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 1

September 11 – 12, 2025

Science and Technology Park Niš, Serbia

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

September 11 – 12, 2025

Science and Technology Park Niš, Serbia

VOLUME 1

Proceedings of the International Conference
Synergy of Architecture and Civil Engineering 2025
SINARG2025
11-12 September 2025
Niš, Serbia
www.sinarg.org
Volume 1

Published by:
Faculty of Civil Engineering and Architecture, University of Niš
Serbian Academy of Sciences and Arts – Branch in Niš

For Publishers:
Slaviša Trajković, PhD
Vlada Veljković, PhD

Editors:
Vuk Milošević, PhD
Andrija Zorić, PhD

Approved to be printed by the Decree of Teaching Counsil of the Faculty of Civil Engineering and Architecture, University of Niš, No. 8/173 on 5 September 2025
Approved to be printed by the Serbian Academy of Sciences and Arts – Branch in Niš, No. 1/25-206-2 on 4 September 2025

Technical Editors:
Miloš Milić, PhD
Lazar Živković

Cover Design:
Jovana Tomić

ISBN 978-86-82810-15-5

Printed by:
Donat Graf DOO Belgrade
100 copies

Organized by:
Faculty of Civil Engineering and Architecture, University of Niš
Serbian Academy of Sciences and Arts – Branch in Niš

In partnership with:
Science and Technology Park Niš

Supported by:
Ministry of Science, Technological Development and Innovation of the Republic of Serbia
Serbian Chamber of Engineers

PROGRAM COMMITTEE

Chairs

Academician Vlada Veljković, PhD, Serbian Academy of Sciences and Arts, Belgrade, Serbia
Professor Slaviša Trajković, PhD, University of Niš

Members

Associate Professor Aleksandar Milojković, PhD, University of Niš
Professor Zoran Grdić, PhD, University of Niš
Professor Ljiljana Vasilevska, PhD, University of Niš
Professor Zoran Bonić, PhD, University of Niš
Professor Miomir Vasov, PhD, University of Niš
Professor Milan Gocić, PhD, University of Niš
Professor Milan Tanić, PhD, University of Niš
Associate Professor Radovan Cvetković, PhD, University of Niš
Associate Professor Marko Nikolić, PhD, University of Niš
Associate Professor Nenad Ristić, PhD, University of Niš
Professor Snežana Đorić Veljković, PhD, University of Niš
Professor Jugoslav Karamarković, PhD, University of Niš

SCIENTIFIC COMMITTEE

Chairs

Academician Branislav Mitrović, PhD, Serbian Academy of Sciences and Arts, Belgrade, Serbia
Academician Dušan Teodorović, PhD, Serbian Academy of Sciences and Arts, Belgrade, Serbia

Members

Academician Fedor Mesinger, PhD, Serbian Academy of Sciences and Arts, Belgrade, Serbia
Professor Božidar Stojadinović, PhD, Swiss Federal Institute of Technology (ETH) Zürich, Switzerland
Professor Ivan Damnjanović, PhD, Texas A&M University, United States, USA
Professor Ivan Rašković, University of Belgrade, Serbia
Professor Irina Baran, PhD, Gheorghe Asachi Technical University of Iași, Romania
Professor Goran Šimunović, PhD, University of Slavonski Brod, Slavonski Brod, Croatia
Professor Elena Lucchi, PhD, University of Pavia, Italy
Professor Christoph Butenweg, PhD, Aachen University of Applied Sciences, Germany
Professor Dietmar Adam, PhD, Technische Universität (TU) Wien, Austria
Professor Andor Wesselényi-Garay, PhD, Obuda University, Hungary
Professor Zlatko Zafirovski, PhD, Saints Cyril and Methodius University, North Macedonia
Associate Professor Jiabin Liu, PhD, Harbin Institute of Technology, China
Associate Professor Janusz Marchwiński, PhD, University of Technology and Arts in Applied Sciences in Warsaw, Poland
Associate Professor Petar Filkov, PhD, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Associate Professor Saša Čvoro, PhD, University of Banja Luka, Bosnia and Herzegovina
Associate Professor Paulo Cachim, PhD, University of Aveiro, Portugal
Associate professor Tomáš Hanák, PhD, Brno University of Technology, Czech Republic
Associate Professor Andreas Savvides, PhD, University of Cyprus, Cyprus
Assistant Professor Ana Perić Momčilović, PhD, University College Dublin, Ireland
Assistant Professor Marija Jevrić, PhD, University of Montenegro, Montenegro
Assistant Professor Luka Pajek, PhD, University of Ljubljana, Slovenia
Assistant Professor Esin Bölükbaş Dayı, PhD, Antalya Bilim Üniversitesi, Türkiye

ORGANIZING COMMITTEE

Chairs

Vuk Milošević, PhD, Associate Professor
Andrija Zorić, PhD, Assistant Professor

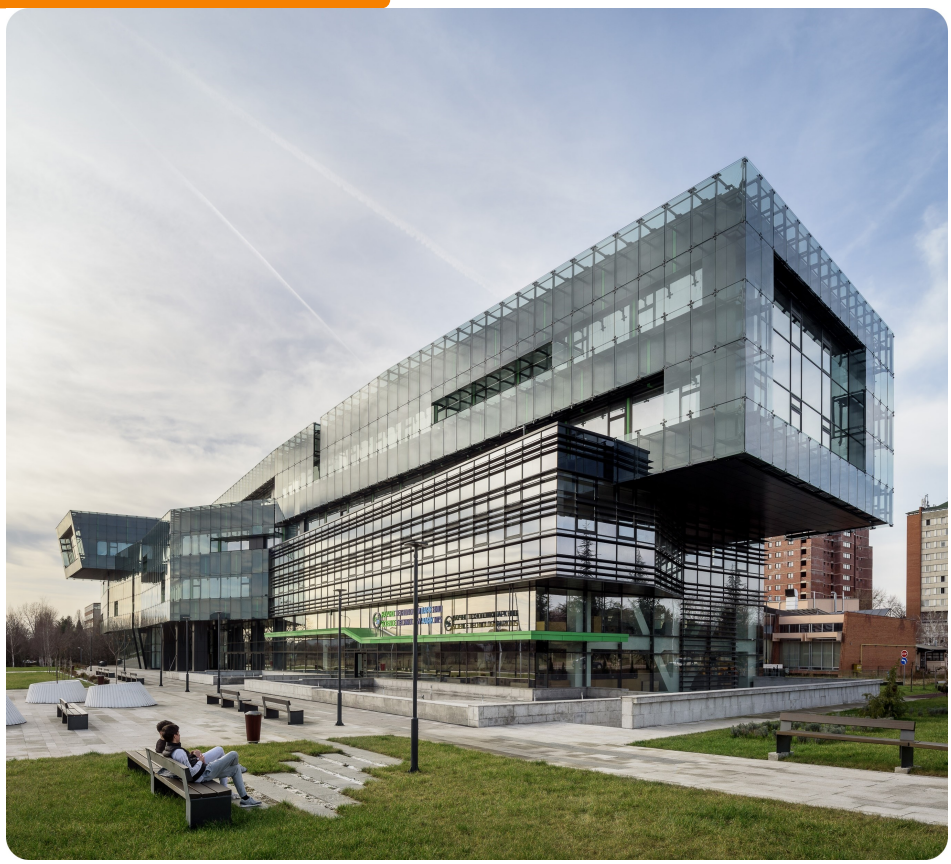
Members

Ljiljana Jevremović, PhD, Assistant Professor
Miloš Milić, PhD, Assistant Professor
Milica Igić, PhD, Teaching Assistant
Aleksandar Đorđević, Teaching Assistant
Ana Stanojević, Teaching Assistant
Jovana Tomić, Teaching Assistant
Lazar Živković, Teaching Assistant
Nikola Janković, Teaching Assistant
Dragan Žunić, PhD, Full Professor

CONFERENCE TOPICS

- Urban and Spatial Planning
- Planning and Designing Smart and Resilient Cities
- Urban and Architectural Design - Theory and Practice
- Architectural Design and Analysis
- Architecture and Built Environment
- Bioclimatic and Biophilic Architecture
- Principles of Eco-friendly Design and Construction
- Built Heritage Protection and Management
- Building Renovation and Recycling
- Architectural Engineering
- Building Information Modeling (BIM)
- Materials in Civil Engineering and Architecture
- Structural Engineering
- Engineering Mechanics
- Aseismic Design
- Water Resources Management
- Highway Engineering
- Geotechnical Engineering
- Construction Engineering and Management
- Project Management
- Circular Engineering
- Entrepreneurship and Engineering
- Transportation Research and Development
- Climate Change Challenges in Engineering
- Disaster Risk Management
- Other areas of Architecture and Civil Engineering

CONFERENCE VENUE



Science and Technology Park Niš,
Aleksandra Medvedeva 2a, Niš, Serbia

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

CONTENTS

ENTREPRENEURSHIP EDUCATION IN THE CONSTRUCTION SECTOR……1-11
Aleksandar Đorđević

USE OF FLY ASH IN ROAD CONSTRUCTION……..13-22
Milan Draganović, Nenad Ristić, Dušan Grdić

INNOVATIVE SOCIAL AND CULTURAL SOLUTIONS FOR RECLAIMING PUBLIC OPEN SPACES IN MULTI-FAMILY NEIGHBOURHOODS……...23-34
Ivana Bogdanović Protić, Ljiljana Vasilevska

STRUCTURAL AND ARCHITECTURAL TRENDS OF CONTEMPORARY CONSTRUCTION IN COUNTRIES WITH DIFFERENT CLIMATIC ZONES: REVIEW STATE OF THE ART……...35-51
Hamed Afsoosbiria, Darja Kubečková

AUTOMATED SYSTEM FOR GEODETIC CONTROL IN BUILDING OF BRIDGE SUPERSTRUCTUTE CONSTRUCTIONS USING THE CANTILEVER CONCRETE OR ASSEMBLY METHOD……53-63
Ani Stefanova

PRESERVATION POLICY OF HISTORICAL CITY CORES: COMPARATIVE ANALYSIS NOVI PAZAR – NOVI SAD……65-79
Merisa Tarhaniš

ADAPTIVE REUSE OF INDUSTRIAL MILLS – BALANCING HERITAGE PROTECTION AND NEW USES……81-92
Ljiljana Jevremović, Ana Stanojević, Uroš Antić, Isidora Đorđević, Aleksandar Milojković

MODELING THE EXPANSION OF URBAN GREEN INFRASTRUCTURE: A GIS BASED APPROACH TO PARK ACCESSIBILITY IN NIŠ……93-103
Petar Vranić, Ivana Petkovski

SPATIAL DOWNSCALING OF LAND SURFACE TEMPERATURE MAPS – A CASE STUDY FOR THE CITY MUNICIPALITY MEDIJANA, THE CITY OF NIŠ, SERBIA……105-118
Nikola Đokić, Borislava Blagojević

INTERNALIZATION OF ARCHITECTURAL SPACES AS A METHODOLOGICAL NOTE IN THE DEVELOPMENT OF THE DESIGN PROCESS……119-130
Milena Grbić, Olivera Dulić

CONSTRUCTION SOLUTIONS OF THE OLD ŽEŽELJ BRIDGE IN THE SPHERE OF INNOVATIVE ACHIEVEMENTS IN DOMESTIC BRIDGE ENGINEERING……131-140
Dušan Kocić, Milan Gligorijević, Marjan Petrović, Nemanja Petrović

REQUIREMENTS FOR TRAIN-TRACK-BRIDGE DYNAMIC INTERACTION ANALYSIS……141-151
Nikola Mirković, Uroš Mirković, Dušan Stevanović

ALGORITHM FOR POSITIONING CYCLING INFRASTRUCTURE WITHIN THE EXISTING CITY ROAD PROFILE……153-160
Dušan Kocić, Miloš Šešlija, Nenad Stojković

THE ROLE OF URBAN PLANNING IN THE PRACTICE OF ADDING LATERAL AND VERTICAL EXTENSIONS TO EXISTING RESIDENTIAL BUILDINGS……...161-170
Kefajet Edip

THE ANALYSIS OF OPEN SPACES IN NEWLY BUILT APARTMENTS IN SERBIA – CASE STUDY: THE CITY OF NIŠ……171-184
Hristina Krstić, Branislava Stoiljković, Nataša Petković

A METHODOLOGICAL FRAMEWORK FOR INTEGRATED LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST OF PASSIVE ENERGY RENOVATION OF RESIDENTIAL BUILDINGS IN SERBIA……..185-196
Bojana Lević, Ljiljana Đukanović

OPTIMIZING BUILDING SUSTAINABILITY: A LIFE-CYCLE CO_2 EMISSIONS ASSESSMENT OF NOVEL AND CONVENTIONAL INSULATION WALL MATERIALS……..197-208
Hamed Afsoosbiria, Hesam Afsoosbiria, Agnieszka Machowska

NON-DESTRUCTIVE INVESTIGATION ON HERITAGE BUILDINGS - CASE STUDY ON ST. NIKITA CHURCH……209-222
Jasna Grujoska-Kuneska, Veronika Shendova

THE MULTIPLE BENEFITS OF POCKET PARKS AS URBAN MICRO-INTERVENTIONS AND THEIR IMPLEMENTATION POTENTIAL IN THE CITY OF NIŠ……223-228
Natalija Stanković, Maša Ranđelović

REUSE OF VACANT OFFICE BUILDINGS: ANALYSIS OF QUANTITATIVE SPATIAL CHARACTERISTICS OF BUILDINGS ACCORDING TO TYPOLOGY……229-238
Damjana Nedeljković, Lidija Djokić, Tatjana Jurenić

RESEARCH LINES IN THE FIELD OF CONVERSION OF VACANT OFFICE BUILDINGS: USE OF MULTI-CRITERIA DECISION-MAKING MODELS……239-250
Damjana Nedeljković, Tatjana Jurenić, Lidija Djokić

INVESTIGATIVE WORKS TO DETERMINE THE NATURE OF CRACKS IN THE INTAKE TOWER OF THE ĆELIJE DAM……251-262
Uroš Mirković, Dušan Stevanović, Nikola Mirković

PRESERVING THE ARCHITECTURAL HERITAGE OF SMALL TOWNS IN SERBIA: VLASOTINCE……..263-273
Ivana Cvetković, Ana Momčilović Petronijević, Đorđe Stošić, Mirko Stanimirović

RAISING ENVIRONMENTAL AWARENESS IN THE URBAN CONTEXT USING GEOSPATIAL AUGMENTED REALITY……...275-284
Petar Vranić, Dušan Tatić

