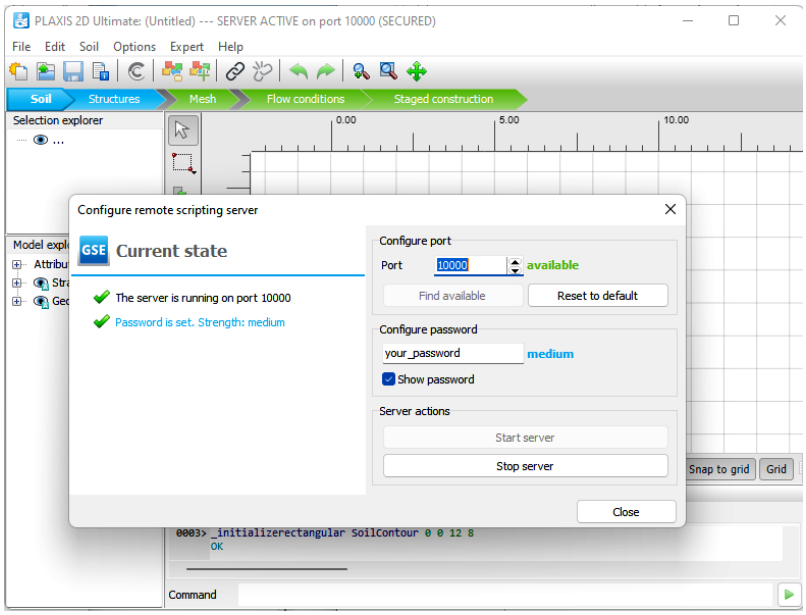

Figure 3. Connecting Python Server in PLAXIS

After the connection has been established, the PLAXIS kernel becomes accessible through Python commands, enabling programmatic control over all aspects of the simulation process. This connection provides a bidirectional communication channel between the Python environment and the PLAXIS computational engine as shown in Figure 4.

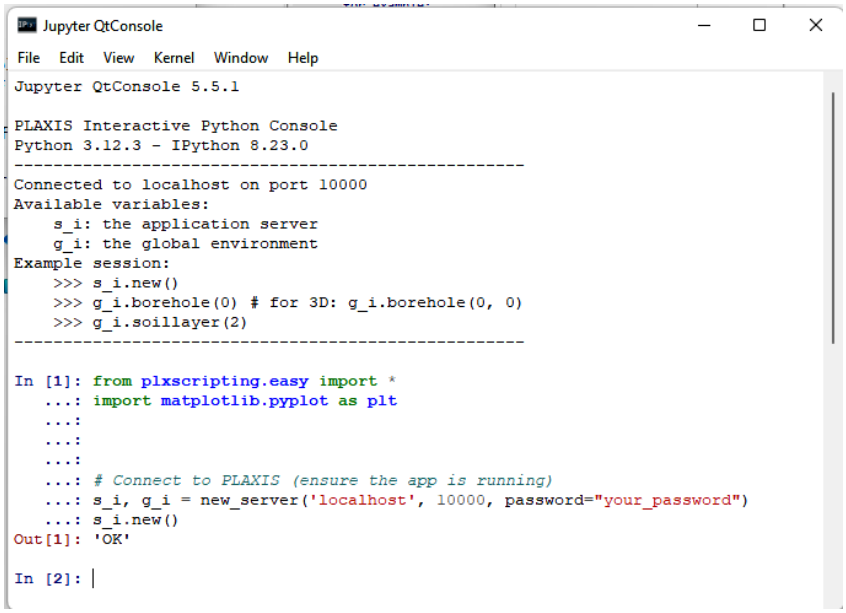

Figure 4. The Python Console of the PLAXIS software

The main advantages of the interactive console over traditional GUI-based modeling include efficient parameter input, the ability to run multiple simulations with varying parameters and comprehensive documentation of all simulation inputs ensuring reproducibility. The input files for the material models are provided in the Appendix. As the file is processed, the PLAXIS software activates a specialized module for material testing, as given in the following Figure 5.

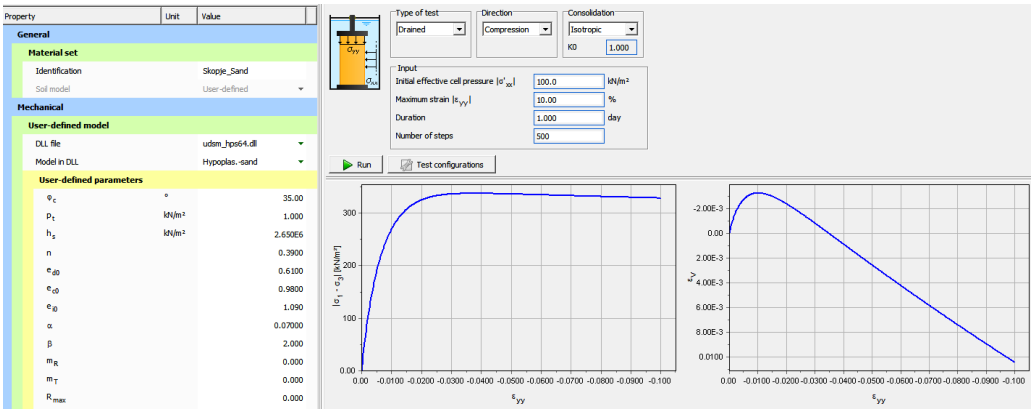

Figure 5. Testing module of PLAXIS software

5. ANALYSIS OF RESULTS

In analyzing the results first the **drained case of monotonic test** has been considered. During the test at the laboratory the valve has been left open in order to simulate the drained case of experiment. The drained triaxial test simulations provide instructive insights into the relative performance of the constitutive models. As illustrated in Figure 6, the experimental

stress–strain curves for Skopje sand exhibit characteristic non-linear behavior with distinct transitions from initially stiff response to progressively softer behavior as strains increase. The Mohr–Coulomb model, while correctly predicting the ultimate strength at large strains, significantly overestimates stiffness in the small to medium strain range. This results in unrealistic displacement predictions that would lead to substantial underestimation of settlements in practical applications. The model's linear elastic assumption prior to failure creates a bilinear stress–strain curve that fundamentally misrepresents the gradual yielding process occurring in the soil. In contrast, the Hardening Soil model demonstrates remarkable agreement with the experimental data across the entire strain spectrum. Its hyperbolic formulation successfully captures the progressive mobilization of shear strength and the continuous transition from small-strain elastic behavior to large-strain plastic deformation. Particularly noteworthy is the model's ability to reproduce both the initial tangent stiffness and the secant stiffness at 50% of failure stress (E_{50}), which proves crucial for accurate settlement predictions. On the other hand, the Hypoplastic model results are closer to the experimental values due to the captured nonlinearity from the beginning of the strain development.

The comparative analysis clearly illustrates that while all models may converge to similar predictions at failure conditions, the deformation path to failure is substantially better represented by the Hardening Soil model and Hypoplastic model.

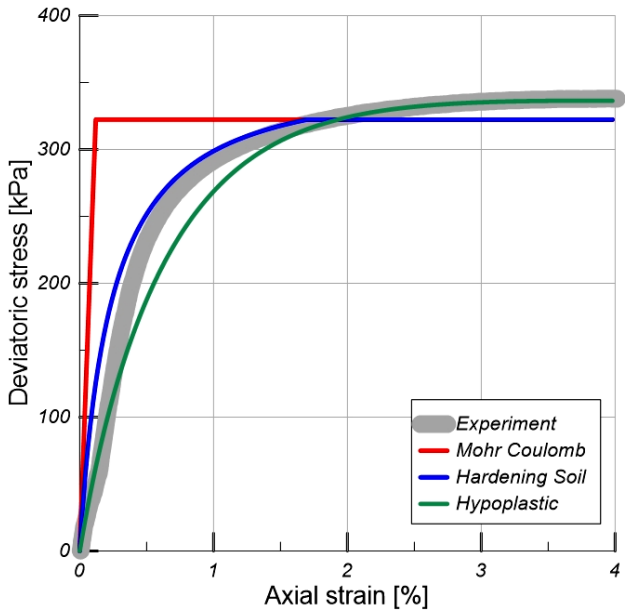

Figure 6. Comparison of drained triaxial test results with different material models

The **undrained triaxial test results**, as shown in Figure 7, reveal significant differences in how the models predict stress–strain behavior under undrained conditions. The experimental data (solid gray line) exhibits the characteristic non-linear response with initial stiffness at small strains gradually transitioning to a more plastic response at larger strains, ultimately approaching a plateau around 550 kPa deviatoric stress at 3% axial strain. The Mohr–Coulomb model together with the Hardening Soil and Hypoplastic model demonstrate good performance, closely tracking the experimental curve throughout most of the loading path. The main reason for the good correlation among the models is due to the fact that

undrained conditions are primarily controlled by the strength parameters not letting the volume change to occur. The Mohr-Coulomb model is demonstrated to be a logical first approxiamtion due to its simplicity. The models successfully capture the initial curved portion of the stress–strain relationship, reflecting the correct undrained stiffness mobilization that is critical for accurately predicting pore pressure development. This comparison underscores the importance of advanced constitutive modeling when analyzing undrained behavior, particularly for dynamic load applications, where the precise prediction of excess pore pressure generation and dissipation can significantly impact design decisions.