IMPLEMENTATION OF SUSTAINABLE TRANSPORT MODELS IN INNOVATIVE AND ENVIRONMENTALLY FRIENDLY URBAN ENVIRONMENTS THROUGH ANALYSIS OF COPENHAGEN AND PARIS……285-293
Marko Jeremić, Natalija Stanković

INFLUENCE OF DRAINAGE MEASURES ON THE UPLIFT RESISTANCE OF THE FOUNDATION JOINT OF A GRAVITY CONCRETE DAM……295-306
Dušan Stevanović, Nikola Mirković, Uroš Mirković

A METHOD FOR SEISMIC PROTECTION OF BRIDGES USING NEW UPGRADED NVF-ISOLATION SYSTEM: SHAKING TABLE TESTS OF BRIDGE MODEL……307-318
Jelena Ristic, Danilo Ristic

PROTECTION OF THE ARCHITECTURAL HERITAGE OF VLASOTINCE – NEMANJINA STREET……319-332
Ana Momčilović Petronijević, Ivana Cvetković, Đorđe Stošić, Mirko Stanimirović

WIND FLOW MODELING IN EARLY URBAN DESIGN……333-344
Danka Kostadinović, Dragana Dimitrijević Jovanović, Vladan Jovanović

ECOURBARCHITECTURAL HOUSES FROM PRINTED MATERIALS……345-353
Nikola Cekić

ERASING MEMORY: THE DESTRUCTION OF GENERALŠTAB AND THE LOSS OF ARCHITECTURAL IDENTITY……355-369
Luka Radosavljević, Katarina Radosavljević

LIFE CYCLE ASSESSMENT OF NOVEL MATERIALS FOR LOW-CARBON CONCRETE PRODUCTION……371-382
Hesam Afsoosbiria, Hamed Afsoosbiria, Agnieszka Machowska

MULTI-FAMILY HOUSING IN SKOPJE DURING THE PERIOD OF MODERNISM FROM 1945 – 1980……383-394
Nataša Matić

POSSIBILITY OF APPLICATION OF ASH, SLAG AND FLOOD GYPSUM AS COMBUSTION PRODUCTS FROM THE KOSTOLAC THERMAL POWER PLANT IN CONSTRUCTION……395-402
Dragan Milošević, Tanja Miladinović

AESTHETIC THEORIES AND THEIR PATHS IN ARCHITECTURE: MILUTIN BORISAVLJEVIĆ AND HIS SCIENTIFIC APPROACH TO AESTHETICS OF ARCHITECTURE……403-416
Irena Kuletin Ćulafić

AGRICULTURAL YARDS IN RURAL AREAS IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT – THE EXAMPLE OF BRODEC VILLAGE……417-429
Dimitar Krsteski, Aleksandar Radevski, Goran Mickovski

APPLICATION OF THE SIMULATION MODEL FOR READY MIXED CONCRETE SUPPLY……431-440
Biljana Matejević-Nikolić, Lazar Živković, Nenad Stojković, Nikola Velimirović

doi.org/10.62683/SINARG2025.004

Review paper

ENTREPRENEURSHIP EDUCATION IN THE CONSTRUCTION SECTOR

Aleksandar Đorđević[1]

Abstract

Small and medium-sized enterprises represent the backbone of the economy, including the construction sector. To sustain and stimulate the growth of the construction industry, it is essential to encourage entrepreneurship and the establishment of new companies. One effective approach is to provide students of technical sciences, particularly civil engineering and architecture, with education on economic principles and entrepreneurship. This can better prepare them for the labour market, especially those who may not secure employment immediately after graduation or who aspire to start their own businesses.

The construction sector has a multidimensional impact on the national economy. It is deeply interconnected with various other sectors and industries, both upstream and downstream, and significantly influences the labour market, financial system, and industrial development. Given this strategic importance, countries must implement measures to support and expand this sector.

This paper highlights the relevance of entrepreneurship education for students in technical fields and advocates for integrating basic economic and entrepreneurial concepts into their curricula. Drawing on international experiences and case studies, it proposes directions for further research in Serbia and the broader region. In addition, it offers conclusions and recommendations based on available data and research, with an emphasis on applicability within the Serbian context.

Key words: *entrepreneurship, education, construction, Republic of Serbia*

[1] MSc, Teaching Assistant, Faculty of Civil Engineering and Architecture University of Niš, Serbia, aleksandar.djordjevic@gaf.ni.ac.rs, https://orcid.org/0000-0002-9683-8582

1. INTRODUCTION

The construction sector represents one of the most significant drivers of economic development due to its extensive impact on other sectors, including manufacturing, transport, energy, and finance [1]. It contributes to infrastructure development, regional connectivity, urban growth, and overall national productivity. Within this sector, small and medium-sized enterprises play a particularly important role, as they stimulate innovation, create jobs, and contribute to GDP growth [2]. Given the sector's project-based nature and high volatility, adaptability and entrepreneurial capacity are crucial for long-term competitiveness and resilience.

In this context, entrepreneurship emerges not only as a mechanism for creating new businesses but also as a set of competencies that can enhance performance in both private and public organizations. Entrepreneurship is increasingly regarded as a transversal skill, valuable not only for business founders but also for employees, managers, and professionals across various fields. However, many engineering and architecture graduates enter the labour market with limited understanding of basic economic principles and entrepreneurial processes, often learning them only after founding their own firms. This highlights a structural gap in higher education, where technical knowledge is emphasized, while entrepreneurial literacy remains underdeveloped.

Entrepreneurship education (EE), if it was integrated well into civil engineering and architecture curricula, could bridge this gap. It would enhance students' capacity to identify opportunities, solve problems innovatively, and create value within complex project environments [3]. Furthermore, entrepreneurship is increasingly understood in a broader sense, not only as business creation but also as a mindset, involving initiative, creativity, and responsibility across various professional contexts [4]. This broader conception of entrepreneurship is particularly relevant in the context of construction, where multidisciplinary collaboration, regulatory complexity, and market dynamics require proactive thinking and adaptive leadership.

Empirical research supports the idea that embedding entrepreneurship education into technical disciplines can significantly increase students' confidence, employability, and willingness to engage in innovative ventures [5]. Moreover, the construction industry, as a labour-intensive and capital-demanding field, benefits from professionals who can combine technical expertise with entrepreneurial thinking, whether by founding firms, leading projects, or improving organizational processes within existing firms or projects.

This paper aims to explore the relevance of entrepreneurship education in construction-related disciplines, with a particular focus on students of civil engineering and architecture. Through an analysis of international practices and current challenges in the Western Balkans region, the study proposes practical recommendations for integrating EE into technical programs in Serbia. Some, out of many other benefits, are to enhance graduate employability, promote sustainable enterprise creation, and support the long-term development of the construction sector.

2. METHODOLOGY

This paper adopts a qualitative and exploratory research approach to assess the relevance and potential of entrepreneurship education in the construction sector, particularly among students of civil engineering and architecture. The methodology is grounded in an extensive literature review, comparative analysis of international practices, and a contextual analysis of the Serbian higher education system. The primary data sources include peer-reviewed journal articles, policy documents from the European Commission, World Bank reports, and national education strategies. Special emphasis was placed on the integration of entrepreneurship education into engineering curricula in selected EU countries, serving as models of good practice.

The analysis is driven by several interrelated research questions: it seeks to understand the role of entrepreneurship education in enhancing the employability and innovation capacity of graduates in construction-related fields; to identify the pedagogical models and teaching methods that are most effective for embedding entrepreneurship within technical disciplines; and to explore how Serbia's educational policies and curricula can be aligned with successful international frameworks in order to improve outcomes for future professionals in the sector.

This study does not involve original empirical research such as surveys or interviews but is based on secondary sources and conceptual synthesis. The findings are discussed in the context of existing educational and institutional frameworks, with the aim of providing actionable recommendations for curriculum development and policy enhancement. Also it is intended to conduct a field research in the near future.

3. FINDINGS FROM LITERATURE AND GLOBAL EXPERIENCE

In recent decades, entrepreneurship education has gained global significance as a vital tool for fostering innovation, employability, and economic resilience. Across different countries and regions, educational institutions have implemented a variety of models, pedagogical approaches, and policy frameworks to include entrepreneurial competencies at all educational levels, from primary schools to universities and vocational training systems.

The European Commission has been one of the pioneers in promoting entrepreneurship education through strategic frameworks and funding programs. According to the Entrepreneurship 2020 Action Plan [6], entrepreneurial education and training are essential for equipping people with the skills needed to turn ideas into action. In alignment with this policy, numerous European projects and networks, such as *EntreComp* and *HEInnovate*, have been developed to support entrepreneurship competence development and institutional transformation in higher education [7].

In the United States, the National Science Foundation (NSF) and its Innovation Corps (I-Corps) initiative represent a structured approach to integrating entrepreneurship into research and STEM education. STEM is an acronym for Science, Technology, Engineering, and Mathematics, and it represents a holistic approach to learning that integrates these disciplines to prepare students for future careers and problem-solving in real-world scenarios. It moves beyond traditional subject-based learning and encourages students to apply knowledge creatively and critically [8]. The I-Corps program trains academic researchers in customer discovery, business modelling, and value proposition design, with the goal of facilitating technology transfer and startup creation.

Similarly, in Nordic countries like Finland, EE is strongly integrated into curricula through interdisciplinary project-based learning and partnerships with industry. Studies highlight how Finnish universities incorporate entrepreneurial thinking into engineering programs, emphasizing creativity, teamwork, and societal impact [9].

In Germany, the EXIST program supports university-based startups through mentoring, funding, and infrastructure, encouraging a startup culture within academic institutions for more than 25 years [10]. Similarly, the United Kingdom emphasizes enterprise education through national strategies and university-led programs such as Enterprise Educators UK and the National Centre for Entrepreneurship in Education [11].

The following Table 1. Summarizes a comparative overview of selected programs and approaches from several countries that represent innovative and transferable practices in entrepreneurship education.

Table 1. Examples of Good Practices in Entrepreneurship Education

Country	Program / Initiative	Program / Initiative
Finland	Project-based EE in engineering	Integrated into curricula; emphasis on teamwork and societal innovation [9]
USA	NSF Innovation Corps (I-Corps)	Lean Startup methodology; supports commercialization of academic research [8]
EU (general)	EntreComp / HEInnovate	Competence frameworks and institutional self-assessment tools [7]
Germany	EXIST	University startup funding and support infrastructure [10]
UK	Enterprise Educators UK	Nationwide network for promoting enterprise education [11]
EU	VET and entrepreneurial schools	Focus on vocational training and practical skills in entrepreneurship [12]

Each of these programs reflects a unique national context and addresses specific educational, economic, and institutional needs. For example, EntreComp offers a flexible framework of entrepreneurial competencies that can be adapted across formal and non-formal learning environments, encouraging the development of personal, social, and business-oriented entrepreneurship [7]. The NSF I-Corps program, on the other hand, focuses on accelerating innovation in scientific research, providing researchers with tools to assess market viability and create impact beyond academia [8]. The Finnish model emphasizes a human-centric and sustainability-oriented approach to entrepreneurship, often linking it to challenges such as climate change or digital transformation [9]. In contrast, Germany's EXIST program is closely aligned with the country's strategic focus on applied sciences and industrial competitiveness, offering strong institutional support to spin-offs in technology and engineering fields [10]. Furthermore, in vocational and technical education (VET), the European Commission has emphasized the integration of entrepreneurial skills through national strategies and EU-funded initiatives [12]. These include teacher training, modular curricula, and transnational cooperation among schools and enterprises.

The review of international practice suggests that effective entrepreneurship education requires systemic integration across policy, curriculum, teacher development, and institutional leadership. Programs that succeed in this regard are those that align educational

goals with broader societal and economic objectives, fostering not only startup creation but also intrapreneurship, innovation in public services, and civic engagement [13].

Furthermore, a key challenge in entrepreneurship education remains the pedagogical approach itself. It is not enough to merely teach about entrepreneurship, about the history, notable figures, or theoretical frameworks. Instead, students should learn through entrepreneurship by engaging in practical activities that simulate or directly involve real business environments. This may include working on real company projects, developing startup ideas, or managing virtual businesses. These approaches foster deeper understanding and can lead to viable entrepreneurial ventures emerging from the classroom experience. However, theory cannot be completely excluded. A solid theoretical foundation enables students to sustain and scale their entrepreneurial projects. As in agile business environments, successful entrepreneurial education should involve continuous testing, feedback, and iteration. Therefore, striking a balance between practical experience and theoretical knowledge is essential, along with mechanisms to assess and adapt the educational approach accordingly. If educators teach students how to be entrepreneurial, they should also implement and practice entrepreneurial thinking and behaviour themselves.

When discussing the terminology, it is important to note that different educational systems apply different concepts. In the United Kingdom, the term enterprise education is commonly used, encompassing personal development, mindset building, and skill acquisition. Entrepreneurship education, in contrast, focuses more narrowly on starting and managing ventures [9], [11]. In the United States, the term entrepreneurship education dominates [16]. Some scholars suggest combining the terms as enterprise and entrepreneurship education, though this may be somewhat impractical [13]. To resolve terminological confusion, Erkkilä proposes the unified term entrepreneurial education, which integrates both perspectives into a comprehensive framework [14]. This distinction is illustrated in the following figure, which shows how the interpretation of entrepreneurial education evolves over time, reflecting pedagogical shifts and a persistent concern about the lack of practical orientation in higher education systems.

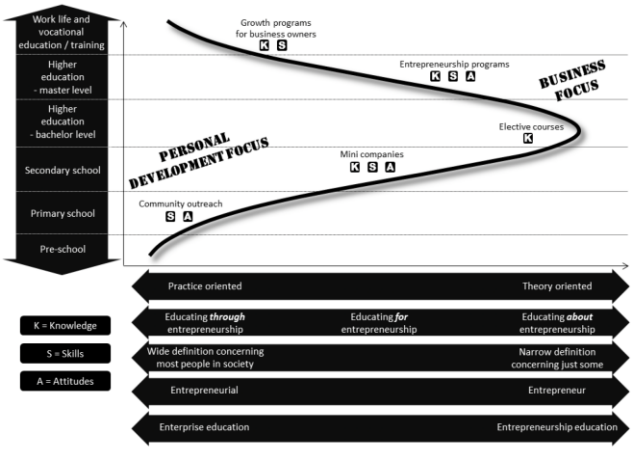


Figure 1. Terms in entrepreneurial education. Source: [13].