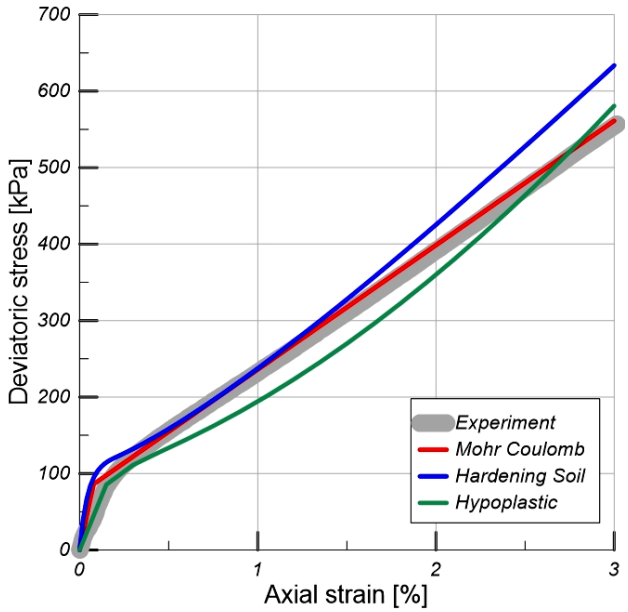

Figure 7. Comparison of undrained triaxial test results with different material models

From the above figures a qualitative assessment of the model capabilities can be given in a tabular way (Table 2) as follows:

Table 2. Qualitative assessment of the model capabilities

Soil behavior aspect	Mohr–Coulomb model	Hardening Soil model	Hypoplastic model
Nonlinear stress–strain behavior	poor	good	good
Stress-dependent stiffness	not captured	well captured	well captured
Small-strain behavior	poor	moderate	good
Computational efficiency	good	moderate	moderate
Parameter determination ease	good	moderate	hard

As can be seen from the Table 2, although both Hardening Soil and Hypoplastic models have similar good predictions on experimental values, the parameter determination can be the deciding factor in selection of the material model.

6. CONCLUSIONS

This study presents a comprehensive comparison of numerical simulations for triaxial tests on Skopje sand using different constitutive models implemented in PLAXIS software. The results demonstrate that while the Mohr–Coulomb model adequately captures ultimate strength parameters, it significantly underperforms in reproducing the initial behavior of sand, including non-linear stress–strain relationships. The Hardening Soil model demonstrates markedly superior performance across multiple aspects of soil behavior, whereas the Hypoplastic model shows the best performance for the numerical simulations. Regarding the parameter determination, on the other hand, it might be time consuming using the hypoplastic material models.

These insights contribute to the broader understanding of soil behavior modeling and highlight the importance of selecting constitutive models that appropriately balance computational efficiency with predictive accuracy for specific geotechnical engineering applications.

APPENDIX

Python input for Hypoplastic model

```
sand_props = [
   "Identification", "Skopje_Sand",
   "SoilModel", "userdefined",
   "gammaUnsat", 17, "gammaSat", 20,
   "PermHorizontalPrimary", 1e-5]
mat = g_i.soilmat(*sand_props)
# Set the DLL file and model
g_i.setproperties(mat, "DLLfile", "udsm_hps64.dll")
g_i.setproperties(mat, "ModelinDLL", "Hypoplas.-sand")
# Set the Hypoplastic parameters using values from the table
g_i.setproperties(mat, "User1", 35)      # φc: Angle of internal friction [°]
g_i.setproperties(mat, "User2", 1)       # pt [kN/m²] (reference pressure, typical value)
g_i.setproperties(mat, "User3", 2650000)    # hs: Granulate hardness [kPa] (2650 MPa = 2650000 kPa)
g_i.setproperties(mat, "User4", 0.39)      # n: Exponent [-]
g_i.setproperties(mat, "User5", 0.61)      # ea0: Minimum void ratio [-]
g_i.setproperties(mat, "User6", 0.98)      # ec0: Critical void ratio [-]
g_i.setproperties(mat, "User7", 1.09)      # ei0: max void ratio [-]
g_i.setproperties(mat, "User8", 0.07)       # α: Numerical parameter [-]
g_i.setproperties(mat, "User9", 2.0)       # β: Numerical parameter [-]
g_i.setproperties(mat, "User16", 0.77)     # SV: e0 or e [-] ()
```

Python input for Mohr–Coulomb model

```
# Define material
sand_props = [
   "Identification", " Skopje_Sand ",
   "SoilModel", "Mohr-Coulomb",
   "gammaUnsat", 17,         # Unit weight above phreatic level [kN/m³]
   "gammaSat", 20,          # Unit weight below phreatic level [kN/m³]
   "Eref", 270000,             # Young's modulus [kN/m²]
   "nu", 0.2,               # Poisson's ratio [-]
   "cRef", 5,               # Cohesion [kN/m²]
   "phi", 35,               # Friction angle [°]
   "psi", 7,                # Dilatancy angle [°]
   "PermHorizontalPrimary", 1e-5  ]
```

Python input for Hardening Soil model

```
# Define material
sand_props = [
   "Identification", " Skopje_Sand ",
   "SoilModel", "Hardening Soil",
   "gammaUnsat", 17, "gammaSat", 20,
   "E50Ref", 90000,
   "EoedRef", 90000,
   "EurRef", 270000,
   "cRef", 5,
   "phi", 35,
   "psi", 7,
   "PowerM", 0.5,
   "pRef", 100,
   "PermHorizontalPrimary", 1e-5]
```

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Research paper

IMPROVING THE MECHANICAL PROPERTIES OF CLAYEY SOIL BY ADDING WASTE MATERIAL - FLY ASH AND ROCK FLOUR

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Abstract

Stabilization of clayey soil with an inadequate physical and mechanical properties in its natural state represents one of the actual challenges in contemporary geotechnical engineering. Among numerous stabilization techniques, chemical stabilization stands out as an effective technique for stabilizing clayey soils. By applying this technique, various types of stabilizers may be used, whereby they react with soil particles and modify its structure, contributing to the permanent improvement of the physical and mechanical properties of the soil. In this study, waste materials obtained as a product of industrial processes, such as fly ash and rock flour, were considered as chemical stabilizers. A comparative analysis of the effects of adding fly ash and rock flour on improving the uniaxial compressive strength (UCS) and the shear strength parameters of clayey soil was performed, while simultaneously monitoring the durability of the achieved effects.

Key words: *chemical stabilization, clayey soil, fly ash, rock flour, UCS, shear strength parameters*

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1. INTRODUCTION

Chemical stabilization of soils is a widely applied technique aimed at enhancing the engineering properties of soils that, in their natural state, fail to meet required performance criteria. With the advancement of industrial processes, increasing attention is being paid to the use of industrial by-products as adequate alternative substitutes for conventional stabilizing agents. This trend is evident across all branches of civil engineering, including geotechnical engineering. Among the by-products with high potential for such applications are fly ash, a residue from thermal power plants, and rock flour (filler), a material generated through the mechanical crushing of rock masses in quarries [1-4].

Traditionally, soil stabilization has relied on the use of binding agents such as cement and lime. However, the production of these materials is associated with considerable CO_2 emissions, high energy consumption and substantial economic costs [5]. Consequently, recent research has increasingly focused on the use of alternative materials—particularly industrial waste products—that can function as reagents, activators, or supplementary stabilizers. These materials not only reduce the overall cost of soil treatment, but also promote environmental sustainability through waste recycling.

The aim of this study is to investigate the effect of fly ash and rock flour on the mechanical properties of clayey soils, with a specific focus on improving the soil uniaxial compressive strength (UCS) and shear strength parameters (cohesion and internal friction angle). The study is based on controlled laboratory testing and a comprehensive evaluation of the technical and environmental feasibility of this soil stabilization approach, and consists of two phases. Firstly, clayey soil samples with each of the selected stabilizers in three different percentages are prepared under laboratory conditions and tested using the UCS test, with the aim of determining the optimal content of each stabilizer in the mixture. Secondly, the influence of the optimal content of each of the tested stabilizers is considered on the soil shear strength parameters. In both phases of the conducted research, the tests are carried out at three different time intervals after soil treatment (3, 14 and 28 days), in order to determine the durability of the effects of the applied chemical stabilization.

2. MATERIALS

The clayey soil used in this study was sourced from the Crvena Reka site, located in the southeastern region of the Republic of Serbia. It was sampled during landslide stabilization activities carried out as part of the construction of the E-80 Highway.

The mineralogical composition of the natural clayey soil was determined using X-ray diffraction (XRD) analysis, which is the most commonly used for the qualitative identification of soil mineral content. The spectrum shows that calcite is the most abundant mineral in the soil (39%), followed by quartz (25%) and clay minerals present at more than 10%: montmorillonite (15%), illite (11%) and chlorite (10%).

The physical and mechanical properties of natural clayey soil were determined by laboratory tests in the accredited Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of Niš, and are presented in Table 1.

Table 1. Properties of the natural clayey soil

Property of Soil	Symbol (unit)	Value
Particle Density	Gs (–)	2.705
Grain Size Distribution	Gravel (%)	1.2
	Sand (%)	4.9
	Silt (%)	40.6
	Clay (%)	53.3
Coefficient of Uniformity	Cu (–)	8.0
Coefficient of Curvature	Cc (–)	2.0
USCS Soil Classification	Symbol (–)	CL
Maximum Dry Density	MDD (g/cm^3)	1.903
Optimal Moisture Content	OMC (%)	18.5
Liquid Limit	LL (%)	49
Plastic Limit	PL (%)	23
Plasticity Index	PI (%)	26
pH Value	pH (–)	9.5
Modulus of Compressibility	Mv (MPa)	12.945
California Bearing Ratio	CBR (%)	2.71
Swelling	s (%)	2.91
Uniaxial Compressive Strength	UCS (kPa)	205
Cohesion	c (kPa)	16.9
Internal Friction Angle	φ (°)	16.5

In contemporary engineering practice, the utilization of *electrostatic precipitator* fly ash has increasingly expanded beyond its traditional role in the concrete industry. While approximately 65% of the total fly ash produced is still predominantly employed in the manufacture of concrete products, its significance in the field of geotechnical engineering—particularly for soil and waste stabilization—has become increasingly evident. Currently, around 7% of total fly ash output is used for such geotechnical applications [6]. Accordingly, recent literature increasingly recognizes fly ash as a standard stabilizing agent, alongside conventional binders such as lime and cement. Numerous studies have demonstrated that fly ash can exert a stabilizing effect even without additional activators, owing to its chemical composition and pozzolanic activity [7-11].

In Serbia's thermal power sector, the annual coal consumption ranges between 35 and 40 million tons, generating approximately 7 million tons of fly ash annually. This accounts for nearly 80% of the country's total industrial waste. Despite its considerable potential, only about 3% of the generated fly ash is currently utilized in the cement industry, highlighting substantial underutilization and indicating ample opportunity for its broader application in geotechnical works, particularly in the stabilization of soils with low bearing capacity. In this study, fly ash sourced from the Kostolac thermal power plant was used, characterized by a dominant content of silicon dioxide (56.38%), alumina (17.57%), ferric oxide (10.39%), calcium oxide (7.46%) and magnesium oxide (2.13%). The effectiveness of stabilization is influenced by several factors, including the properties of the native soil, the proportion of fly ash in the mixture with the soil, curing time and moisture content. Previous research suggests that the optimal fly ash content ranges between 10% and 30%, depending on the soil type and the specific characteristics of the fly ash.