The figure illustrates the evolution of terminology and approach, highlighting the growing emphasis on practice-oriented learning in recent years. The visual progression from personal

development to business focus also underscores the increasing alignment of entrepreneurship education with labour market demands and innovation-driven economies. This evolution across educational levels highlights the importance of adaptability and contextualization in both policy and practice. With these global trends in mind, the next section turns to the national context, exploring how entrepreneurship education is approached within the Serbian construction sector and what challenges remain in aligning it with contemporary educational and economic priorities.

4. ENTREPRENEURSHIP EDUCATION IN THE SERBIAN CONSTRUCTION SECTOR

In parts of Northern and Eastern Europe, particularly in Sweden and the Balkans, the term *entrepreneurial learning* is often used as a substitute for *enterprise education*. However, this can create confusion, as the same term is also associated with research on how entrepreneurs learn outside formal education settings. In Finland, a different set of terms is applied: *internal* and *external* entrepreneurship education. Internal entrepreneurship education typically refers to enterprise education, while external entrepreneurship education corresponds to the more business-oriented understanding of entrepreneurship education. The terminology becomes even more complex when *internal entrepreneurship* is occasionally used to describe intrapreneurship, that refers to entrepreneurial behaviour within established organizations [13].

The importance of entrepreneurship education in the construction sector has gained increasing attention in Serbia over the past decade, particularly considering the country's efforts to align its policies and practices with European standards. Although systemic implementation of entrepreneurship in education is still developing, several initiatives have emerged to promote innovation, business skills, and entrepreneurial thinking, especially in technical and engineering disciplines. Entrepreneurship education in Serbia has been included in national strategies, such as the Strategy for the Development of Education in Serbia 2020, which recognizes entrepreneurial competencies as essential for improving employability and competitiveness [15]. Moreover, the Strategy for the Development of Startups in the Republic of Serbia for the period from 2021 to 2025 emphasizes education as a key pillar for fostering entrepreneurial ecosystems [16]. However, implementation in the field of construction remains uneven, and formal integration into curricula at technical faculties is still limited. What is a good practice that there is a continuation in this policy. In the following version of this document some new aspects and key progress indicators that have been added to track the entrepreneurial development. Efforts will be made to increase the inclusion of entrepreneurship-related content in higher education study programs. This aligns with the Smart Specialisation Strategy of the Republic of Serbia (2020–2027) [17], which aims to boost economic growth and competitiveness by linking research, industry, and innovation. Priority investment areas identified include ICT, food for the future, advanced manufacturing, and creative industries. Among the defined goals is education focused on innovation and entrepreneurship. To support this, a Fund for the Promotion of High-Tech Entrepreneurship will be established, financing initiatives such as incubators, spin-offs, technology transfer and IP centres. The percentage of study programs that include entrepreneurship modules will serve as a key performance indicator, alongside regular monitoring and evaluation of the Fund's impact [18].

In the construction sector specifically, some universities have initiated elective courses related to project management, innovation in construction, or basics of entrepreneurship. For example, the Faculty of Civil Engineering in Belgrade offers an elective course titled “Innovation and Entrepreneurship”, aiming to develop business judgement among engineering students [19]. Also Faculty of Civil Engineering and Architecture, University of Niš, developed a special study programme which includes subjects related to entrepreneurship, economics and internet business. However, these efforts are still largely fragmented and depend on individual institutional initiative rather than national coordination. Other obstacles that persist include a lack of trained teaching staff for entrepreneurship, insufficient cooperation among industry and university, as well as limited access to seed funding or incubator support for student start-ups in construction. Furthermore, many students in technical faculties still perceive entrepreneurship as distant from their core professional competencies.

To strengthen entrepreneurship education in the Serbian construction sector, systemic reforms are needed. These include curriculum integration, capacity building for academic staff, increased collaboration with construction companies and startups, and the development of interdisciplinary learning environments. Aligning these efforts with EU frameworks such as EntreComp could provide a structured path for the development of entrepreneurial competencies among future construction professionals [7]. Despite systemic challenges, several notable initiatives in Serbia demonstrate the potential for developing entrepreneurship education in the construction sector. These initiatives often emerge through collaboration between academic institutions, public sector bodies, and international projects. Also, some universities and faculties have implemented new study programs which incorporate entrepreneurial and economic subjects. The following table 2 presents some selected programs and projects that have contributed to promoting entrepreneurial competencies and innovation in the construction and in general domain.

Table 2. Examples of Entrepreneurship Education Initiatives in Serbia

Program / Initiative	Institution / Organization	Description
Innovation and Entrepreneurship	University of Belgrade – Faculty of Civil Engineering	An elective course aimed at introducing students to entrepreneurship in the construction sector [19]
Project management in construction	Faculty of Civil Engineering and Architecture University of Niš	Study programme with subjects relating entrepreneurship, economics and internet business [20]
(Niš) Startup School; The (Niš) Innovation School	Science and Technology park Niš	Start-up schools for entrepreneurship [21]
ParkUp, SoftLanding…	Science and Technology park Belgrade	Start-up schools and camps for entrepreneurship [22]
“3alet” (jump-off)	Science and Technology park Novi Sad	Start-up education for entrepreneurship [23]
Campino	Science and Technology park Čačak	Summer camp for entrepreneurship [24]

Now as many initiatives are made through science and technology park as a certain catalyst of entrepreneurship, a separate section will be dedicated to them. They do foster general entrepreneurship without a special focus on construction sector, but that definitely does not exclude that very important sector of every national economy from taking part in their programmes.

5. SCIENCE AND TECHNOLOGY PARKS AS DRIVERS OF ENTREPRENEURSHIP IN SERBIA

Science and technology parks (STPs) represent key institutional mechanisms for stimulating entrepreneurship and innovation across various sectors in Serbia, including the traditionally less innovative construction industry. As infrastructural and organizational platforms, STPs provide targeted support for the development of start-ups, small and medium-sized enterprises, and research-based ventures by offering access to modern workspaces, mentoring, seed funding, and opportunities for networking and cooperation with academic institutions and private sector stakeholders. In Serbia, several STPs operate under the support of the Government of the Republic of Serbia, the Ministry of Science, Technological Development and Innovation, and international development partners. Notable examples include the Science Technology Parks in Belgrade, Novi Sad, Niš, and Čačak, which collectively form a network designed to promote innovation-based entrepreneurship and commercialize research outputs. These parks serve as catalysts for entrepreneurial ecosystem development by implementing programs such as BoostMeUp, Raising Starts, and IP Consult, which provide structured support to early-stage ventures through mentoring, training, and access to investors [21,22,23,24].

While the construction sector has not historically been a focus of high-tech innovation, science and technology parks provide an opportunity to change this dynamic. By fostering start-ups that offer solutions in fields such as green construction, energy-efficient materials, building information modelling, and construction automation, STPs can help modernize and increase competitiveness in the sector. The integration of entrepreneurial and technological competencies supported by STPs also contributes to addressing key priorities identified in national policy frameworks, including those related to smart specialization and digital transformation. Moreover, STPs play a critical role in building entrepreneurial communities by facilitating interdisciplinary cooperation among researchers, engineers, students, and business practitioners. This ecosystemic approach is particularly valuable in the construction industry, where innovation requires the convergence of technical, environmental, and business knowledge. By linking faculties of architecture and civil engineering with start-up initiatives and private sector actors, STPs contribute to the development of practical and scalable solutions for sector-specific challenges [25]. Overall, science and technology parks in Serbia have demonstrated a strong potential to act as accelerators of entrepreneurial activity, including in the construction sector. Their continued development and deeper integration into sectoral policies and academic-industry cooperation models represent a strategic opportunity to foster sustainable and innovation-driven growth.

6. CONCLUSION AND RECOMMENDATIONS

The findings of this study underline the growing importance of entrepreneurship education in shaping the future of the construction sector, particularly in transitional economies like Serbia. As the sector faces increasing demands for innovation, adaptability, and sustainability, integrating entrepreneurial competencies into engineering and architecture curricula becomes a strategic imperative. International experience demonstrates that when embedded systematically and contextually, entrepreneurship education can significantly improve student readiness for the labour market, stimulate startup activity, and enhance organizational performance across both public and private domains.

In Serbia, current educational policies and strategies recognize the relevance of entrepreneurial competencies, yet implementation within technical faculties remains fragmented and inconsistent. The construction sector, as a labour-intensive and innovation-dependent field, stands to benefit greatly from a structured and practice-oriented approach to entrepreneurship education. However, this requires a shift from isolated course offerings to integrated pedagogical frameworks, including project-based learning, collaboration with industry, and real-world application of entrepreneurial methods.

In this regard, Science and Technology Parks emerge as important enablers of innovation and entrepreneurship among students and young professionals. By offering incubation services, mentoring, technical infrastructure, and access to funding, STPs bridge the gap between academic knowledge and market application. In the context of civil engineering and architecture, they provide a testing ground for innovative construction techniques, green building solutions, and digital transformation initiatives. Strengthening the links between universities, STPs, and the construction industry can create a vibrant ecosystem where entrepreneurial ideas are not only generated but also scaled and sustained.

Ultimately, for Serbia to foster a resilient and forward-looking construction sector, it must reimagine its educational landscape through the lens of entrepreneurship. This involves not only curriculum reform but also institutional capacity building, policy alignment, and cultural change within academic environments. By doing so, higher education institutions can play a transformative role in producing graduates who are not just technically competent, but also entrepreneurial, innovative and socially responsive. They would also become both more employable and self-employable.

Further research is planned be undertaken among the bachelors, master and PhD students, or graduates that are part of a company or who have made their own firms, in order to find out which knowledges did they require and what would have helped them if they knew it before their business venture or before starting to work in an existing company.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] Ofori George: **Nature of the construction industry, its needs and its development**: **A review of four decades of research**. *Journal of Construction in Developing Countries*, Vol. 20, No. 2, 115–135, 2015.
[2] World Bank: **Small and medium enterprises (SMEs) finance**. *World Bank, 2020*. Retrieved from https://www.worldbank.org/en/topic/smefinance (5.3.2025.)
[3] Holzmann Patrick, Hartlieb Erich, Roth Michael: **From Engineer to Entrepreneur – Entrepreneurship Education for Engineering Students: The Case of the Entrepreneurial Campus Villach**. *International Conference on Interactive Collaborative Learning* (ICL2017), Budapest, 2017.
[4] European Commission.: **Entrepreneurship education: A road to success A compilation of evidence on the impact of entrepreneurship education strategies and measures**. *Publications Office of the European Union*, Luxembourg, 2015.
[5] Nabi Ghulam, Linán Francisco, Fayolle Alain, Krueger Norris, Walmsley Amanda: **The impact of entrepreneurship education in higher education: A systematic review and research agenda**. *Academy of Management Learning & Education*, 16(2), 277–299, 2017. https://doi.org/10.5465/amle.2015.0026
[6] European Economic and Social Committee. **Entrepreneurship 2020 Action Plan**. *European Commission*, Brussels, 2013.
[7] Bacigalupo Margherita, Kampylis Panagiotis, Punie Yves, Van den Brande Godelieve. **EntreComp: The Entrepreneurship Competence Framework**. *Publications Office of the European Union*, Luxembourg, 2016.
[8] National Science Foundation: **NSF Innovation Corps (I-Corps) Program**. *NSF*, Washington, D.C., 2022.
[9] Reffstrup Tilde, Christiansen Susanne Kærn: **Nordic Entrepreneurship Islands: Status and Potential – Mapping and Forecasting Entrepreneurship Education on Seven Selected Nordic Islands**. *Nordic Council of Ministers*, Copenhagen, 2017.
[10] https://www.bmwk.de/Thema/Startup/EN/Navigation/home.html (07.5.2025.)
[11] Penaluna Andy: **Enterprise and Entrepreneurship Education: Guidance for UK Higher Education Providers**. *The Quality Assurance Agency for Higher Education*, Gloucester, 2018.
[12] Cedefop: **The future of vocational education and training in Europe: Volume 4 – Delivering lifelong learning: the changing relationship between IVET and CVET**. *Publications Office of the European Union*, Luxembourg, 2023. http://data.europa.eu/doi/10.2801/726631
[13] Lackéus Martin: **Entrepreneurship in Education. What, Why, When, How**. *OECD*, European Commission, 2015.
[14] Erkkilä Kari: **Entrepreneurial Education: Mapping the Debates in the United States, the United Kingdom and Finland**. *Taylor & Francis*, 2000.

[15] Ministry of Education, Science and Technological Development: **Education Development Strategy in Serbia until 2020**. Belgrade, 2012.
[16] Government of the Republic of Serbia: Strategy for the Development of the Startup Ecosystem of the Republic of Serbia for the Period 2021–2025. Belgrade, 2021.
[17] Ministry of Education, Science and Technological Development of the Republic of Serbia: **Smart Specialisation Strategy of the Republic of Serbia for the Period 2020 to 2027**. *Ministry of Education, Science and Technological Development,* Belgrade, 2021.
[18] Ministry of Education, Science and Technological Development of the Republic of Serbia: **Strategy for the Development of Education in the Republic of Serbia until 2030**, Belgrade, 2021.
[19] Faculty of Civil Engineering, University of Belgrade: https://web1.grf.bg.ac.rs/studije/pta?o=0&pid=1657&t=1&v=0 (10.5.2025.)
[20] Faculty of Civil Engineering and Architecture, University of Niš https://www.gaf.ni.ac.rs/akreditacija2020/studijski/2021/index.php?dir=OAS%20Upravljanje%20projektima%20u%20graditeljstvu/Knjiga%20predmeta_OAS%20Upravljanje%20projektima%20u%20graditeljstvu/ (13.05.2025.)
[21] Science and Technology park Niš https://ntp.rs/en/programi/ (17.05.2025.)
[22] Science Technology Park Belgrade. (n.d.). *About us*. Retrieved from https://ntpark.rs/en/about-us/
[23] Science Technology Park Novi Sad. https://ntpns.rs/edukacija/ (17.05.2025.)
[24] Science Technology Park Čačak https://www.ntpcacak.rs/sr/razvoj-biznisa/
[25] Xie, Kefan, Song, Yimin, Zhang, Wei, Hao, Jing, Liu, Zhiqiang, Chen, Yuhong: **Technological entrepreneurship in science parks: A case study of Wuhan Donghu High-Tech Zone**. *Technological Forecasting and Social Change*, *135*, 156–168 (2018).

doi.org/10.62683/SINARG2025.006

Review paper

USE OF FLY ASH IN ROAD CONSTRUCTION

Milan Draganović[1], Nenad Ristić[2], Dušan Grdić[3]

Abstract

Fly ash is a by-product of coal combustion in thermal power plants. While the European Union recycles and utilizes almost all of its fly ash across various industries, only 2.7% is used in our country. This paper researches the potential applications of fly ash in road construction, including its use in embankment layers, enhancement of mechanical properties, soil stabilization, and as a filler replacement in asphalt mixtures. Research has shown that the use of fly ash can significantly reduce road construction costs, ranging from 30% to 80%.The paper also researches the technical, ecological, and economic aspects of fly ash utilization in infrastructure projects.