Rock flour, a by-product of rock extraction and crushing in quarries, represents another promising alternative material for soil stabilization. Approximately 20% of the total extracted rock mass converts into this fine fraction during crushing operations. Traditionally used as a surface layer in road construction, recent studies have highlighted its considerable potential in enhancing geotechnical properties of various soil types, including expansive and lateritic soils [9,10]. Notably, improvements have been reported in terms of the soil reduced plasticity and increased load-bearing capacity, depending on the rock flour content in the mixture with the soil. In most cases, the recommended optimal content of rock flour for soil stabilization does not exceed 15%.

The rock flour sourced from the Gradac quarry ("Straževica" – Batočina) was used in the present research. The mineralogical composition of the rock flour was predominantly dolomite, with secondary minerals including calcite and muscovite.

In the scope of this study, for the sake of determining the optimal stabilizer content in the mixture with the soil, clayey soil samples were analyzed with the addition of 10%, 15% and 20% fly ash, on the one hand, and 5%, 10% and 15% rock flour, on the other hand.

3. METHODS AND RESULTS

All tests were performed in the accredited Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of Niš, according to the valid national SRPS EN standards that are in accordance with the European regulations [12,13]. In addition, all samples were prepared with the optimal natural soil moisture content of 18.5% (Table 1), for reasons of adequate and relevant comparability of results.

3.1. Uniaxial Compressive Strength (UCS)

For the purpose of determining the soil UCS value, tests were made on samples with the addition of fly ash in the amount of 10%, 15% and 20% and on samples with the addition of rock flour in the amount of 5%, 10% and 15% in relation to the dry weight of the soil sample. It is noticeable that the time interval that has passed since the chemical treatment had no significant effect and that both stabilizers contributed to a certain increase in the UCS value.

The maximum UCS values obtained with the addition of fly ash in the amount of 10% (307 kPa) and 20% (342 kPa) were lower than those with the addition of 15% fly ash (371 kPa). This result indicates that the optimal fly ash content can be considered to be 15%. The UCS value obtained by the test performed 3 days after treatment did not change significantly with further passage of time.

A similar trend in the change in the UCS value was observed in the samples with the addition of rock flour. Namely, compared to the natural state of the soil (205 kPa), the maximum improvement (289 kPa) was achieved with the addition of 10% rock flour, 14 days after treatment. Similar results were obtained after 3 days (268 kPa) and after 28 days since the treatment (275 kPa). The addition of 5% and 15% rock flour did not contribute to a significant increase in the UCS value. This finding indicates the conclusion that 10% can be considered the optimal content of rock flour.

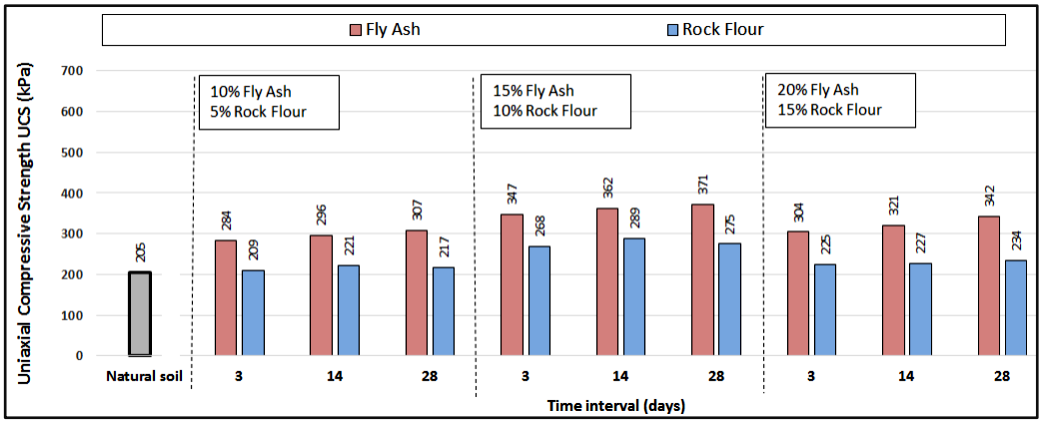

Figure 1. Comparison of the soil UCS value obtained after the chemical treatment for the selected contents of the considered stabilizers in the mixture with clayey soil

3.2. Soil Shear Strength

The shear strength of the soil is one of the most important geomechanical properties of the soil. It is defined by the Coulomb–Mohr failure criterion, which gives the dependence of shear stress (τ) and normal stress (σ) in the form $\tau = \sigma \cdot tg\varphi + c$, where c and φ are the shear strength parameters of the soil, i.e. cohesion and angle of internal friction. These parameters were determined as part of the research by direct shear tests.

The tests were performed on samples with the optimal content for each of the selected stabilizers obtained from the UCS test. The tests were carried out in three time intervals, i.e. 3, 14 and 28 days after mixing the stabilizer with the natural soil.

Shear stress at failure (τ) of clayey soil mixtures with the considered stabilizers under normal stress (σ) of 50 kPa, 100 kPa and 200 kPa is shown in Table 2. It can be seen that the shear strength increased over time in case of all the considered stabilizers. According to these results, all the maximum shear strength values were obtained at the test time of 28 days after the treatment, at a normal stress of 200 kPa.

Table 2. Variation of shear stress at failure (τ) of clayey soil mixtures with the optimal content of the considered stabilizers under various levels of normal stress (σ) and over time

Soil conditions	Normal stress σ (kPa)	Shear stress at failure τ (kPa)		
Natural soil	50	30.9		
	100	49.8		
	200	78.1		
Stabilized soil		Time elapsed after treatment		
		3 days	14 days	28 days
Fly ash (15%)	50	32.4	35.7	38.7
	100	54.6	56.7	60.8
	200	81.1	89.1	93.2
Rock flour (10%)	50	40.6	42.7	46.7
	100	59.8	66.7	65.2
	200	91.7	97.5	98.7

From Figure 2, it can be seen that the addition of fly ash does not significantly affect the increase in cohesion, whereas the increase in the angle of internal friction is more pronounced. With regard to rock flour, on the other hand, there is a significant increase in cohesion, whereas the increase in the angle of internal friction is approximately the same as in the case of adding fly ash.

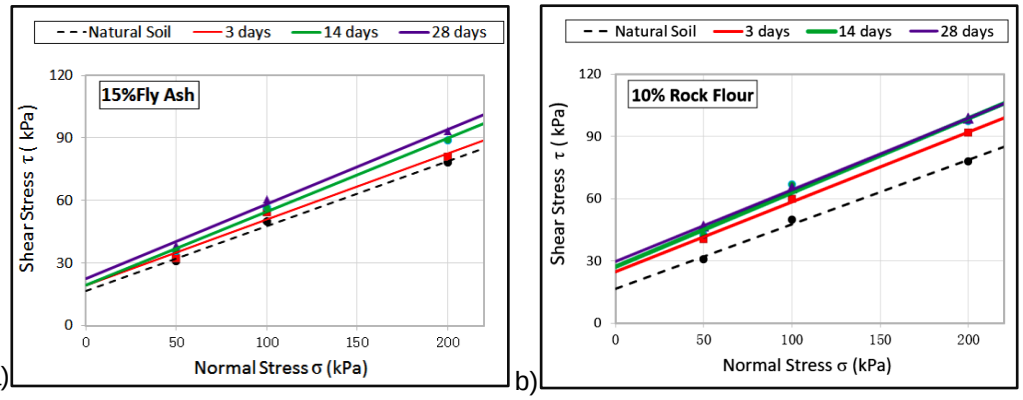

Figure 2. Coulomb–Mohr lines of clayey soil mixtures with the optimal content of the considered stabilizers, for the selected time intervals after the soil treatment: a) fly ash (15%); b) rock flour (10%)

The recorded changes in the values of shear strength parameters (cohesion (c) and internal friction angle (φ)) relative to the natural state of clayey soil (c = 16.9 kPa and φ = 16.5°) are presented in Table 3. Both stabilizers contribute to the improvement of soil cohesion and the internal friction angle. The best results are achieved 28 days after treatment. The optimal amount of fly ash contributes to a maximum increase in cohesion of 22.5 kPa and an internal friction angle of 19.3°. On the other hand, the addition of rock flour significantly affects the increase in cohesion value (29.9 kPa), whereas the internal friction angle value is also slightly increased (19.0°) as in the case of the addition of fly ash. The maximum value of the internal friction angle with the addition of rock flour is achieved after 14 days, amounting to 19.6°.

Table 3. Variation of shear stress parameters of clayey soil mixtures with the optimal content of the considered stabilizers over time

Soil conditions	Shear strength parameters			
	Symbol (unit)	Value		
Natural soil	c (kPa)	16.9		
	φ(°)	16.5		
Stabilized soil		Time elapsed after treatment		
		3 days	14 days	28 days
Fly ash (15%)	c (kPa)	18.5	19.5	22.5
	φ(°)	17.6	19.3	19.3
Rock flour (10%)	c (kPa)	24.6	27.3	29.9
	φ(°)	18.7	19.6	19

4. CONCLUSION

In this study, the individual effects of adding different materials (based on by-product) using the chemical stabilization technique on improving the mechanical properties of clayey soil were investigated.

The study consisted of two phases. First, clayey soil samples with each of the selected stabilizers in three different percentages were prepared under laboratory conditions and tested using the UCS test. This phase of the research aimed to determine the optimal content of each stabilizer in the mixture. Changes in the UCS values of the tested samples were also monitored at different time intervals after treatment (3, 14 and 28 days), in order to determine the durability of the effects of the applied chemical stabilization. Based on the obtained UCS values, the greatest improvement in quality was achieved with the addition of 15% fly ash (UCS value increased around 2 times) and 10% rock flour (UCS value increased around 1.5 times).

In the second part of the study, the influence of the optimal content of each of the tested stabilizers was considered on the soil shear strength parameters (cohesion and internal friction angle). In this phase, as in the previous one, the tests were conducted at the different time intervals with the same goal, to determine the long-term effectiveness of the improvements with the selected stabilizers. Given the soil shear strength parameters, the value of cohesion increased significantly with the addition of rock flour (around 1.8 times), whereas in the case of fly ash an increase was somewhat lower (around 1.3 times). On the other hand, considering internal friction angle, almost the same effect was achieved for both selected stabilizers (an increase of 1.15 times in the case of rock flour and 1.17 times in the case of fly ash). It was also observed that the values of the strength parameters increased over time.

The findings of this study have demonstrated that the enhancement of the mechanical properties of clayey soils can be effectively achieved through the application of alternative stabilizing agents derived from industrial by-products. Each of the investigated stabilizers, when added to untreated clayey soil, has exhibited the potential to improve its mechanical properties, thereby contributing to its suitability for diverse applications in engineering practice. It is important to note, however, that all conclusions drawn in this research are based on tests conducted on a locally sourced clayey soil with a specific mineralogical composition. Consequently, further extensive research is needed to evaluate the effectiveness of these stabilizers on clayey soils of different mineralogical and geotechnical characteristics.

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Research paper

ANALYSIS OF THE BEHAVIOR OF LATERALLY LOADED PILE–SOIL SYSTEM

Zoran Bonić[1], Andrija Vlašković[2], Nikola Romić[3]

Abstract

Piles, as a type of deep foundations, are primarily intended to accept the vertical load from the superstructure; however, under certain circumstances, they are also exposed to significant lateral loads. This is the case with retaining structures, bridge piers, transmission line poles, chimneys, tall buildings, dock facilities, oil platforms, etc. In the focus of this paper is the analysis of the behavior of laterally loaded piles. First, the most common analytical models for the calculation of this problem were presented, and then the described models were evaluated with the results of experimental investigations on laterally loaded piles tested in situ. Based on the conducted comparative analysis, it was concluded that the integrated approach – the enhancement of existing analytical models with the results of experimental investigations – results in models that more realistically take into account the interaction of the pile and the surrounding soil, which is of crucial importance in the case of laterally loaded piles.

Key words: *Geotechnical engineering, laterally loaded piles, soil–structure interaction, load–displacement response.*

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1. INTRODUCTION

Like other deep foundations, piles are primarily designed to support significant vertical loads. However, under certain conditions, they are also exposed to significant transverse (horizontal) loads. This is the case with retaining structures, transmission line poles, dock facilities, oil platforms, bridge piers, chimneys, etc. For some structures, the criterion for the design of piles is the ultimate force that causes the pile to fail or the soil around the pile to fail, whereas for other structures the criterion is the maximum displacement of the pile. In both cases, when designing piles, it is necessary to determine the values of bending moments, shearing forces and displacements along the depth of the pile.

When dimensioning piles (as is the case with sheet piles and diaphragms), the most common starting point is the differential equation of the elastic line of the pile as a structural element exposed to the effect of vertical and horizontal loads:

$$EI\frac{d^4y}{dx^4} + V\frac{d^2y}{dx^2} + p = 0 \tag{1}$$

where: EI – bending stiffness of the pile,

V – vertical force in the pile,

y – displacement of the elastic line of the pile (deflection),

p – reactive lateral soil pressure (soil reaction).

For practical calculation purposes, the influence of the vertical force V on bending is usually neglected, which is justified in the case of sheet piles and diaphragms, where the vertical force (if present at all) is almost always of low intensity, but not in the case of piles, where V represents the predominant load. However, considering that the presence of vertical force reduces the lateral displacements and bending, and consequently the remaining influences in the pile (bending moment, shear force and lateral soil resistance), its neglect is on the side of safety. Thus, the basic differential equation of the elastic line of the pile takes its final form:

$$-EI\frac{d^4y}{dx^4} = p \tag{2}$$

Figure 1 shows the distribution of basic static quantities along the pile.

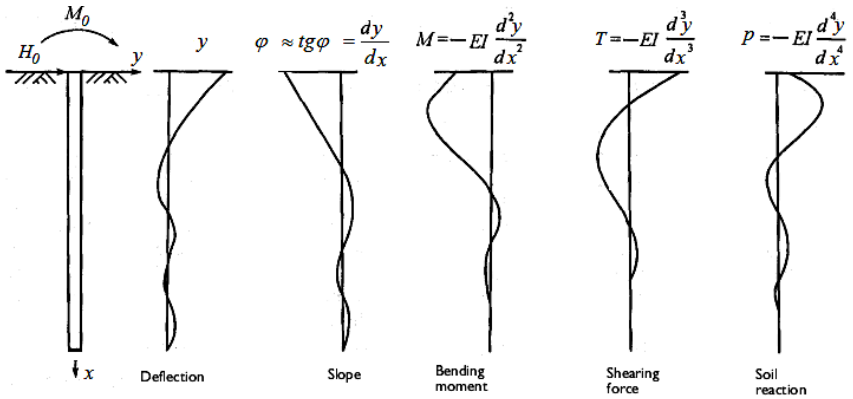

Figure 1. Functions of deflection (y), slope of the elastic line (φ), bending moment (M), shear force (T) and soil reaction (p) along the depth of pile [1]

2. CALCULATION METHODS FOR LATERALLY LOADED PILES

The design of laterally loaded piles primarily depends on the method of soil modeling and the applied calculation method. Commonly applied soil models are:

- ideal-elastic constitutive models (one-parameter and two-parameter models),
- simple elasto-plastic constitutuve models and
- elasto-plastic hardening models.

As for the calculation method, the following are most often applied:

- calculations starting from the differential equation (1) and solving the problem in analytical form,
- calculations based on the concept of discretization of the differential equation (1) or discretization of the pile and the surrounding soil.

The majority of calculation methods found in the literature and design practice treat the soil with the simplest and most easily applicable Winkler's one-parameter model. Here, the soil is represented by a system of independent linear-elastic springs (fictitious struts), where deformations occur only in those springs where the load also occurs. The soil is described by a single parameter – the soil reaction modulus (in the vertical or horizontal direction), which is usually taken as constant or linearly increasing with depth. Using this soil model, a well-known analytical solution, the Hetenyi method (1946), was developed, where the soil reaction modulus is constant with soil depth. The most common analytical solutions where the soil reaction modulus increases linearly with depth include the method of initial parameters (СНиП 2.02.03-85) [2], and the solution of Reese and Matlock [3]. In addition, the Winkler's one-parameter model is widely used in numerous software packages in the field of civil engineering (SAP, STAAD, TOWER, STRESS), based on the principle of discretization of piles and surrounding soil.

Two-parameter soil models also belong to the group of methods based on the ideal-elastic soil model, of which the most widespread is the linear-elastic, homogeneous continuum model. Here the soil properties are defined by two parameters, the modulus of elasticity E_s (which can also be constant or variable with depth) and Poisson's ratio v. Analytical method for solving the problem based on this more realistic, but significantly more complex model for application, has not been commonly used, precisely due to the cumbersomeness of the solution. However, this soil model can often be found in methods based on the concept of discretization of the differential equation (1): the finite difference method, as well as software packages for specialized geotechnical purposes (PLAXIS, GEO-SLOPE, GEO5) and general purposes (ANSYS, NASTRAN and more recently TOWER) based on the finite element method. The well-known analytical–empirical solution of Poulos [4], as well as Randolph's solution [5], are based on this soil model.

Simple elasto-plastic soil models (the Coulomb–Mohr model [6] and the Drucker–Prager model [6], which are the most common in geotechnical engineering) are an integral part of the above-mentioned specialized and general packages, whereas elasto-plastic hardening models (the Cam clay model [7], the modified Cam clay model [8] and similar) are represented only in geotechnical softwares.

In order to compare different calculation methods, calculations performed manually without the use of software packages were selected in this study, as the most commonly used in geotechnical practice: the method of initial parameters (СНиП 2.02.03-85), the method of Poulos and the method of Randolph.

The first two belong to methods based on the Winkler's one-parameter soil model described by the soil reaction modulus. In addition to the basic drawback of this soil model that it does not simulate continuous soil properties, a major difficulty of the model is the determination of the only parameter – the soil reaction modulus. Namely, the modulus does not represent a fundamental property of the soil, but rather the coefficient of linear dependence of the pressure at the observed point of the contact surface and the displacement of the soil at that point. Therefore, in addition to the type of the soil and its condition (in terms of density for coarse-grained soils, or water content, consistency state and consolidation for fine-grained soils), the soil reaction modulus also depends on numerous factors related to the structure itself. These are, primarily, the size and shape of the contact surface of the foundation, the foundation stiffness and depth, the load intensity, etc. Therefore, when designing piles, the values of the soil reaction modulus usually given in tables in the literature should be considered as an approximation, and therefore much more attention should be paid to their precise determination. By applying this simplest soil model, sufficiently good calculation results can be obtained if the value of the soil reaction modulus is determined in such a way that it satisfactorily reflects the behavior of the pile–soil system. In both methods of calculating piles, it is assumed that soil stiffness increases with depth, which primarily corresponds to sands and normally consolidated clays.

The other two methods (of Poulos, as well as the Randolph method) treat the soil with a linear-elastic, homogeneous continuum model. The parameters of this model – the Young modulus of elasticity E_s or shear modulus G_s and Poisson ratio v – can be determined by laboratory or field experiments, and therefore their reliability is higher compared to the soil reaction modulus. In addition to soil homogeneity in depth, these two methods can also be used for soils that are linearly inhomogeneous with depth or for layered soils. They are suitable for simulating soil behavior in the elastic range, which can roughly correspond to the service load of piles.

3. EXAMPLES OF CALCULATION OF LATERALLY LOADED PILES

To analyze the quality of the calculations using the four methods mentioned above, data from field tests of two piles were used. The piles were vertical and loaded with a horizontal force H_0 at the pile cap, whereby the horizontal displacements at the pile cap u_0 were recorded. Both tested piles were Franki reinforced concrete piles; the first one was located near Subotica and the second one was in New Belgrade. Data on soil obtained by cone penetration test (CPT), characteristics of piles and test results were given by Milović and Đogo [9]. Table 1 provides data on the type and dimensions of the tested piles, the type and characteristics of the soil, as well as the maximum applied horizontal loads (H_0) and the corresponding recorded displacements (u_0) at the pile caps.