Key words: fly ash, road construction, embankment, pavement construction, asphalt mixture

[1] M.Sc., PhD Candidate, GAF Nis, Serbia, dmilan997@gmail.com, ORCID N/A
[2] PhD, Associate Proffesor, GAF Nis, Serbia, nenad.ristic@gaf.ni.ac.rs, ORCID 0000-0002-8201-892X
[3] PhD, Assistant Professor, GAF Nis, Serbia, dusan.grdic@gaf.ni.ac.rs, ORCID 0000-0002-2651-7388

1. INTRODUCTION

Fly ash, generated by the combustion of fossil fuels in thermal power plants, presents a significant environmental challenge due to its high concentration of harmful substances. However, the implementation of electrostatic filtration systems allows for efficient removal of ash particles from flue gases, thereby reducing the environmental impact. This process produces fly ash, which can be repurposed for various industrial applications.

Utilizing fly ash in industry not only reduces waste generation but also contributes to the sustainability of production processes across different sectors. Notably, the application of fly ash in road construction offers several advantages, including:

- **Reduction of environmental impact**: Fly ash use limits the need for natural materials and reduces landfill burdens.
- **Improvement of soil properties**: Fly ash can enhance the mechanical behavior and bearing capacity of subgrade soils.
- **Increased material strength**: When properly mixed, fly ash contributes to stronger, more durable structural layers.
- **Conservation of natural resources**: By substituting fly ash for conventional materials like cement and lime, the consumption of non-renewable resources is decreased.
- **Economic benefits**: Fly ash is typically more cost-effective than traditional construction materials, leading to significant financial savings in large-scale projects.

2. FLY ASH – GENERATION PROCESS AND CLASSIFICATION

The formation of fly ash is directly associated with the combustion of coal in thermal power plants. The generation process is as follows:

- **Combustion Process and Ash Formation**: Fly ash is primarily generated during coal combustion in power plant boilers for electricity production. The combustion process involves complex chemical and physical transformations, including heat release, conversion of organic and inorganic components in coal, and the creation of combustion by-products, among which ESP fly ash is a major constituent.
- **Chemical Composition of Fly Ash**: Fly ash consists of fine, spherical particles that are carried by flue gases during combustion. Its composition depends on the type of coal burned, combustion conditions, and the type of power plant. Common components of fly ash include silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and unburnt carbon.
- **Separation of Fly Ash**: As the flue gas containing ash travels through the boiler and enters the gas purification system, fly ash particles are separated from the gas stream. Various collection devices, such as electrostatic precipitators or bag filters, are used to capture the fine particles before the gas is released into the atmosphere.

As shown in Figure 1, which illustrates the generation of fly ash in a thermal power plant boiler, approximately 20% of the total ash is removed from the boiler as bottom ash, while 80% is collected from flue gases via electrostatic filters—this fraction constitutes fly ash.

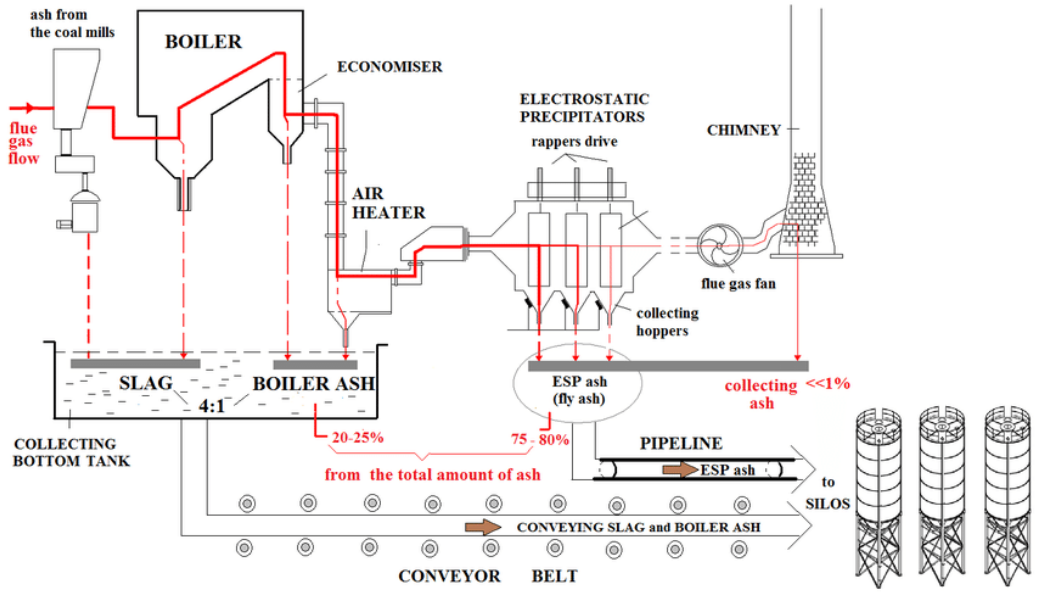


Figure 1 -Distribution of slag and ash in a typical thermal power plant [1]

- **Classification of Fly Ash:** Fly ash is categorized into two main types: Class F and Class C. Class F fly ash is derived from the combustion of anthracite or bituminous coal and is characterized by a low calcium oxide content. In contrast, Class C fly ash is produced from the combustion of sub-bituminous or lignite coal and contains a higher proportion of calcium oxide. The type of fly ash significantly influences its properties and potential applications [2,3,4].

3. APPLICATION IN ROAD CONSTRUCTION

Fly ash has long been used in concrete production both in the European Union and in our country; however, in Europe and the United States, a significant amount is also used in road construction. In the EU, countries do not face issues with fly ash disposal—out of 18 million tons of fly ash produced in 15 EU member states, 14 million tons are consumed in concrete production, while approximately 23% is used in road construction [5]. In contrast, in our country, only 2.7% of the produced fly ash is utilized, and solely for concrete production; it is not used at all in road construction, despite the fact that its application in subgrade layers could reduce construction costs by 30% to 80% [5].

In road construction, fly ash can be used in embankments, road subgrades, lower bearing layers of pavement structures, asphalt mixtures, utility trench backfills, mechanical property improvement, soil stabilization, and the rehabilitation of degraded areas.

Figure 2 illustrates the percentage of fly ash utilized in the production of various construction materials and structures in the year 2006.

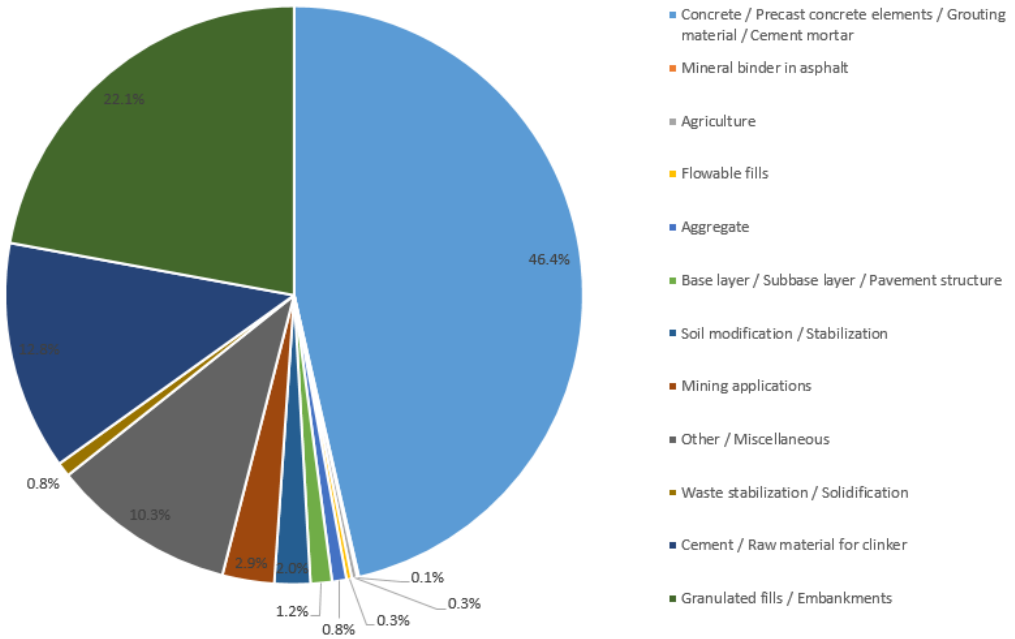


Figure 2 - Standard application of fly ash

3.1. Application in Embankments or Fill Material

According to data from the American Coal Ash Association, the second most widespread use of fly ash, after its application in concrete production, is in embankment and fill construction. The use of this material in embankments and granular fills gained momentum in the 1950s in the United Kingdom, where it was employed as an alternative borrow material for the subgrade of railway lines [6].

The standard guide for the design and construction of granular fills with fly ash, ASTM E2277-03, recommends the use of this material in embankments and backfills. Fly ash offers several advantages over traditional soil or stone materials, including relatively low specific weight, high shear strength, easy handling and compaction, and economic viability in regions where it is readily available. Due to its low specific gravity, it can be placed over weak or soft subgrade soils, while its high shear strength minimizes settlements. When placed at optimum moisture content, compaction is significantly faster compared to natural soils.

Over a period of more than three years, the behavior of two fly ash embankment projects (in the U.S. states of Delaware and Pennsylvania) was monitored during both construction and operational phases. During this period, no evidence of excessive settlement or negative environmental impact was observed [7].

The optimal moisture content for fly ash in embankment construction is between 3% and 4%, and the material should be delivered to the site in this condition [7].

The most important technical properties of fly ash include:

- Shear strength
- Moisture-density relationship (compaction curve)
- Unconfined compressive strength
- Gradation (particle size distribution)
- Consolidation characteristics
- Hydraulic conductivity

Design calculations for embankments using fly ash follow the same procedures as those used for natural soil. Such embankments will have comparable strength and compaction properties but lower dry density. Fly ash embankment bases should not be exposed to moisture, wet soil, or areas with a high groundwater table. A practical method to prevent capillary rise or seepage in fly ash embankments or backfills is to install a drainage layer of coarse crushed material at the base [8].

Additionally, erosion control must be considered. Slopes should be protected immediately after embankment construction to reduce runoff-induced erosion from water or strong winds. One method is to construct coarse-soil cells over the slope surface and fill them with fly ash. These cells act as barriers that reduce the kinetic energy of water and prevent the washing out of fine particles [6].

Another effective method is to apply topsoil and vegetation cover. The bearing capacity of the subgrade is expressed similarly to standard embankments, using the California Bearing Ratio (CBR) for flexible pavements or the subgrade reaction modulus (K) for rigid pavements.

Construction should be suspended during severe weather conditions such as heavy rainfall, snowstorms, and prolonged periods of freezing temperatures. It is not recommended to place and compact fly ash at ambient temperatures below -4°C [6]. As previously mentioned, freeze–thaw cycles do not significantly affect the strength of fly ash, allowing for ice expansion without compromising material integrity [9]. However, replacing frost-resistant soil with fly ash in frost-susceptible zones may introduce performance issues [6].

3.2. Application in Stabilized Subbase and Subgrade Layers

Fly ash can also be used for the construction of stabilized subbase and subgrade layers. Both fully bitumenized fly ash (Class F) and partially bitumenized fly ash (Class C) can be applied. Class F fly ash requires the addition of chemical reagents (activators), aggregates, and water to achieve the desired binding properties, whereas Class C fly ash typically does not require chemical additives due to its self-cementing characteristics [6].

For coarser aggregates, the required amount of fly ash is lower compared to that needed for finer aggregates.

In the late 1950s, a pavement base layer mixture called "Poz-o-Pac" was patented. It consists of a combination of lime, fly ash, and aggregates. All mixtures containing fly ash can generally be categorized as pozzolan-stabilized bases (PSB), where the aggregate serves as the main component [6].

A similar application of fly ash as a binder layer is the cold in-place recycling (CIR) method. This process involves milling and crushing the existing pavement layer, mixing it with an asphalt emulsion as a stabilizer, and reapplying it on-site. This creates a reliable base for a

new pavement layer and, in some cases, serves as a final layer itself. Replacing the asphalt emulsion with fly ash in this method can yield similar results [10].

Research in the United States has shown that fly ash performs well in stabilizing subbase layers under low-traffic conditions such as access roads, parking lots, and sidewalks.

Adding 10% to 20% of Class C fly ash to the top layer of embankments or subgrade soil improves unconfined compressive strength and CBR values. Additionally, reducing the time between soil compaction cycles when fly ash is present positively affects subgrade bearing capacity.

Class C fly ash has been successfully used in soil stabilization tests at two construction sites in Wisconsin. Both subgrades consisted of more than 90% fine-grained aggregates with in-situ moisture contents 6% to 7% above the optimum. CBR values were initially low (between 1 and 3). At both sites, stabilization with self-cementing fly ash significantly improved soil strength and stiffness. The increased stiffness enhanced load-bearing capacity and reduced deformation under construction traffic. Laboratory tests showed improved unconfined compressive strength, higher CBR values, and better resilient modulus (Mr) of the soil after fly ash addition. Mixing more than 20% fly ash resulted in diminished improvements, while mixtures with 10% to 12% fly ash provided optimal cost-efficiency and mechanical performance. Field-measured CBR values for the optimal mixture were about two-thirds of those recorded in the lab—sufficient to support construction equipment loads [11].

3.2.1. Design Considerations

Once the particle size distribution of the pozzolanic stabilization mixture is determined, it is necessary to quantify the fraction smaller than 0.063 mm. This is assessed using the Proctor compaction test at the optimal moisture content. After determining the gradation, the next step is to establish the ratio of activator to fly ash in the mixture. Based on the results of strength and durability tests on a series of trial samples—and in accordance with ASTM C593 procedures—the optimal mixture composition is defined [12].

Typically, the combined content of fly ash and activator ranges between 12% and 30% of the total mixture mass. The most cost-effective composition is usually the one with the lowest amount of activator in the finest fraction, provided it still meets the required strength and durability criteria. For safety reasons, pozzolanic stabilization intended for field application must include at least 0.5% more activator than the amount determined in the optimal lab mixture [13].