Table 1. Pile test data [9]

Tested pile	Pile properties	Maximum horizontal load applied	Maximum horizontal displacement	Soil properties
Franki	• Pile length: 16.0 m • Pile diameter: 0.52 m	H_0 = 100 kN	u_0 = 10 mm	• Silt and silty sand. • The result of ili cone penetration test: recorded cone resistance q_c = 1.5–6.5 MPa.
Franki	• Pile length: 10.0 m • Pile diameter: 0.60 m	H_0 = 100 kN	u_0 = 7 mm	• Silty sand and sand with gravel. • The result of cone penetration test: recorded cone resistance q_c = 5.0–12.0 MPa.

4. CALCULATION RESULTS

As already mentioned, in order to compare different calculation methods with the results of field tests of horizontally loaded test-piles, calculations according to the method of initial parameters (СНиП 2.02.03-85), the method of Poulos and the method of Randolph were selected. The results of this analysis are presented in the diagrams in Figures 2 and 3.

All the listed methods treat the soil with an ideal-elastic linear model, whereby the method of СНиП 2.02.03-85 belongs to the group of one-parameter soil models, whereas the calculation method according to Poulos and the Randolph method belong to the group of two-parameter soil models.

The method according to СНиП 2.02.03-85 represents the analytical solution of the basic differential equation (2) by the method of initial parameters, and the soil is represented by the Winkler's model with a single parameter – the soil reaction modulus, which increases linearly with soil depth and is equal to zero on the ground surface.

In the calculation method according to Poulos, the soil is treated as an ideal, homogeneous, elastic and isotropic half-space that simulate continuous soil properties and is defined by the Young modulus of soil elasticity E_s and Poisson ratio v_s.

In the Randolph calculation method, the soil is also treated as an ideal, homogeneous, elastic and isotropic half-space and is defined by the soil shear modulus *Gs* obtained from a field pressuremeter test (PMT) and Poisson ratio v_s. To develop this calculation method, Randolph used the finite element method in numerous examples analyzing homogeneous and inhomogeneous soil.

The conducted analysis and its graphic presentation show a good agreement between the results obtained by applying the developed analytical solutions and the recorded displacements of the pile caps during the experiments.

From the given diagrams (Figure 2 and Figure 3), it can be seen that the Randolph method results in pile cap displacement values that were smaller than the measured displacement values of the tested piles for all applied load levels. On the other hand, the displacement values obtained by applying the method of СНиП 2.02.03-85 are larger than the experimentally recorded ones also for all load levels. The Poulos method, as the third

one considered in this analysis, gives results that were closest to the experimental ones during the entire loading of the piles. Almost up to half of the test load intensity, the results did not differ from the magnitude of the measured displacements, whereas up to a magnitude of approximately two-thirds of the test load intensity, the differences were less than 20%.

However, for the generalization of such conclusions, it is necessary to make a significantly larger number of such theoretical–experimental comparisons.

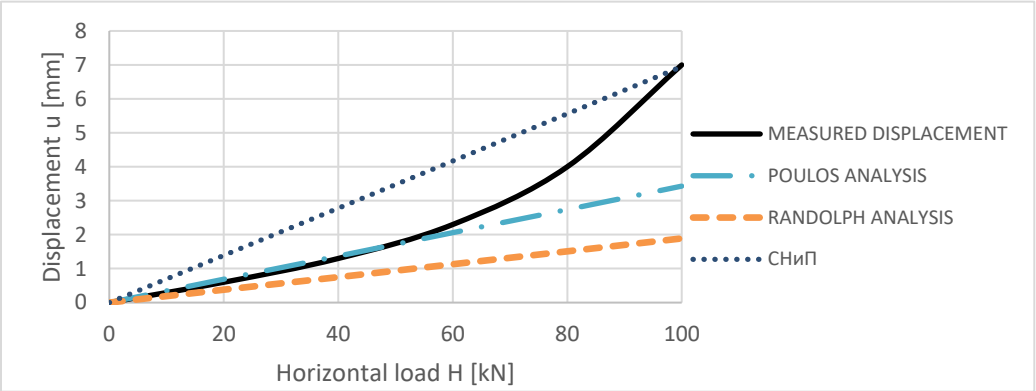

Figure 2. Diagram comparing horizontal displacements at the pile cap of the first pile

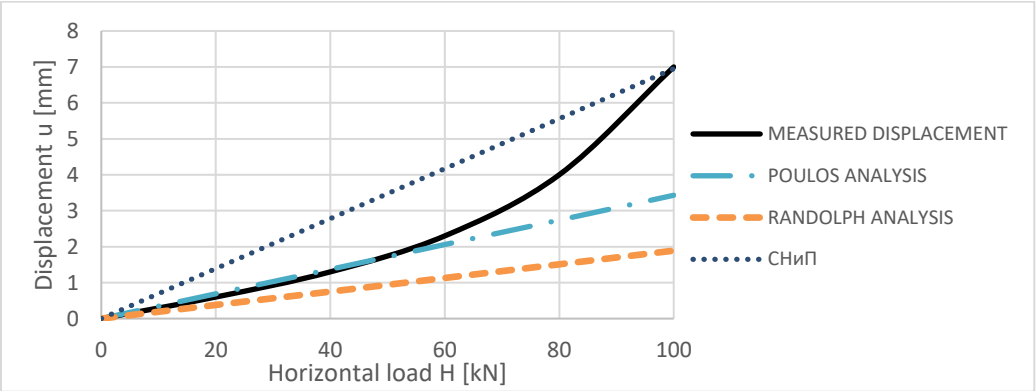

Figure 3. Diagram comparing horizontal displacements at the pile cap of the second pile

5. CONCLUSIONS

The main drawback of the presented analytical solutions, which are based on the application of ideal-elastic linear soil models, is that they do not account for the more realistic nonlinear soil behavior. However, for load levels that can significantly exceed the service load levels, the obtained results show very good agreement with the results of pile test loading. This idealization of soil behavior is justified when calculating displacements due to the action of transverse forces of intensities that are far bellow the ultimate value, which is a condition that is always met when it comes to service loads of piles. For these load levels, it can be considered with sufficient accuracy that the pile behavior is in the linear-elastic region.

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Research paper

EMPIRICAL ANALYSIS OF FIBER REINFORCED SHOTCRETE

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Abstract

Reinforced shotcrete has been used for 40 years and is widely used in both construction and mining engineering. In recent years, the use of fiber-reinforced concrete has increased significantly, with significant progress being made in terms of quality and application techniques. Due to its advantage in improving certain material properties, fiber-reinforced shotcrete is widely used in tunnel construction, industrial flooring and airport runways, slope protection, and in mining tunnels, fiber-reinforced shotcrete is used. The use of this type of reinforced concrete has a number of advantages over other types of concrete. Using reinforced shotcrete provides a number of advantages. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages include increased load-bearing capacity, higher initial strength, smaller rebounds and a smaller amount of installation. From the analysis of time savings in the process of installing shotcrete with and without fibers, it appears that up to several hours of savings are achieved with the process of building shotcrete reinforced with fibers. A similar example is the application of shotcrete with an area of 30 m². The entire process using steel mesh takes 11.5 hours, while with fibers, 7.5 hours. From this it can be seen that for only 30 m², 1/3 of the total time is saved by using shotcrete reinforced with one of the fibers. This combination is combined in the unit price with using shotcrete reinforced with steel mesh and fibers. Unlike ordinary shotcrete, the strength decreases with the appearance of the first crack, while in reinforced shotcrete this is not the case because the stresses on the fibers are transferred to the adjacent sections. This means that if there is a larger amount of fibers in the concrete mixture, then it has the ability to carry greater loads. This has been confirmed by a series of experiments, which confirm the durability and flexibility of reinforced concrete reinforced with steel fibers.

Key words: *Shotcrete, fibers, strength, tunnel construction, flexibility*

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1. INTRODUCTION

Concrete has many advantages, which makes it by far the most used and most important construction material. However, like other materials, concrete also has disadvantages, such as: low tensile strength, brittle fracture, low specific strength, low ductility, need for formwork, long curing time, appearance of cracks, etc. Gradually, work is being done to improve the physical and mechanical properties of concrete and various additives are being found that will improve the characteristics and performance of this material. Various additives, synthetic and fiber fibers, mineral additives, and others are being added. So today, highly technologically developed types of concrete are being produced, such as reinforced concrete. Reinforced concrete, since ancient times, was used as a binding material. Thus, straw was used as a binder for clay, and horsehair for gypsum. In the 20th century, intensive technological development and development in engineering practice occurred. But it must be admitted that reinforced concrete is very rarely used alone and its use in combination with screws, reinforcing bolts, iron bars or steel structures further complicates the problem of analyzing the contribution of the support. The first tests on reinforced concrete were made in 1874 by A. Beranda, by adding steel scrap to the concrete. After the publication of the results by the American scientist Porter, the world began to work intensively on this topic.

2. FIBRE REINFORCED SHOTCRETE

Reinforced shotcrete has been used for 40 years and is widely used in both construction and mining engineering. In recent years, the use of fiber reinforced shotcrete has increased significantly, and significant progress has been made in terms of quality and application techniques. Due to its advantage in improving certain material properties, fiber reinforced shotcrete is widely used in tunnel construction, industrial floors and airport runways, slope protection, and in mining tunnels, fiber reinforced shotcrete is used. There are a number of advantages to using this type of reinforced concrete compared to other types of concrete.

2.1. Steel fibre reinforced shotcrete

Steel fibres are often used as reinforcement of shotcrete. To select the appropriate shape of the steel fibres, their tensile strength and length-to-diameter ratio have to be considered in line with the design requirements. The following improve-ments of the shotcrete can be expected by application of steel fibres:

- increased ductility;
- higher compressive and tensile strength;
- reduced crack formations.

Figure 1. Steel fibre

The amount of steel fibres in the final concrete mix should be in the range of 30 - 90 kg/m³. Because of the loss by rebound during the application of shotcrete, 35 – 120 kg/m³ of fibres should be included in the basic mixture. Steel fibres with a high length-to-diameter ratio are essential for efficient reinforcement. However, the pro-cessing is difficult with such steel fibres. In current practice, bundles of 30 to 50 fibres are added to the shotcrete mix. The wrapping of these bundles is water-soluble, which leads to a dispersion of the fibres in the mixture at the beginning of the mixing process. Steel fibre reinforced shotcrete has economic benefits if the required project specific static values are equivalent to the use of shotcrete lining with one- or multi-layered reinforcements (steel meshes). It can also be applied as a subsequent rein-forcement. Figure 2 shows the variations of compressive strength against the defor-mation for shotcrete with different contents of steel fibre reinforcements (plate loading test) [1].