Parameters such as CBR, unconfined compressive strength, and resilient modulus (Mr) generally increase up to 5% with the addition of cement. However, increasing the lime content has shown an opposite effect.

Structural design of pavement systems with stabilized subbase layers incorporating fly ash follows the same methodology used for conventional pavement structures and adheres to AASHTO standards.

3.2.2. Construction and Handling Procedures

When constructing and placing self-cementing fly ash mixtures, attention must be paid to the following:

- **Uniform distribution of fly ash** within the mixture;
- **Proper pulverization and thorough mixing** of fly ash with the subgrade material;
- **Moisture control** to achieve maximum dry density and strength;
- **Final compaction** within the prescribed time frame [14].

Pozzolanic stabilization can be carried out either in a plant or directly on-site. Plant mixing enables precise control of composition and material homogeneity, which improves the quality of the final mixture. The process may be batch-based, using a rotating drum, or continuous, where calibrated quantities of aggregate, fly ash, and activator are mixed in cycles of 30–45 seconds [15]. The mixture is then transported to the construction site and placed using bulldozers or pavers, allowing for controlled layer thickness and moisture content.

On-site mixing is commonly used in pavement recycling. Although the mixture may be less uniform compared to plant mixing, high-quality material can still be achieved. Fly ash is spread directly onto the subgrade or aggregate layer, followed by the addition of activator and in-place mixing. Maintaining optimal moisture levels is critical—excess water can hinder workability and reduce stabilization efficiency.

Class C fly ash must be compacted within two hours of placement to prevent loss of strength [16,17]. Compacted pozzolanic stabilization layers should be no thinner than 100 mm and no thicker than 200–225 mm in their final compacted state. Loose layers should be spread about 50 mm thicker than the required compacted thickness. The surface of each compacted layer should be scarified before the next layer is placed [6].

After placement and compaction, the stabilized material must be protected from drying out to allow it to gain sufficient strength. This can be achieved by water curing or applying an asphalt emulsion before placing the final pavement layer. If asphalt surfacing is planned, it is recommended to install it within 24 hours. Opening the section to traffic before placing the surface layer is permitted only after the stabilized base layer reaches a compressive strength of 2410 kPa, which typically occurs within 7 days [13].

Base layers stabilized with fly ash are less likely to develop reflective cracking compared to those stabilized with Portland cement, due to weaker intermolecular bonding. Field and laboratory tests have shown that layers stabilized with fly ash or lime are generally less prone to cracking and shrinkage than those stabilized with cement [18]. On some test sections using mixtures of cement and fly ash, cracking was observed due to lower density and strength, whereas studies conducted in Wisconsin indicated that sections stabilized with fly ash alone performed better over time [19,20].

3.3. Application in Asphalt Layers

Asphalt mixtures are composite materials made of bitumen and mineral aggregate, used primarily for road construction. The most common method of production is hot mix asphalt (HMA), in which the aggregate is heated to approximately 150°C and the bitumen to around 90°C before mixing.

Fly ash can be used as a mineral filler in these mixtures, filling voids and binding coarser aggregate particles. This approach not only reduces the amount of fly ash disposed of in landfills, but also lowers material costs [21]. Typically, fly ash is added in small quantities

(around 5% by dry mass). Asphalt mixtures containing fly ash exhibit performance characteristics similar to those using conventional fillers such as limestone powder [22].

Fly ash can also partially replace bitumen in proportions ranging from 10% to 30%, without significantly compromising the strength and durability of the mixture [23,24]. Due to its lower specific gravity, it increases the volume of the binder phase, which can enhance mixture economy and longevity. However, additional field testing is needed to confirm long-term performance.

Fly ash has also been successfully used as a substitute for stone dust in asphalt concrete mixtures, due to its comparable physical properties. Its hydrophobic nature reduces the stripping of bitumen from the surface of aggregate particles, improving the water resistance and durability of the pavement.

Early studies, dating back to 1931, demonstrated that fly ash could effectively fill voids in asphalt mixtures and improve stability. More recent evaluations, including those by the U.S. Federal Highway Administration (FHWA), confirmed that asphalt mixtures containing fly ash exhibit greater resistance to moisture damage and stripping compared to those using other fillers like limestone or silica flour [25,26].

Testing conducted at North Dakota State University further indicated that lignite-based fly ash increases the strength and abrasion resistance of asphalt mixtures, especially when used in combination with cement or lime [27].

As of 2006, over 29 million tons of fly ash had been used as filler in asphalt across the United States, with most states reporting satisfactory results [28]. This broad application underscores the potential of fly ash as an economical and environmentally friendly alternative that enhances both durability and performance of asphalt pavements.

For fly ash to be used as an asphalt filler, it must be completely dry. Therefore, moistened fly ash or ash from storage lagoons is not suitable. In thermal power plants, fly ash is collected and stored in sealed, moisture-proof silos, ready for transport and use in asphalt concrete production.

4. CONCLUSION

The use of electrostatic precipitator fly ash in road construction offers significant benefits in terms of ecological sustainability, economic efficiency, and performance improvements for road infrastructure. As a by-product of thermal power plants, fly ash can serve as an alternative material for embankments, stabilization of subbase layers, and enhancement of asphalt mixtures. Literature confirms that the addition of fly ash improves the mechanical properties of asphalt, including its resistance to deformation and increased load-bearing capacity.

This material contributes to the reduction in the use of natural resources such as cement and lime, which lowers CO2 emissions and promotes sustainable construction practices. The economic advantages of fly ash are also evident, as it is often more affordable than conventional materials, leading to significant cost savings in large-scale construction projects.

Moreover, fly ash mixtures have shown higher resistance to water and freezing, which is crucial for the durability of roads in diverse climatic conditions.

The power utility EPS possesses large quantities of fly ash that could be used for road infrastructure development, potentially even for a 2,000-kilometer highway. EPS had previously been exempt from paying an environmental tax on each ton of ash, representing

a significant financial saving. However, fly ash storage sites in Serbia cover 1,400 hectares, and EPS spends around 50 million euros annually on maintaining these deposits. Compared to traditional materials, the use of fly ash in construction could save between 30% and 80%. While fly ash has been successfully used for road construction in countries like the Netherlands and the Czech Republic, its application remains limited in Serbia. For example, during the construction of the Belgrade-Čačak highway, the contractor failed to meet the technical specifications for embankments made from fly ash, leading to the rejection of the donated fly ash. Additionally, fly ash could become an export product, especially for markets in the Middle and Far East. However, additional investments in infrastructure and facilities would be required for export.

In conclusion, the use of electrostatic precipitator fly ash in road construction represents a sustainable and economical alternative to traditional materials, with proven improvements in performance and a reduced environmental impact.

REFERENCES

[1] Despotovic,Z.: **Reconstruction of vibratory sieves drives in system for separation boiler ash from slag on thermal power plant „TENT-B“**, *International Conference Power Plants 2016*, Zlatibor, 2016.

[2] Hower, J. C., et al.: **Coal Combustion Residues: *Variation in Major and Trace Element Concentrations with Depth in Two Waste Impoundments***. *Fuel*, Vol 180, 211-222, Elsavier, Amsterdam, 2016.

[3] ACAA (American Coal Ash Association): **Production & Use of Coal Combustion Products (CCPs) - Statistics.** *[Online]. Available: https://acaa-usa.org/Public-Resources/Production-Use-Reports.*, 2016. (2.2.2025.)

[4] Bates, A., et al.: **Coal Combustion Residues: A Global Perspective.** *Coal Combustion Residues*, 1-33, Elsevier, Amsterdam, 2018.

[5] Tanasijević Lj.: **Upotreba elektrofilterskog pepela I šljake proizvedenih iz termoenergetskih postrujenja**, *2. Sednica odbora Privredne komore Srbije*, 2011 , Beograd, 2011.

[6] Izveštaj "**Uputstvo za korisnike nusproizvoda I upotrebu sekundarnih sirovina u izgradnji puteva**", *Projekat za Republiku Srbiju G2G09/SB/5/4 u okviru kratkog G2G programa*, Agentschap NL TerrAdvies, Amsterdam, 2010.

[7] Collins RJ, Srivastava L.: **Use of ash in highway construction: Delaware demonstration project**. *Electric Power Research Institute*, *Report nr GS-6540*. Palo Alto, California, 1989.

[8] ASTM: **E2277-03 standard guide for design and construction of coal ash structural fills**. *Annual book of ASTM standards*. ASTM, West Conshohocken, Pennsylvania, 2003.

[9] Cocka E.: **Frost susceptibility properties of Soma-B fly ash**. *Journal of Energy Engineering*. Vol 123(1), 1-10. USA, 1997.

[10] Thomas T, Kadrmas A, Huffman J.: **Cold in-place recycling on US-283 in Kansas**. *Transportation Research Record 2000*; Vol 1723(1), 53-56. USA, 2000.

[11] Bin-Shafique MS, Edil TB, Benson CH, Senol A.: **Incorporating a fly-ash stabilized layer into pavement design**. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering 2004*. Vol 157,239-249. UK, 2004.

[12] ASTM: **C593-06 standard specification for fly ash and other pozzolans for use with lime for soil stabilization**. *Annual book of ASTM standards*, ASTM. West Conshohocken, Pennsylvania, 2006.

[13] American Coal Ash Association (ACAA): **Flexible pavement manual: Recommended practice - coal fly ash in pozzolanic stabilized mixtures for flexible pavement systems**.ACAA, USA,1991.
[14] American Coal Ash Association (ACAA): **Soil stabilization and pavement recycling with selfcementing coal fly ash**. ACAA*;* Aurora, CO, 2006.
[15] Barenberg EJ, Thompson MR.: **Lime-fly ash stabilized bases and subbases**. *National Cooperative Highway Research Program Synthesis of Highway Practice 37, Transportation Research Board*. Washington, DC, 1976.
[16] White DJ, Harrington D, Thomas Z.: **Fly ash soil stabilization for non-uniform subgrade soils**. *Volume I: Engineering properties and construction guidelines*. Iowa State University, Ames, IA: Center for Transportation Research and Education, Iowa State University, USA, 2005.
[17] Little DN, Males EH, Prusinski JR, Stewart B.: **Cementitious stabilization**. *Transportation in the new millennium: State of the art and future directions, perspectives from TRB standing committees*. Transportation Research Board, National Research Council. Washington, DC, 2000.
[18] Shirazi H.: **Field and laboratory evaluation of the use of lime fly ash to replace soil cement as a base course**. *Transportation Research Record 1999*. Vol. 1652(1), 270-275 USA,1999.
[19] Crovetti JA.: **Construc.tion and performance of fly ash-stabilized cold in-place recycled asphalt pavement in Wisconsin**. *Transportation Research Record 2000*; Vol 1730, 161-166. USA, 2000.
[20] Ramme BW, Tharaniyil M.: **Coal combustion products utilization handbook**. *We Energies*, Milwaukee, WI, 2004.
[21] Churchill EV, Amirkhanian SN.: **Coal ash utilization in asphalt concrete mixtures**. *J Mater Civ Eng 1999*. Vol 11, 295-301. USA, 1999.
[22] Kandhal PS, Lynn CY, Parker F.: **Characterization tests for mineral fillers related to performance of asphalt paving mixtures**. *Transportation Research Record 1998*; Vol 1638,101-110. USA, 1998.
[23] Butul B.: **Performance characteristics of coal fly ash and wood ash-modified asphalt binder.** *Florida Atlantic University*, Florida, USA; 2000. ID: 192.
[24] Simms SA.: **Use of coal fly ash in asphalt concrete mixes**. *DalTech - Dalhousie University* , Canada, 1998. ID: 190.
[25] Zimmer FV.: **Fly ash as a bituminous filler**. *Proceedings of the second ash utilization symposium*. U.S. Bureau of Mines. Pittsburgh, Pennsylvania:, 1970.
[26] Federal Highway Administration (FHWA), American Coal Ash Association (ACAA): **Fly ash facts for highway engineers**. *Federal Highway Administration (FHWA);. Report nr FHWA-IF-03-019*. USA, 2003.
[27] Carpenter CA.: **Cooperative study of fillers in asphaltic concrete**. *Public Roads 1952*; Vol 27, 101-110. USA, 1952.
[28] American Coal Ash Association (ACAA).: **2006 coal combustion product (CCP) production and use**. *American Coal Ash Association*; Aurora, CO, 2007.

doi.org/10.62683/SINARG2025.007

Review paper

INNOVATIVE SOCIAL AND CULTURAL SOLUTIONS FOR RECLAIMING PUBLIC OPEN SPACES IN MULTI-FAMILY NEIGHBOURHOODS

Ivana Bogdanović Protić[1], Ljiljana Vasilevska[2]

Abstract

This paper explores innovative social and cultural solutions for reclaiming public open spaces (hereafter, POS) in multi-family neighbourhoods, focusing on the following aspects: 1) satisfaction with living condition and neighbourhood perception; 2) socio-economic status of residents; and 3) residents' engagement and participation in (re)claiming POS. The theoretical framework is grounded in an analysis of literature and planning documents, while practical insights are drawn from case studies of best practices in the neighbourhoods of Drewitz (Potsdam) and Poptahof (Delft). The findings suggest that effective social and cultural approaches to reclaiming POS include the early integration of diversity, inclusive design strategies, the implementation of non-discriminatory policies, and the active involvement of residents in the design process.

Key words: *public open space (POS), multi-family neighbourhood, social and cultural solutions (SCS)*

[1] PhD, Associate Professor, Serbia, Faculty of Civil Engineering and Architecture of Niš, ivana.bogdanovic@gaf.ni.ac.rs, ORCID 0000-0003-0987-7127

[2] PhD, Full Professor, Serbia, Faculty of Civil Engineering and Architecture of Niš, ljiljana.vasilevska@gaf.ni.ac.rs, ORCID 0000-0002-6836-0139

1. INTRODUCTION

Public open spaces (hereafter, POS) in multi-family housing are considered a common good essential to the social, cultural, and economic development of neighbourhoods. Current documents highlight their role and implementation of innovative social and cultural solutions within them (hereafter, SCS) in realizing human rights, fostering social interaction, empowering marginalized groups, and improving both neighbourhood perception and overall quality of life [1,2,3]. In some countries, these commitments are integrated into national and local development policies, urban strategies, and planning frameworks [2], while in others, the lack of their operationalization leads to various social, cultural, economic, and physical issues and disparities in multi-family neighbourhoods [3].