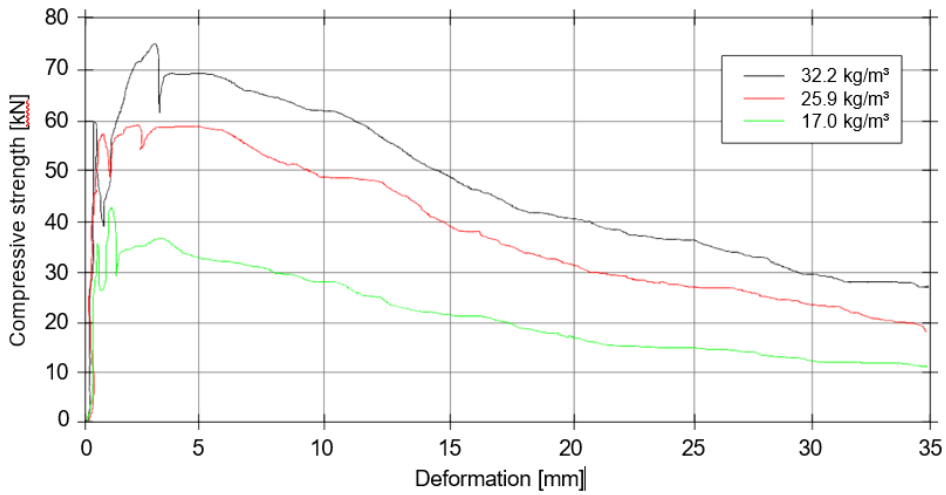

Figure 2. Compressive strength versus deformation: plate loading tests on shotcrete with different amount of steel fibers

In Tabela 1 shows experimental results for Young's modulus and Poisson's ratio obtained from uniaxial compressive tests on three steel fibre reinforced (30 kg/m³) shotcrete samples at different curing times. The UCS increases with time, but elastic properties (Young's modulus and Poisson's ratio) do not show a systematic variation.

Table 1: Uniaxial compressive test on steel fiber reinforced shotcrete samples

Sample No	Curing (days)	Compr. Strength (MPa)	Elastic properties	
			Young's modulus (MPa)	Poisson's ratio
			E	v
1	1	16.2	-	-
2	1	18.1	14000	0.42
3	1	18.3	11000	0.19
1	3	23.4	-	-
2	3	18.3	12000	0.28
3	3	22.9	8000	0.16
1	7	28.5	-	-
2	7	23.2	16000	0.22
3	7	25.7	14000	0.17
1	28	32.8	14000	0.21
2	28	27.2	17000	0.29
3	28	31.5	10000	0.15

2.2. Synthetic fibre reinforced shotcrete

Synthetic fibers are additives that improve the properties of concrete and can completely replace steel mesh, or steel fibers. This type of fiber is new and was first used in 1990 to compete with steel fibers. Their positive and negative properties have yet to be investigated. Synthetic fibers, just like steel fibers, can be used in combination to improve properties and eliminate microcracks.

Synthetic fibers have similar characteristics to other types of fibers, but they also have something additional that makes them a step ahead of others:better processing:

- higher density,
- higher adhesive tensile strength,
- increased chemical resistance,
- improved thermal behaviour,
- improved quality of thin lining,
- higher early / final strength,
- does not damage the rubber hoses of the jet spray pump,
- compared to steel fibers, they have a low bulk density, meaning that 5-6 times less per m^3 is added to the mixture than other fibers, and this feature facilitates field work.

Figure 3. Synthetic fibre

Synthetic fibers, although new, show good results in all aspects. In any work, one of the most important things is the environment, and by using these fibers, it is protected and there are no major negative impacts on the environment. In addition to protecting the environment, the use of synthetic fibers also saves financial resources: a thinner layer of shotcrete, less rebound losses, etc. And by using this type of reinforcement of reinforced concrete, the safety of contractors is also increased because when installing shotcrete with macrosynthetic fibers, the nozzle is not under a rock mass that is not yet stable [1].

There are two types of synthetic fibres:

1. Synthetic macro fibres,
2. Synthetic micro fibres.

Synthetic macro-fibres have lower Young's modulus values than steel fibres. They are very effective in preventing cracks in the shotcrete and reducing the crack width. The shotcrete becomes more ductile and shows better corrosion protec-tion when these fibres are used. The Young's modulus of synthetic micro-fibres is even lower than those of synthetic macro-fibres. This type of fibres can reduce the shotcrete shrinkage in the early stage of the hydration process. The application of synthetic micro-fibres is beneficial when there is a potential for heat exposure, e.g. fire. If the temperature increases up to 160 °C, the polypropylene fibres melt inside the concrete forming new cavities, which help to release additional pressures. Therefore, explosive spalling of concrete can be re-duced. This type of reinforcement is often used for the renovation of tunnels. After 28 days this type of reinforced shotcrete shows a UCS in the range of 44 - 61 MPa.

Table 2: Data for synthetic fibers

	Macro-fibres	Micro-fibres
Amount	3 - 10 kg/m³	0.6 - 2 kg/m³
Length	40 - 60 mm	5 - 15 mm
Diameter	0.4 - 1 mm	0.015 - 0.2 mm

2.3. Mixing of shotcrete with fibers

The most important part in relation to ordinary shotcrete and shotcrete with fibers is the dosing and mixing of the fibers into the concrete mix itself. Many details in this work, so that there is no stopping of the construction equipment and clumping of the material to be built. In order to avoid changes, special machines have been produced that mix the concrete mix and various fibers as reinforcements. It is not only the hose that transports the mix from the machine to the nozzle, but also in the network itself, clumping of the reinforced concrete can be avoided.

The wet method is mainly used for mixing the concrete mix with fibers because in the dry method the bounce is very bad. But it does not mean that the dry method is excluded. In the dry method, the fibers are first placed in a drum so that there is no clumping of the material. The slurry is moved under pressure to the nozzle. In the meantime, the aggregate and cement are mixed, and then water is added. When using a wet method for spraying concrete with steel fibers, the fibers are poured into the nozzle and mixed with the concrete mixture before the nozzle [2]. The same can be done in the concrete production plant

Regardless of which method is used, there should be a correct distribution of the concrete on the concrete surfaces and adequate mixing of the concrete with the fibers before it is applied to the surface. Mixing the fibers with the concrete mass should pay attention to:

- the fibers should be added slowly to prevent clumping of the material;
- the fibers should not be twisted to prevent clumping of the material, which in turn causes clogging in the installation pump;
- to place the electron so that the material does not clump;
- the fibers can cause a risk of kickback, so when installing, mechanized nozzles are used, paired from a distance and others.

Figure 4. Machine for applications of Steel Fiber Reinforced Concrete

3. ANALYSIS OF FIBER REINFORCED SHOTCRETE

Using fiber reinforced shotcrete provides a number of advantages. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages are: increased load-bearing capacity, higher initial strength, less rebound and a smaller amount of installation. Time savings is one of the listed factors [3].

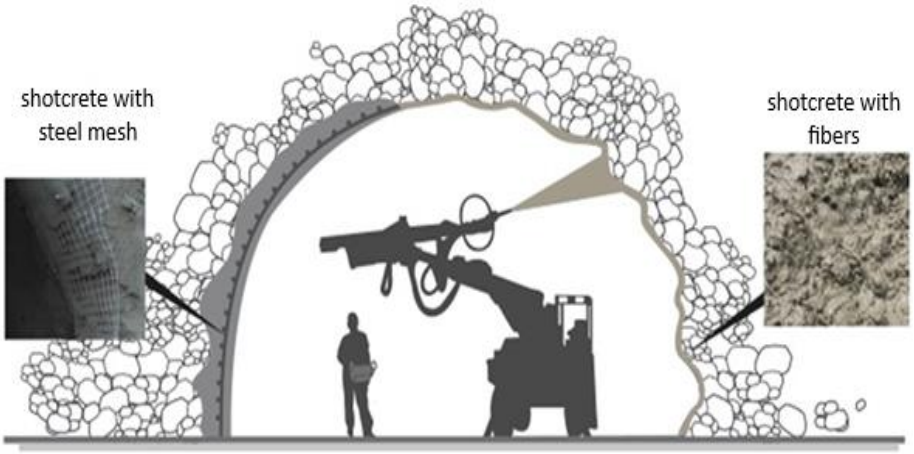

Figure 5. Shotcrete with steel mesh and with fibers

I cannot give examples from my country because this type of concrete is not used. The popularity of shotcrete reinforced with various types of fibers can be gauged from how widely it is used in Australia, and this can only help to shed some light on the full picture of its applications. Of the 650,000 m³ of shotcrete installed, 500,000 m³ is fiber-reinforced shotcrete. Macrosynthetic fibers are the dominant form of reinforcement, with a small number of mines continuing with steel fibers, and a minority also including microsynthetic fibers for control of rebound and fall-outs immediately after spraying. The versatility of fibre reinforced shotcrete, both in terms of structural capacity and mixture design, allows miners a higher degree of adaptability in the implementation of ground control and development of underground infrastructure than is possible using any of the currently available alternatives. The direct material and labor costs associated with initial ground control using the fibre reinforced shotcrete and bolt system are about 20% higher than for alternatives such as mesh and bolts. When the superior speed, versatility, efficacy, durability, and safety of fibre reinforced shotcrete are considered, however, their combined economic advantage make this system of ground control the most attractive presently available in the majority of circumstances [4].

From the analysis of time savings for the process of installing shotcrete with and without fibers, the conclusion is that several hours are saved with the process of installing shotcrete reinforced with fibers. A similar example was made in Australia for the application of shotcrete with a surface area of 30m². The entire process using steel mesh took 11.5 hours, while with fibers 7.5 hours. From this it can be seen that for only 30m² 1/3 of the total time was saved by using shotcrete reinforced with one of the fibers. This comparison is transformed into the total cost of using shotcrete reinforced with steel mesh and fibers. From Figure 6 it can be concluded that by increasing the thickness of the shotcrete layer, the cost of shotcrete reinforced with steel fibers decreases [3].

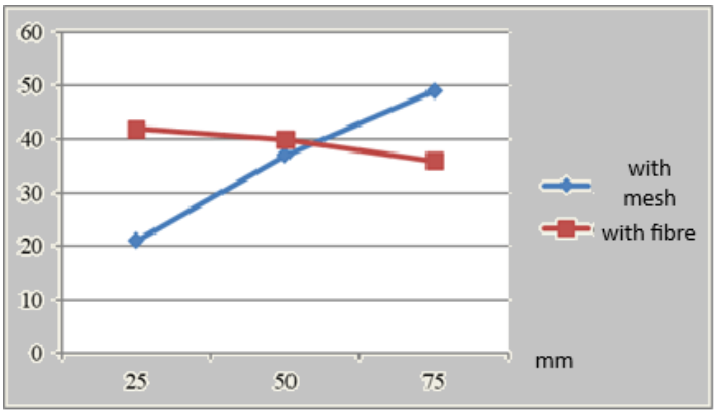

Figure 6. The cost of shotcrete reinforced with steel fibers and thickness of the shotcrete layer

4. CONCLUSION

Due to its advantage in improving certain material properties, fiber-reinforced shotcrete is widely used in tunnel construction, industrial flooring and airport runways, slope protection, and in mining tunnels, fiber-reinforced shotcrete is used. The use of this type of reinforced concrete has a number of advantages over other types of concrete. The economic advantages include: less labor, removal of ordinary reinforcement, a smaller layer for installation and saving time and material. While the technical advantages include increased load-bearing capacity, higher initial strength, smaller rebounds and a smaller amount of installation. From the analysis of time savings in the process of installing shotcrete with and without fibers, it appears that up to several hours of savings are achieved with the process of building shotcrete reinforced with fibers.

I cannot give examples from my country because this type of concrete is not used. Example in Australia for the application of shotcrete with an area of 30 m². The entire process using steel mesh took 11.5 hours, while with fibers 7.5 hours. From this it can be seen that for only 30 m², 1/3 of the total time was saved by using shotcrete reinforced with one of the fibers. This comparison is transformed into the total costs for using shotcrete reinforced with steel mesh and fibers.

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Research paper

PHOTOMETRIC ANALYSIS OF HOMOGENIZED X-RAY IMAGES IN DETERMINING THE MECHANICAL PROPERTIES OF WOOD: PRELIMINARY RESULTS

Andrej Josifovski[1], Irina Živković[2], Nebojša Todorović[3], Marko Veizović[4], Jelena Milošević[5], Aleksandar Rajčić[6]

Abstract

Previous research demonstrated a link between wood strength and brightness intensity in X-ray images. Wood samples were subjected to compression testing along and across the grain, with X-ray imaging performed on the same specimens before the mechanical tests. Differences in the brightness of X-ray images of test specimens were clearly noticeable, both in relation to the type of sampled wood and depending on the specific alignment of X-ray beams relative to the direction of wood fibers in the test specimen. Because wood has an anisotropic structural composition, it is expected that the X-ray image of the tested sample would exhibit uneven brightness. Photometric analysis of the X-ray image using computer software allows for assigning appropriate mechanical properties to each point on the image via x, y, v parameters. However, since an individual light point cannot represent the cumulative mechanical properties of the sampled test specimen, it is clear that the task at hand also includes the need for homogenizing the X-ray image. This is achievable through the program's three-dimensional approximation capabilities. The creation of a tonal grayscale through image homogenization would enable the alignment of mechanical strength parameters with brightness intensity values. This process would effectively represent the overall mechanical potential of the wood sample as a cumulative result, linking the homogenized brightness of the X-ray image with the wood's strength characteristics.

Key words: *Photometric, X-ray, OsiriX, Tonal gray scale, Equalization, Wood*

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1. INTRODUCTION

The concept for this research arose from the necessity of restoring wooden structures in architectural objects of cultural and historical significance, where such work is governed by specific regulations that require a specialized, non-invasive diagnostic approach. This methodological framework is also recommended for the restoration and reconstruction of other structures of potential heritage value, as each may be regarded as a monument to the era in which it was created. The procedures for such restoration efforts are outlined in a document adopted by ICOMOS during the General Assembly held in New Delhi in 2017. This document details the principles for the conservation of wooden architectural heritage, emphasizing the protection of their authenticity and structural integrity [1, 2].

Identifying the most stressed points of the structure and detecting signs of degradation and damage in wood are essential prerequisites for developing an appropriate rehabilitation plan. The non-destructive nature of the diagnostic process necessitates in situ examination. Therefore, this study aimed to establish a reliable and easily applicable non-destructive diagnostic method. The use of X-rays was considered for this purpose, as their orientation can be aligned either parallel or perpendicular to the wood grain, analogous to laboratory-based static mechanical testing [3, 4].

In our previous research involving X-ray application, tabulated strength values of experimental wood samples were used, and it was confirmed that samples with higher strength yielded brighter X-ray images, validating the analogy. The harmonization of mechanical and radiographic parameters now required standardized mechanical calibration of the wood specimens and computerized objectification of image brightness. This methodology was supported by the capabilities of the OsiriX software, indicating its suitability for the intended analysis [5, 6].

2. METHODOLOGY

X-ray testing was conducted on wood samples from diffuse-porous hardwoods—beech (Fagus sylvatica) and poplar (Populus spp.); ring-porous hardwoods—black locust (Robinia pseudoacacia) and oak (Quercus spp.); and softwoods—pine (Pinus spp.) and silver fir (Abies alba), including a control group of samples from horse chestnut (Aesculus hippocastanum). To ensure X-ray image homogenization, the specimens were cut to dimensions of 20 × 20 × 40 mm. These samples were prepared similarly to those used in standard compressive strength tests, with the longitudinal axis aligned with the grain direction. The longitudinal plane intersecting the sample perpendicularly to its length was parallel to the grain lines and considered the axial plane, while the planes intersecting the two longitudinal sides at right angles represented the tangential and radial planes [4, 7, 8].

A second set of specimens had a transverse profile, with the axial plane intersecting the longest dimension at a right angle. Testing was carried out using a medical-grade X-ray machine operating within a range of 40–125 kV and 0.50–360 mA/s, similar to those used in clinical diagnostics, where upper limits are typically 100 kV and 70 mA/s. Each sample set was imaged using a current voltage of 37 kV and a strength of 70 mA/s. Following radiography, standard compressive strength testing was also performed on the same specimens.

The brightest X-ray images were observed in the ring-porous hardwoods, which also exhibited the highest measured compressive strength. Progressively lower brightness was observed in the diffuse-porous hardwoods, with the lowest intensity seen in the softwood samples. The brightest images in all test groups were obtained when X-rays were directed along the axial plane; lower brightness was noted when X-rays were directed in the radial direction, and the lowest when directed tangentially, corresponding proportionally to the measured compressive strengths [9, 10, 11] (see Appendix).

3. RESULTS

3.1. Photometric Analysis:

Photometric analysis of the X-ray images represented the final step in the harmonization of mechanical and radiographic parameters. This was performed using OsiriX software, which is widely used in medical diagnostics. Its three main operational components—Database Window, Viewer Window, and 3D Volume Rendering—enable the importation of X-ray datasets, 2D/3D image viewing, and image manipulation within the study list environment [6, 11, 12].

Of particular importance is the drop-down menu tool *WW/WL* (Window Width/Window Level), used to adjust image brightness and contrast. The software's CLUT (Color Look-Up Table) module offers additional tools for selecting and adjusting color ranges, which can enhance operational precision.

Due to the heterogeneous and anisotropic nature of wood—where mechanical properties vary according to the direction of grain flow, leading to image brightness variability—the software tools especially valuable for structural wood visualization include *Orientation* (for spatial positioning relative to horizontal, frontal, and sagittal planes) and *Thick Slab* (for deepening cross-sectional views) [13].

Key tools for image homogenization and analysis include:

- **ROI Tools** (Region of Interest): Enable targeted image analysis.
- **Repulsor Tool**: For manipulating defined ROIs.
- **Selector Tool**: Allows grayscale and color adjustments within selected ROIs.
- **Propagate Tool**: Applies defined ROIs across all cross-sections.
- **Region Growing**: Expands areas around selected points, useful for diagnosing damage and degradation in structural wood elements.
- **Filters**, particularly **Convolution Filters** in the 2D Viewer menu, used in bone diagnostics, offer potential applicability here by producing 3D renderings with enhanced contrast.

The **3D Volume Rendering** module enables each point in the image to be assigned corresponding mechanical properties based on its x, y, z coordinates. However, due to the anisotropic nature of wood, a single point cannot fully represent the collective mechanical properties of the entire specimen, even though dimensional uniformity helps in achieving a certain level of homogenization.

Therefore, X-ray image brightness homogenization must ultimately rely on additional operational tools such as **Engine Tools**, which support Ray Cast and 3D Texture applications.