To assess the potential of SCS in planning and project activities related to POS within multi-family neighbourhoods, and to define guidelines for the sustainable development of POS, this research aims to investigate the following:

a) the general characteristics of SCS and their application in development activities concerning the reclamation of POS in multi-family neighbourhoods, with a focus on the following SCS aspects: 1) satisfaction with living conditions and neighbourhood perception; 2) socio-economic status of residents; and 3) residents' engagement and participation in (re)claiming POS; and

b) institutional, planning, and design approaches to SCS aimed at (re)integrating POS at the neighbourhood level.

The general characteristics of the selected aspects of SCS are grounded in an analysis of literature in the field, while institutional, planning, and design approaches are drawn from an analysis of best practices in the neighbourhoods of Drewitz (Potsdam) and Poptahof (Delft), serving as illustrative examples of applied SCS.

In line with the research focus, the paper is structured as follows: after presenting the methodology, the theoretical framework is examined, along with selected examples of best practices for the chosen aspects of SCS. The potential for their implementation is discussed, and the paper concludes with key findings and recommendations for the sustainable development of POS in multi-family neighbourhoods.

2. METHODOLOGY

The main method used in the paper is documentary analysis of both primary and secondary sources (including legislation, regulatory documents, strategies, plans, projects, grey literature, and scholarly articles), as well as chosen best practice related to SCS. The list of primary and secondary sources is provided in Section 8. Citing References.

3. SOCIAL AND CULTURAL SOLUTIONS FOR RECLAIMING POS IN MULTI-FAMILY NEIGHBOURHOODS: FRAMING THE CONTEXT

In this section of the paper, the following are examined: 1) relevant literature in the field related to the selected aspects of SCS, and 2) relevant best practice examples that illustrate the potential and significance of applying these aspects.

3.1. Social and cultural solutios: Analysis of literature in the field

One of the longest-standing debates in community development, including SCS implementation, is between 'place-based' and 'people-based' approaches. These approaches are applied in the context of various development and planning activities such as housing affordability, combating community decline, and poverty. Pugalis & Bentley [4] highlight that 'place-based' strategies are not a unified model, but a range of approaches that depend on local context and needs.

The question of whether to focus on distressed places (neighborhoods) or distressed people is complex. Crane [5] explores the strengths and weaknesses of both, noting that 'people-based' policies address individual needs, while 'place-based' approaches may better target areas/neighbourhoods with concentrated problems. The challenge is determining which approach is more effective for long-term change and how both can be combined for sustainable development. Bentley & Pugalis [6] argue that the debate overlooks the dual nature of community development, advocating for the integration of human needs into development strategies to achieve more successful and lasting transformations.

- **SCS aspect 1: Satisfaction with living conditions and neighbourhood perception**

While the living environment influences well-being and quality of life, both the physical characteristics of space and how individuals perceive and experience it play a key role. Housing satisfaction is a subjective measure shaped by physical, social, and economic factors, and reflects the degree of alignment between individuals and their surroundings [7,8]. Satisfaction with living in a neighbourhood can thus be described as an individual and group assessment and perception of three neighbourhood categories - physical, social, and economic [9,10,11,8], though some authors also include a symbolic dimension.

The social characteristics of a neighbourhood include the ability to interact with neighbours, a sense of belonging, perception of privacy and security, etc. [12], where POS plays a significant role. Analyses of certain implemented urban regeneration projects in multi-family residential neighbourhoods [7] indicate that negative outcomes can arise after the implementation of such projects if little attention is paid to the social needs of residents during the design phase. The most common negative outcomes are: 1) absence of identity and connection with the space, 2) the space not providing a sense of harmony with the social and cultural status of the residents, 3) poor environmental quality of the space, 4) dissatisfaction with the neighbourhood, and a lack of residents' willingness to engage in the care of the area due to its unfavorable "new" physical characteristics [7]. These consequences also apply to POS. In some cases, the project may even lead to greater insecurity, higher migration rates, and social and spatial segregation compared to the pre-regeneration situation.

- **SCS aspect 2: Socio-economic status of residents**

Empirical evidence suggests that the reclamation and enhancement of POS, both within the context of urban regeneration of multi-family neighbourhoods and in newly developed housing areas, can generate a variety of socio-economic benefits. The most notable among these are:

1. An increase in property values, attributable to improved environmental quality and altered perceptions of the neighbourhood following project implementation. The value of real estate tends to correlate with the quality of the surrounding environment [13], which is significantly influenced by the character and design of POS. Numerous examples of good practice [8] demonstrate that regeneration efforts which prioritize the preservation and enhancement of existing physical characteristics, particularly through the application of Nature-based Solutions (NbS) and innovative stormwater management systems (e.g., Sustainable Drainage Systems – SuDS), yield more pronounced economic benefits in terms of property value appreciation [8,9].
2. Employment generation, particularly when regeneration or development initiatives involve changes in the functional composition of the area, such as the introduction of mixed-use development strategies [9].

Furthermore, research identifies the following as key economic determinants of neighbourhood quality of life and resident satisfaction:1) real estate value; 2) cost of living within the community, and 3) the socio-economic status of the neighbourhood.

- **SCS aspect 3: Social inclusion of residents**

Creating inclusive and diverse communities within multi-family housing requires intentional action and thoughtful planning. By embracing diversity from the outset, designing with inclusivity in mind, implementing non-discriminatory policies, and engaging with the local community, stakeholders can foster environments that promote a sense of belonging for all residents. Based on the literature review, opportunities for promoting resident inclusion in multi-family housing can be identified at five key stages: planning, design, construction, operation, and renewal of multi-storey neighbourhoods [8, 9]. Key recommendations for achieving social inclusion in both existing and newly developed multi-family neighbourhoods are presented in Table 1.

Table 1. Key recommendations for achieving social inclusion in multi-family neighbourhoods.

Recommendation	
Embrace diversity from the start	In planning new multi-family developments or urban regeneration projects, prioritizing diversity from the outset is essential. This includes understanding the demographic and socio-economic characteristics of target groups through market research, enabling the design of POS to meet the needs of various age groups, cultures, and lifestyles.
Design with inclusivity in mind	Design is a key factor in fostering inclusivity, with universal design principles ensuring accessibility for individuals of all abilities—for instance, POS without architectural barriers or visual aids for people with hearing impairments.
Fostering a sense of belonging	Fostering an inclusive and diverse community requires creating a sense of belonging through shared spaces and activities that promote social interaction, such as gardens, community rooms, and regular events.
Implement non-discriminatory policies	Ensuring inclusivity also depends on the implementation of clear, non-discriminatory policies that protect all residents regardless of race, gender, age, or health condition.
Inclusion in the local community and participation of residents	Active participation of residents, local communities, and stakeholders through partnerships is essential for the successful realization of inclusive planning and development initiatives

- **SCS aspect 4: Residents engagement and participation**

The core of the participatory approach lies in enhancing the capacity of communities to take part in development and planning processes, enabling specific target groups to actively contribute to planned activities and thus support sustainable development. Leipzig Charter on Sustainable European Cities [14], emphasizes the importance of public participation in planning, advocating for the active involvement of residents and urban space users in the formulation of urban policy and planning. This integral and participatory approach is recognized as a central paradigm in current strategic frameworks, including the UN New Urban Agenda [15], and the Urban Agenda for the EU [16].

Resident participation is often a key factor—and an essential condition—for the success of various programs and planning or design activities (whether place-, people-, or institution-based), including those related to POS. In this context, community participation is seen not only as a prerequisite for the acceptance of proposed planning and design solutions [9], but also for the ongoing care and maintenance of POS in both urban regeneration and new residential developments.

For participation to be truly effective, it is essential to establish clear ground rules, define specific goals, and avoid treating the process as a mere formality. In practice, a wide range of tools is available to help local government representatives, planning, and design teams develop and implement meaningful community participation strategies that include both formal and informal groups [17]. Local institutions and stakeholders, including urban planners and project teams, can employ various methods and techniques for communication and consultation with the public and neighbourhood residents throughout the participatory process of POS planning and design (Table 2).

Table 2. Techniques and tools for citizen participation

Purpose	Techniques for participation
Preliminary understanding of the situation	Interviews with key actors Stakeholder survey analysis
Opinion polling	Questionnaire Group interview Target group survey
Promoting participation	Event (symposium, observation, festival, concert, fair) List of addresses Formulation of corporate identity
Dialogue	Information and data collection Open dialogue Workshop Working group
Dissemination, understanding of opinion	Information materials for public relations (brochures, flyers, catalogues) Open lines for comments and suggestions Website Media Information center

Source: Horita and Koizumi, 2009.

Resident participation is a particularly critical factor for the success of planning and design in urban regeneration projects, as these activities take place within an existing, physically defined environment [18]. This context imposes limitations on the spatial distribution and applicability of design solutions related to POS, which can ultimately influence how users perceive the justification—or lack thereof—of the proposed interventions. Ongoing communication, education, and meaningful community involvement can ensure that POS

reclamation projects address residents' concerns, attitudes, and needs, thereby increasing acceptance among the local population.

3.2. Social and cultural solutions: Best practice examples

3.2.1. Drewitz, Potsdam

Drewitz is the youngest of ten multi-family neighbourhoods constructed on the outskirts of Potsdam during the former GDR era (1950s–1989), featuring 4,500 prefabricated apartments arranged in five-story panel buildings around large inner courtyards [19]. Like similar neighbourhoods, Drewitz experienced gradual deterioration of both its housing stock and POS, which, combined with socio-economic challenges and high unemployment, made regeneration a priority.

Following the political changes of the early 1990s, the federal and state Programme for Urban Development of Large Housing Estates (*Städtebauliche Weiterentwicklung großer Neubaugebiete*) was launched in 1997. In addition to housing renovation, the programme also addressed the renewal of numerous POS such as squares and courtyards. Recognizing the importance of resident-oriented development, early community participation was emphasized. Information sessions and workshops organized by district management enabled residents to contribute their ideas and fostered a stronger connection to their neighbourhood. For instance, involving children and youth in designing recreational areas was seen as a strategy to reduce vandalism (Figure 1).

The improved image of “Platte” neighbourhoods and the continued involvement of local stakeholders reflect the success of this participatory approach. Today, residents' committees actively support urban development initiatives in nearly all renewal areas—such as the “Initiative Am Schlaatz,” project advisory boards in *Waldstadt II*, and citizen forums at *Am Stern*. In 2006, advisory boards were established for the districts of *Am Stern/Drewitz/Kirchsteigfeld* and *Schlaatz/Waldstadt I and* II, comprising representatives from political parties, citizen groups, the housing sector, external experts, and urban development coordinators [19].



The exhibition "Potsdamer Platte" as a participatory tool for realization of wider public discussion and citizen’s involvement

Residents participate in the planning of the Drewitz residential area



Figure 1. Different forms of participation of residents in Drewitz, Potsdam. Source: Potsdamer Platte…im grunen Bereich, 2008.

One of the projects realized in this way was a pilot initiative for the regeneration and redesign of the inner courtyard between *Robert-Baberske-Straße* and *Eduard-Winterstein-Straße* in Drewitz (Figure 2). Implemented between 2002 and 2005, the project covered an area of approximately 5,000 m². Led by the urban development agency *Stadtkontor*, the project followed a participatory approach, with residents of the surrounding buildings actively involved in all phases of design and implementation.



Residents were involved in the entire process of (re)designing and renovating the inner courtyard. Rainwater is channelled from the roofs of the surrounding buildings through open gutters into bioretention areas. In addition to managing rainwater runoff, the bioretention system has contributed to increased biodiversity and a reduction in the urban heat island effect, while also creating an aesthetically appealing and comfortable POS. The design of the newly created children's playground reflects the theme of water and nature, with equipment stylized in the form of reeds.

Figure 2. Inner courtyard Robert-Baberske-Straße/Eduard-Winterstein-Straße, Drewitz, Potsdam, Germany. Pilot project of POS regeneration funded by the "Social City" fund, based on the application of participatory approach, SuDS and NbS. Source: Straube Peer, ed., 2008.

Guided by the belief that the urban environment should include as much greenery and natural elements as possible, residents selected “water” as the central theme, enabling the implementation of Nature-based Solutions (NbS) and innovative stormwater management approaches—not only in this project, but also in subsequent POS regeneration initiatives [8, 19]. This project became both an inspiration and a model for many similar efforts in Drewitz, which is now known as the “garden city.

3.2.1. Poptahof, Delft

Poptahof is a multi-family neighbourhood located in central Delft, built in the 1960s as one of the first developments outside the historic city centre. Covering 18.6 hectares, it is home to approximately 2,800 residents. Over time, the neighbourhood became marked by multiple forms of deprivation, cultural diversity without cohesion, and neglected, anonymous POS. Challenges included a high concentration of minority groups, lack of social cohesion, and degraded, mono-functional POS that lacked hygiene, equipment, and appeal—leading to insecurity, a weak sense of community, and user-unfriendly spaces, as seen in many post-WWII housing areas [9,20].

In response, the Delft municipal government and housing association Woonbron launched a restructuring initiative in 2000, aiming to make Poptahof a more livable and attractive place. A Master Plan was introduced and, in 2002, presented to residents through public events. Based on their feedback, the plan was revised in 2003 to address key issues: improving the monotonous housing stock (which was poorly rated on the market), enhancing safety (e.g., by introducing caretakers), and redesigning and upgrading POS as part of an integrated neighbourhood renewal strategy (Figure 3) [21].

The regeneration of POS in Poptahof was initiated by the housing corporation, but final decisions were made by residents, who opted for a mixed-use concept. The most significant outcome was the creation of the 25,000 m² multipurpose Poptapark (Figure 3), developed as part of the IMAGE12 project. Residents also advocated for a public vegetable garden and a children’s playground. A key factor in the project's success was the establishment of a public-private partnership to jointly improve the neighbourhood, along with the introduction of "neighbourhood branding" in 2005, which helped shape activity planning, social and economic programs, and identify future residents’ needs [9].



Master plan | Poptapark | Segments of Poptapark

Poptapark was designed in the central part of the LHE area and completed in 2008, on the site of a former river corridor surrounded by dense greenery. The park includes a children's play area, open lawns, and a green hill used for sunbathing, sledding, festivals, and other events. A cycling and walking path connects the park with the main street and shopping area. In addition, a community gardening space encourages social interaction and a sense of territorial belonging. To celebrate the transformation and promote the value of improved public open spaces, the "Poptahof Metamorphosis" festival was held in the park.

Figure 3: Multifunctional Poptapark
Source: van AltenaVanessa al., 2007.