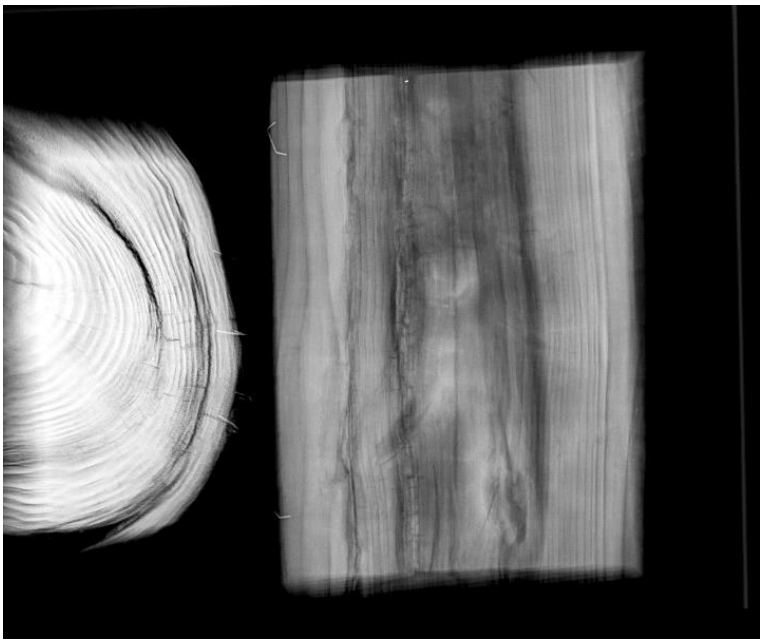

Figure 1. X-ray of a log of wood

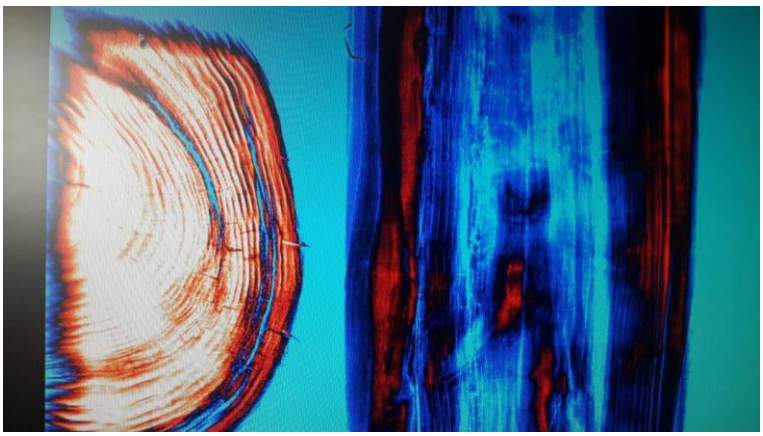

Figure 2. X-ray image through OsiriX software - example

4. CONCLUSION

The harmonization of mechanical and photometric parameters should result from a comprehensive evaluation of the material's mechanical properties.This approach significantly enhances the diagnostic reliability and practical value of the material evaluation process. Future work could focus on refining this diagnostic method for larger structural elements and validating it through in situ testing.

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APPENDIX

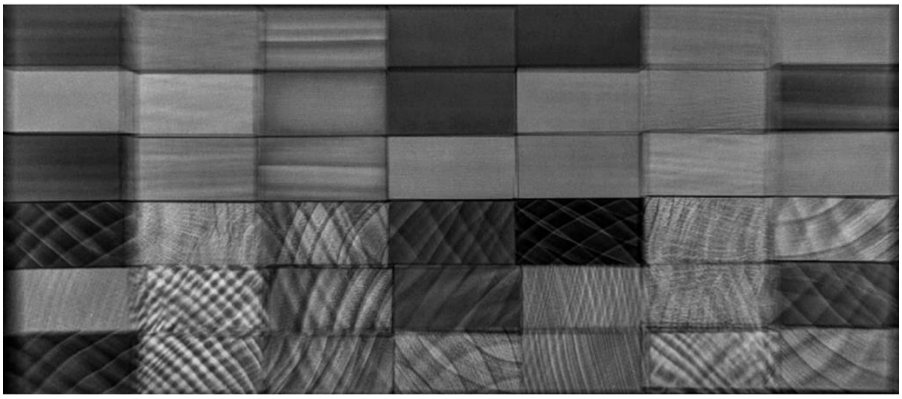

Figure 3. Mosaic.

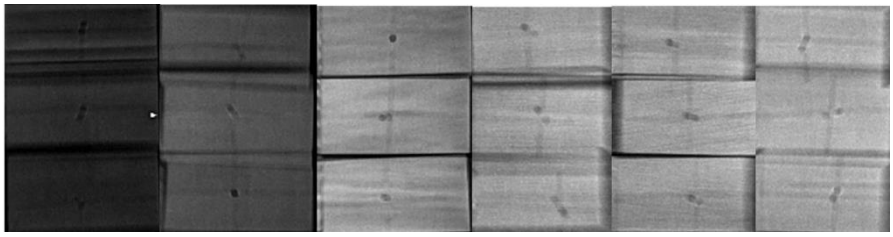

Figure 4. Zebra.

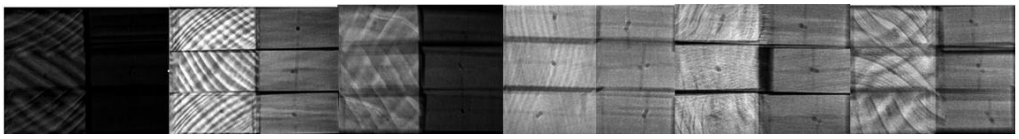

Figure 5. Tonal palette.

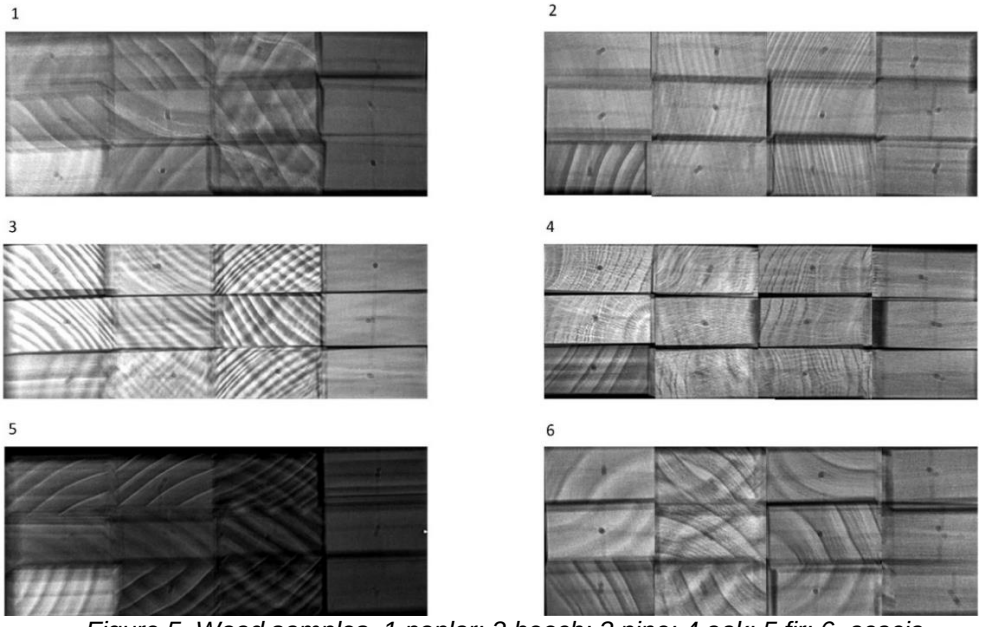

Figure 5. Wood samples. 1.poplar; 2 beech; 3 pine; 4.oak; 5.fir; 6. acacia.

Table 1. Values of compressive stresses determined on test sample in the calibration procedure of the stress-sound wave application method.

	Softwood					Hardwood					
						Ring Porous				Diffuse Porous	
	Spruce 1	Fir 1	Fir 2	Pine 1	Pine 2	Oak 1	Oak 2	Black Locust1	Black Locust2	Beech 1	Beech 2
Length (mm)	39.72	40.2	39.13	39.37	39.1	39.04	39.3	39.32	39.3	39.48	39.57
Width (mm)	20.18	20.16	19.96	20.12	19.93	19.92	19.86	19.79	20.27	19.94	19.8
Thickness	/	/	/	/	/	/	/	/	/	/	/
Compressive force—transversal (lateral)	3113	1883	1648	13129	4979	4149	4621	5839	4736	4624	4760
Compressive force—axial (transverse)	/	/	/	/	/	/	/	/	/	/	/
Transversal stress	3.9	2.3	2.1	16.6	6.4	5.3	5.9	7.5	5.9	5.9	6.0
Axial stress	/	/	/	/	/	/	/	/	/	/	/
Length (mm)	/	/	/	/	/	/	/	/	/	/	/
Width (mm)	19.75	10.86	19.94	20.08	20.29	19.84	19.84	19.93	20.02	19.82	19.96
Thickness	19.86	19.85	19.89	20.09	20.08	19.77	19.79	19.9	20.12	19.19	19.9
Compressive force—transversal (lateral)	/	/	/	/	/	/	/	/	/	/	/
Compressive force—axial (transverse)	19,550	2116	21,212	34,214	27,739	24,223	27,742	39,241	37,842	31,563	29,053
Transversal stress	/	/	/	/	/	/	/	/	/	/	/

Table 2. Values of bending stress determined on test samples in the calibration procedure of the stress sound wave application method.

	Softwood					Hardwood					
						Ring Porous				Diffuse Porous	
	Spruce 1	Fir 1	Fir 2	Pine 1	Pine 2	Oak 1	Oak 2	Black Locust1	Black Locust Acacia 2	Beech 1	Beech 2
h [mm]	19.74	19.86	19.84	20.01	19.78	19.89	19.85	19.79	20.1	19.88	19.91
b [mm]	19.72	19.83	19.88	20.11	19.91	19.88	19.84	19.94	20.06	19.92	19.81
Bending strength MPa [N/mm^2]	88.9	79.9	71.6	132.9	102.8	91.09	124.5	86.4	170.3	169.8	128
Modulus of elasticity MPa [N/mm^2]	6108	8137	7905	11567	7448	6792	8232	11020	14788	11987	9145
Force max. [N]	1627	1488	1334	2572	1907	1706	2316	1605	3288	3182	2393
Deflection max. [mm]	13.85	11.78	10.28	9.39	17.95	16.58	15.04	10.27	14.5	12.64	16.67
h [mm]	19.74	19.83	19.89	19.98	20.03	19.85	19.94	19.9	10.07	19.9	19.8
b [mm]	19.78	19.79	19.86	19.92	20.14	19.83	19.85	19.92	20.31	19.84	19.8
Bending strength MPa [N/mm^2]	84.1	81.3	76.9	152.1	119.1	103.3	105.8	200.9	185.2	135.9	133.3
Modulus of elasticity MPa [N/mm^2]	8784	8262	7304	12,778	10,337	7722	6882	15,175	13,920	10,315	9722
Force max. [N]	1544	1506	1438	2880	2291	1921	1987	3773	3607	2542	2464
Deflection max. [mm]	12.58	11.26	11.06	18.21	12.6	17.36	20.05	13.16	14.74	11.61	12.59

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