It was recognized that the central park had strong potential to enhance the quality of life in Poptahof and establish a distinct residential identity. In 2009, a year-long research project on POS improvement was launched, focusing on differentiation, redesign, and beautification. The objectives included: 1) mapping different types of POS; 2) identifying parameters that support social interaction; and 3) encouraging collaboration between professionals and residents. Data were collected through field observation, mini-interviews with residents, and passer-by surveys.

The research was conducted in three phases - first, analysis of different POS types, their features, and user activities; second, interviews on usage patterns, problems, and improvement needs; and third, surveys examining daily use (frequency, companions, activities), perceived qualities, and design suggestions—particularly regarding functionality, safety, and programming (Figure 4).

The main success factors were: 1) resident participation, which fostered ownership and responsibility for the housing environment; 2) cultural openness and acceptance of diverse lifestyles; 3) spatial variety, enabling formal and informal gathering spaces across different POS types; and 4) active monitoring to prevent crime and vandalism. Ultimately, the park's regeneration modernized the image of the entire residential complex and helped attract additional investment in mixed-use (residential and commercial) developments.



Residents participation in the preparation of the Master plan proposal | Project organization information day - dialogue between residents and the project manager | Workshop sessions held to explore the identity of Poptahof

Figure 4: Different forms of participation of residents in Poptahof
Source: van AltenaVanessa al., 2007.

Besides all the above, the regeneration of POS is also significant as an example of the application of green-blue infrastructure. In this context, by creating visible water features (including a water playground), based on the winning idea from a children's competition as a way of involving the local community in the design process, the area has become more engaging and enjoyable for residents [22]. Disconnecting impervious surfaces from the water system enhances flood resilience and sustainability. Furthermore, the participation of children means that they became partly responsible for the newly created water features, which helps prevent vandalism. The natural treatment systems and wetlands also provide opportunities for ecological development, educational programs, and recreational use, adding value beyond water management.

This holistic approach not only enhances the urban landscape but also addresses critical environmental challenges such as water management, sustainability, and climate resilience. By combining water-saving technology, natural water treatment, and community-oriented green spaces, the project in Poptahof sets a valuable example of how urban planning can balance ecological health with social and recreational needs

4. DISCUSSION

The conducted research, especially the analysis of best practice examples, indicates that the SCS aimed at reclaiming POS within multi-family neighborhoods are mostly spatially concentrated, whether referring to an entire neighborhood (Poptapark) or one or several urban blocks (Drewitz). In this sense, it can be concluded that place-based SCS, as well as the planning and project activities leading to POS reclamation, are more prevalent, which is particularly characteristic of urban regeneration in inherited neighborhoods. These neighborhoods are often characterized by low incomes, high social service demands, deteriorating housing stock, high unemployment rates, social exclusion, etc. They also suffer from inadequate infrastructure, public services, POS, failing schools, and a lack of jobs matching the residents' skills. It seems that the most direct step to help these communities is to preserve these places, including POS, which is the main focus of urban regeneration projects, as well as most social and economic development programs and plans.

Additionally, the research indicates that SCS can be implemented in two ways: 1) as primary, i.e. as a need (when the focus of program and project activities is on social problems and needs, with the increase in the usability, design, and ecological potential of POS being seen as a key factor in addressing these issues); and 2) as secondary, i.e. as an opportunity (when they appear as additional benefits of programs and project activities aimed at creating or improving the physical, functional, and ecological characteristics of the neighborhood or POS).

Although the analysis of best practice examples focused on civic engagement and citizens' participation, the research findings also highlight a wide range of benefits from implementing SCS in reclaiming POS. The most important benefits include: 1) satisfaction with housing and living conditions; 2) positive changes in the perception of the neighborhood; 3) improvement in the socio-economic status of residents; 4) reduction of social inequality; and 5) social inclusion.

A review of the literature and analysis of best practice examples also indicate that creating inclusive and diverse communities within multi-family housing requires intentional actions and thoughtful planning and design. The following key recommendations for achieving social

inclusion in multi-family housing and the POS within them can be identified: 1) embrace diversity from the outset; 2) design with inclusivity in mind; 3) foster a sense of belonging; 4) implement non-discriminatory policies; and 5) involve local communities and enable resident participation.

Based on the literature review, opportunities for resident engagement and participation are recognized at five stages: planning, design, construction, operation, and renewal. Active engagement of the local community, stakeholders, and residents through various forms of partnership and cooperation were recognized in the analyzed best practice examples as important factors for the successful implementation of program and project activities.

The analysis of selected best practice examples highlighted various forms of resident participation in the operationalization of social and cultural solutions in restoring POS in multi-family neighborhoods. The analysis also emphasized the benefits of participation-based programs or planning activities for the quality of POS, strengthening social interactions, neighborhood identity, and the overall quality of life in the neighborhood. Research findings indicate that by combining NbS, SUDS, UGI, and other eco-oriented urban approaches with social and cultural solutions, the analyzed examples demonstrate how urban planning and design can balance ecological health with social and recreational needs.

5. CONCLUSION

SCS play a significant role in reclaiming POS in multi-family residential neighborhoods, both inherited and newly planned. The purpose of their implementation through strategic documents, urban planning, and urban regeneration varies — they may be applied either as primary activities (a need) or as part of broader actions (an opportunity) aimed at sustainable urban development or neighborhood regeneration, where they are recognized as predominantly place-based.

The most important goals and benefits of applying SCS in both cases are: 1) satisfaction with housing and living conditions; 2) a positive change in the perception of the neighborhood; 3) improvement of the socio-economic status of residents; 4) reduction of social inequality; 5) increased social inclusion; and 6) community engagement.

Resident participation is often a key factor and imperative for the success of programs, planning, and design activities that help realize the aforementioned goals and benefits. In this sense, community participation strategies are seen as a prerequisite not only for the acceptance of proposed planning and design solutions but also for the ongoing maintenance and care of the POS.

Some key recommendations for achieving social inclusion in multi-family neighborhoods include: 1) embracing diversity from the outset; 2) designing with inclusivity in mind; 3) fostering a sense of belonging; 4) implementing non-discriminatory policies; and 5) involving local communities and enabling resident participation.

When SCS are applied in synergy with ecologically based approaches such as Nature-based Solutions (NbS), Ecosystem-based Adaptation (EbA), Urban Green Infrastructure (UGI), Blue-green Infrastructure (BGI), Water Sensitive Urban Design (WSUD), and Sustainable Drainage Systems (SuDS), the benefits are even wider. In this case, they can include enhancing the resilience of neighborhoods to climate change, increasing the social resilience of neighborhoods, and supporting their sustainable urban development.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025. and by the Science Fund of the Republic of Serbia, #GRANT No 7572, Reclaiming Public Open in Residential Areas: Shifting Planning Paradigms and Design Perspectives for a Resilient Urban Future – RePOS.

REFERENCES

[1] UN-Habitat: **Global Public Space Toolkit: From Global Principles to Local Policies,** 2015, https://unhabitat.org/global-public-space-toolkit-from-global-principles-to-local-policies-and-practice

[2] Carmona Matthew: **Contemporary public space: Critique and classification, Part One: Critique.** *Journal of Urban Design*, Vol.15, No.1, 123–148, 2010, https://doi.org/10.1080/13574800903435651

[3] Low Setha, Taplin Dana, Scheld Suzanne: **Rethinking Urban Parks: Public Space and Cultural Diversity.** *University of Texas Press*, Austin, 2005.

[4] Pugalis Lee, Bentley Gill: **Place-based development strategies: Possibilities, dilemmas and ongoing debates**, *Local Economy*, Vol.29, No. 4-5, 271–287, 2014, https://doi.org/10.1177/0269094214541617

[5] Crane Randall, Michael Manville: **People or place. Revisiting the who versus the where of urban development**. *Land Lines*, Vol.20, No.3, 2-7, 2008, https://ds4ps.org/cpp-528-fall-2020/articles/revitalization/people-or-place-revisiting-the-debate.pdf

[6] Bentley Gill, Pugalis Lee: **Shifting paradigms: People-centred models, active regional development, space-blind policies and place-based approaches**, *Local Economy,* Vol.29, No. 4-5, 288–303, 2014,

[7] Hani Razavi Fard, Shilan Gharanfoli: **Impact of Urban Regeneration on Housing Satisfaction: A comparative study in Iran and Turkey**. *Tafter Journal*, Vol. 107, 2019, https://www.tafterjournal.it/impact-of-urban-regeneration-on-housing-satisfaction-a-comparative-study-in-iran-and-turkey/

[8] Slavković Magdalena: **Urbanistički modeli primene integrisanih pristupa upravljanju kišnim oticajem u finkciji održive regeneracije i planiranja područja višeporodičnog stanovanja**. Doctoral dissertation. *Građevinsko-arhitektonski fakultet Univerziteta u Nišu*, Niš, 2024.

[9] Bogdanović Protić Ivana: **Definisanje modela revitalizacije slobodnih prostora kompleksa sa višespratnim stanovanjem u funkciji unapređenja kvaliteta života**. Doctoral disertation. *Građevinsko-arhitektonski fakultet Univerziteta u Nišu*, Niš, 2016.

[10] Brown Barbar, Douglas D. Perkins, Graham Brown: **Place attachment in a revitalizing neighborhood: individual and block levels of analysis.** *Journal of Environmental Psychology*, Vol. 23, No.3, 259-271, 2003, https://doi.org/10.1016/S0272-4944(02)00117-2

[11] Lansing John, Robert Marans: **Evaluation of neighborhood quality.** *Journal of the American Institute of Planners*, Vol. 35, No. 3, 195-199, 1969.

[12] Weidemann Sue Anderson James: **A conceptual framework for residential satisfaction**. *Home environments*. Boston, MA: Springer US, 153-182, 1985.

[13] Uitermark Justus, Maarten Loopmans: **Urban Renewal without Displacement? Belgium's Housing Contract Experiment and the Risks of Gentrification**. *Journal of Housing and the Built Environment*, 28, Vol 1,157-166, 2013, doi.org/10.1007/s10901-012-9299-0, hdl.handle.net/1765/39739

[14] European Union: **Leipzig Charter on Sustainable European Cities. Informal Ministerial Meeting on Urban Development and Territorial Cohesion,** 2007, https://ec.europa.eu/regional_policy/archive/themes/urban/leipzig_charter.pdf, accesed on May 4th 2025.

[15] UN Habitat, United Nations Human Settlement Program: **The New Urban Agenda,** ISBN: 978-92-1-132731-1, 2017, https://habitat3.org/wp-content/uploads/NUA-English.pdf, accesed on May 4th 2025.

[16] European Commission: **Urban Agenda for the EU – Pact of Amsterdam.** Futurium, 2016, https://ec.europa.eu/futurium/en/urban-agenda, accesed on May 4th 2025.

[17] Horita Masahide, Hideki Koizumi: **Inovations in Collaborative Urban Regeneration**. *Springer Science & Business Media*, 2009.

[18] Bogdanović Protić Ivana, Mitković Petar, Vasilevska Ljiljana: **Toward regeneration of public open spaces within large housing estates–A case study of Niš, Serbia.** *Sustainability*, Vol. 12, No.24, 10256, 2020, https://doi.org/10.3390/su122410256

[19] Straube Peer, ed.: **Stadtkontor GmbH Potsdam, Potsdamer Platte... im grünen Bereich: zur Entstehungsgeschichte, Weiterentwicklung und den Perspektiven der Potsdamer Wohngebiete der 60er bis 80er Jahre**, 2008, https://www.stadtkontor.de/wp-content/uploads/2013/04/PotsdamerPlatte.pdf, accesed on March 15th 2025.

[20] Bogdanović Protić Ivana, Dinić Branković Milena, Igić Milica, Ljubenović Milica, Mitković Mihailo: **Modalities of tenants participation in the revitalization of open spaces in complexes with high-rise housing**. *Facta universitatis-series: Architecture and Civil Engineering*, Vol.16, No.2, 203-211, 2018, https://doi.org/10.2298/FUACE171218003B

[21] van AltenaVanessa, José Meijboom, Wessel Tiessens. **The image project new tools for neighbourhood regeneration**, *City of Delft,* 2007.

[22] https://urbangreenbluegrids.com/projects/poptahof-delft-the-netherlands, accesed on March 23rd 2025.

doi.org/10.62683/SINARG2025.010

Review paper

STRUCTURAL AND ARCHITECTURAL TRENDS OF CONTEMPORARY CONSTRUCTION IN COUNTRIES WITH DIFFERENT CLIMATIC ZONES: REVIEW STATE OF THE ART

Hamed Afsoosbiria[1], Darja Kubečková[2]

Abstract

The article focuses on the structural and architectural design of buildings for civic amenities in the city, considering different climatic zones, and maps the current construction in the context of sustainability principles. Construction trends show that society aims to focus on modern construction technologies while applying a comprehensive building design in combination with an appropriate material solution. A meaningful combination of building design, technologies, and material solutions is a motivational tool for contemporary society. The article aims to present new construction trends in selected countries with different climatic zones, based on the State of the Art, and to compare selected aspects of this construction, which then leads to the definition of functional connections creating a common segment for the future of modern construction. Using the example of Iran in Western Asia, a subtropical country with a pronounced continentality, and the example of Europe, which is characterized by three climatic zones, we demonstrate the construction and architectural trends of contemporary construction by describing them. The results show that the countries studied are oriented towards sustainability, the use of new materials and technologies, and emphasize the environmental aspect.

Key words: *Continent, Climate, Construction, Sustainability.*

[1] MSc. Hamed Afsoosbiria, Doctoral study, VSB-TU Ostrava, Faculty of Civil Engineering, e-mail: hamed.afsoosbiria@vsb.cz, Czech Republic, ORCID: 0000-0002-7210-6379.
[2] Prof. Darja Kubečková, Ph.D., professor, VSB-TU Ostrava, Faculty of Civil Engineering, e-mail: darja.kubeckova@vsb.cz, Czech Republic, ORCID: 0000-0001-9664-6129.

1. INTRODUCTION

The construction industry plays a critical role in the economic development of nations, significantly impacting overall growth, infrastructure, and quality of life [1]. Historically a focal point of societal interest, the sector is undergoing rapid transformation driven by advancements in technologies, structural solutions, and material sciences, which align with increasing emphasis on sustainability, energy efficiency, and the circular economy. The adoption of advanced construction technologies delivers numerous benefits, including long-term cost savings, enhanced precision, improved performance, and faster project timelines. These innovations encompass breakthroughs in materials science, architectural design, structural analysis, cost estimation, facilities management, and management studies, collectively reshaping the industry. By integrating these innovative methodologies and technologies, the construction sector is advancing to meet the evolving demands of modern society while promoting sustainable and efficient practices.

The global population, now approximately 7 billion, has grown dramatically over the years, creating an urgent need for new cities to accommodate this expansion. Advancements in industries such as construction, education, and healthcare have enhanced modern lifestyles, making them more dynamic and appealing [2]. As Maslow's "Hierarchy of Needs" suggests, shelter is a fundamental necessity, forming the basis for fulfilling higher-level needs and underscoring the indispensable role of construction in society [3]. Infrastructure, which relies heavily on the construction industry, is vital for a modern economy, as it facilitates economic activities and societal development. Governments worldwide are increasingly focused on developing cities with comprehensive facilities to ensure the well-being of their populations. However, rapid population growth poses significant challenges, particularly in underdeveloped countries, where issues such as inadequate planning, financial constraints, time pressures, and limited access to construction technologies hinder the effective creation of sustainable urban spaces.

Over the years, researchers have published numerous articles on advanced construction technology, smart construction materials, and modern construction methods, contributing to the ongoing development of the field. Ghodawa (2022) explored smart construction materials and advanced construction techniques, offering an overview of the available materials and shedding light on innovative methods and techniques that are poised to drive progress and improvement within the construction industry [4]. Similarly, Kawahata and Murayama (2011) examined advanced construction technologies in the context of Nuclear Power Plant (NPP) projects, particularly focusing on the exceptional construction technology implemented by Hitachi, the main contractor responsible for the entire plant. Their study highlighted how these technologies led to a 25% reduction in peak workload at construction sites through improvements in construction procedures in areas with dense activity. The strategies they employed included: the broader application of large module/block construction methods, open-top and parallel construction methods, the application of floor packaging construction methods, and the full integration of information technology to enhance quality in plant engineering and construction achievements [5].

In 2023, Abdilah et al. conducted a study on the analysis of new advanced technologies and their adaptation within the context of civil engineering construction in Bangladesh. Their research reveals that while Bangladesh has historically embraced advanced construction methods, dating back to the 19th and 20th centuries, the country has not sufficiently developed its environment by fully leveraging these technologies [6]. Additionally, Krupík

(2021) provided an in-depth exploration of advanced building materials, as well as prefabricated and modular designs, as key components of Construction 4.0, with a specific focus on transport construction [7].

The European Union's strategic targets for 2030 and 2050 imply that energy action, CO2 reduction, climate neutrality, and emphasis on the Green Deal strongly highlight the construction industry [8, 9]. This article examines developmental innovations in Europe and Iran that promote sustainability within the construction industry. The analyzed data, along with the findings from a narrative review, are used to assess the current situation and pinpoint the key factors affecting the development sectors in both Europe and Iran.

Europe and Iran are located in different climatic conditions. However, even here it turns out that the structural and architectural approach to modern construction trends has the same basis, which is a highly modern, energy-efficient building that is sustainable and has a positive contribution to circularity.

2. MODERN METHODS OF CONSTRUCTION (MMC): CURRENT APPLICATIONS

Modern Methods of Construction (MMC) is an expression that emphasizes the use of novel building materials, advanced types of equipment, and developed techniques to construct. This technic has been approved by many industries around the world because it suggests a wide range of benefits to builders and consumers. Based on the CIF [10] definition, ''Modern Methods of Construction (MMC) is a term used to cover a range of offsite manufacturing and onsite techniques that provide alternative approaches to traditional construction. Modern construction methods include the following:

- Modern materials
- Modular construction
- Volumetric system,
- Hybrid system (semi-volumetric system)
- Pods
- LSF structures (modular frames)
- Precast construction system
- Sub-assemblies and Component
- Cite-Based
- Mivan Formwork in Construction

Our research focuses on the interpretation of aspects of structural and architectural creation that lead to innovative approaches. The discourse of contemporary creation is significantly influenced by environmental aspects that positively affect the world architectural events, both theoretically and practically. Using the description method, we observe new methods of building design and architectural strategies. The paradigm of innovative creation influences the construction and architectural sector, accelerating the pressure on sustainability. If we observe architectural creation and structural strategies in different climatic zones of the country, the identity of the approach to strengthening sustainability is evident.

Advanced building materials refer to innovative and high-performance building materials that improve durability, strength, insulation, energy efficiency, and sustainability in

comparison with traditional building materials. Modern materials are designed to meet the needs of modern construction projects, such as skyscrapers, buildings, bridges, tunnels, and infrastructure developments. Aiming to improve the safety, cost-effectiveness, and environmental impact of construction [11]. Modular construction is a construction method that increases the efficiency and effectiveness of construction using conventional methods with modern mass production procedures [12]. The volumetric methods are also known as Modular construction. In this system, three-dimensional units are made in a factory and then transported to the site for assembly; about 85-90% of the process is done in the factory [13].

Figure 1 shows a mind map that presents a proposed classification framework for modern materials used in MMC. This classification encloses key properties, including sustainable materials, innovative construction materials, smart materials, recycled and low-carbon materials, and high-performance materials. These materials are typically lightweight, durable, and appropriate for prefabrication and modular construction. They consist of precast concrete, advanced composites, engineered timber, high-strength steel, and environmentally friendly alternatives like recycled or low-carbon materials. Modern materials allow faster assembly, promote energy efficiency, and reduce environmental impact, making them necessary for the Methods of Construction (MMC).

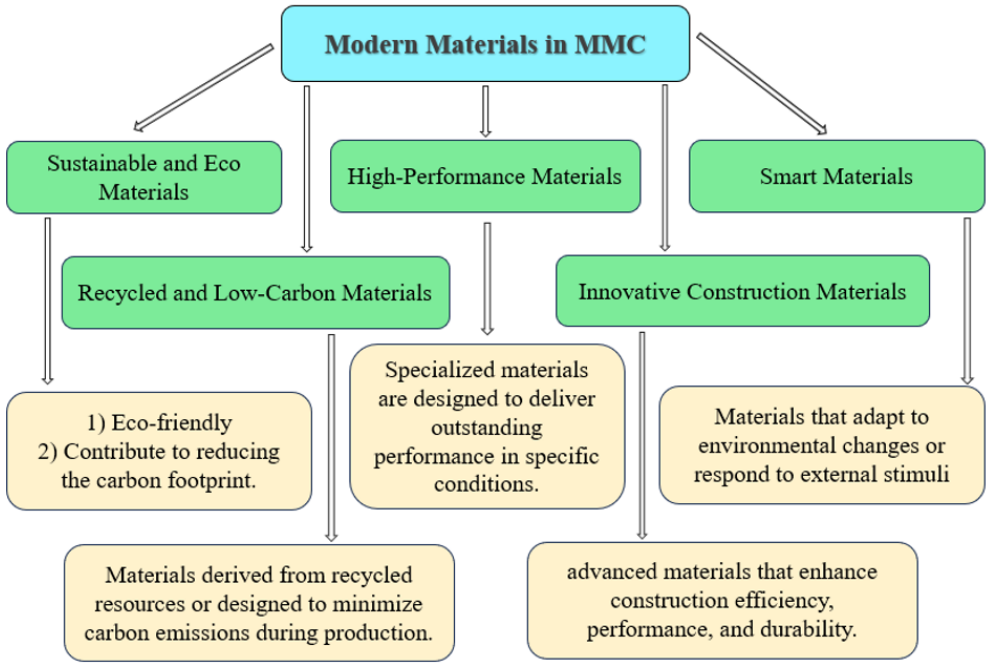


Figure 1. Mind map of modern material in MMC (source: author) [14].

Hybrid building system construction is known as the semi-volumetric method, and it is a building approach that uses both modular and prefabricated elements [15, 16]. The bespoke component assembly is demonstrated to be a real significant shift in the current way of the construction industry, and it has now entered the domain of equipment housing unit [17, 18, 19]. Prefabrication is a highly sought-after and progressive method for the current construction industry, contributing to faster construction, being financially efficient.

Nowadays, Lightweight metal frame structures (LSF) are included in one of the well-known types of walling systems and very ideal solutions for professional architects due to their modular structure in the construction industry. Modularization of buildings can be very essential for increasing the speed of construction management, reducing debris and waste of construction materials, cost savings, and its visual impact from an aesthetic point of view. Many studies have been conducted to present LSF wall systems as more effective and efficient in numerous aspects, like; financial consequences, sustainability, fire and energy performance, also structural performance [20, 21, 22]. In 2022, Rukavina et al. investigated the progress of lightweight steel-framed building systems for nearly-zero-energy buildings, and this article aimed to investigate state-of-the-art major components for such systems to be applied for utilization in nearly-zero-energy buildings [23]. Design and dimension a single-family residential project, using LSF profile dimensioning software was done by Vicente et al in 2023 [24]. Precast is a construction product manufactured using casting in a reusable form, which is then cured in a controlled environment, transported to the construction site, and lifted and set into place. Also, elements of precast buildings and various systems include these items: flat panel system, precast footings, beams, columns, slab, shear walls, partition walls, roofs, and floors, connection between precast elements, concrete foundation, cladding panels, etc. which are made from flat, pre-engineered panels and are assembled on site. panel systems can be separated into two principal classifications, open and closed systems. In open systems structural elements are taken to the site where the rest of the work is done on-site and in closed systems which are more complex different components like windows, doors, insulation, internal finishes, external cladding, etc. can be fitted in the factory [11, 25, 26, 27].



Figure 2. Precast concrete Twin Wall [28].

Figure 2 shows the Precast Concrete Twin Wall, which is a new technology that can be used as a cross-wall construction, and when combined with filigree slabs, a complete monolithic ‘‘paint-ready’’ structure is provided [28]. Sub-assemblies and components can be added to existing brick-and-mortar buildings or those built using other modern methods of construction [29]. Innovative approaches to construction are used on-site. They consist of thin joint blockwork and insulated formwork [17]. The progress in build quality achieved from the utilization of the Thin-Joint System includes: improved thermal performance, improved stability during construction, improved build accuracy of finished walls, and reduction of site wastage [30]. Mivan formwork is more likely to be used in Europe, Asia, the Gulf Countries,

and other parts of the globe. This innovative solution of work can be appropriate for building houses in large quantities in a short period, using room-size forms to construct walls and slabs in one constant pour of concrete [31, 32].

3. CONSTRUCTION METHODS IN IRAN

Iran has a subtropical climate with a pronounced continentality, while the south has a hot and dry tropical climate. Snowfall occurs in the northern regions of the country and the plateaus in the northwest. Current construction trends are modern, based on traditions, the use of modularity, and also eco-design.

Urban planning, using new technology, design, and architectural aspects in construction, is different from any part of Iran due to the climate, because there has been a noticeable change in seasons and different geographical regions. Another important thing about construction in Iran is the specific weight of the urban population in various zones of Iran. because the community is unevenly distributed, according to Ref. [33], only 30% of the area of land has a relatively sufficient amount of water to provide the inhabitants. Also, population growth in Iran stimulates the progress of construction and will require an increase in the number of housing units, as well as boosting their standard.

Being located in one of the most seismically active zones in the world, Iran has experienced many destructive 26 earthquakes throughout history [34]. Due to this fact, certain attention should be given to architectural and construction recommendations that have an impact on the design of houses in seismically hazardous regions. Apart from the requirements for the new dwellings, in Iran, 3.8 million residential buildings must be reinforced [35]. Achieving this goal using traditional construction methods alone seems almost impossible; traditional methods of construction have not been able to meet the current demand.

3.1. Elementary Construction System

These buildings were built in ancient times, their age reaches more than 200 years, and traditional locally available materials have been used. According to the diverse climate in Iran, the construction materials include brick, stone, wood, mud, and plaster, also their covering is made of brick arches or wooden beams, and vegetable fibers are used. Nowadays, these buildings are known as historical monuments in Iran, and governments should act to preserve these buildings because they can show every culture from all parts of Iran. Figure 3 shows Kolah Farangi Mansion and Masuleh, which are located in the north of Iran. Also, Figure 4 presents an ancient town in a region with a dry and hot climate in Yazd.

Kolah Farangi Mansion is a relic from the Qajar period. It offers eye-catching views, and it is one of the most prominent tourist attractions. This mansion consists of a four-story building. Numerous windows provide suitable lighting and ventilation in the hot seasons of the year. Additionally, it features a stunning summer building with a 360-degree balcony [36]. Both buildings are constructed with local materials. Figures 3 and 4 states that construction has been famous in Iran in the past, and builders according to existing facilities and materials consider details in designing so people who want to live in these places have a comfortable feeling, for example; in both construction, natural lighting, and ventilation were provided in the best way.



Figure 3. Typical House in a Temperate-Humid Climate; Kolah Farangi Mansion, Rasht, Iran [37].

Moreover, in dry and hot climates, a windcatcher or wind tower was used; this traditional architectural component was used to provide cross ventilation and passive cooling in the house. It comes in diverse designs, depending on whether local prevailing winds are unidirectional, bidirectional, or multidirectional, on how they alter with altitude, on the daily temperature cycle, on humidity, and on how much dust needs to be removed [37].



Figure 4. Typical House in a Dry and Hot Climate; Traditional Architecture in Abarkuh, Yazd, Iran (left), and Old Kharanagh village in Yazd, Iran (right) [38, 39].

3.2. Traditional Building System

Buildings with load-bearing brick walls are considered in this classification. Due to the load-bearing walls supporting the building's load, the thickness of the lower layer's walls is increased, which is one of the factors inhibiting the addition of layers or height. Earthquake damage can be lessened by creating actions like horizontal concrete barriers. The height of the building must not be more than 12 meters in this method.

The construction of several buildings in Rasht Square, including the municipal building shown in Figure 8, took place between 1907 and 1922 during the Pahlavi era. Additionally, it represents one of the Conventional Building Systems that remains functional in rural areas.



Figure 5. Modern Heritage in Rasht, Iran (Rasht Municipality Square) [40].

3.3. Advanced Construction

Structures with a steel and concrete frame are considered in this group. The most important equipment used in this type of construction is: concrete preparation machines, fixed and mobile cranes, electric hoists, scaffolds, welding machines, and paint spraying machines. Due to the use of concrete and steel frames, the number of floors and the height of the building can be predicted to be more than 50 floors and the speed of construction operations can be increased to a great extent by using mechanical and electrical equipment.

3.4. Industrialized Building System (IBS)

An industrialized building system (IBS) is a construction approach with centralized practices that comprise techniques, products, and a set of linked elements that proceed concertedly to achieve objectives [41]. IBS can cause MMC in the construction industry.

This technique has been recognized as a suitable method for developing overall construction performance in terms of quality, cost, safety and health, waste reduction, and productivity [41]. IBS practices mainly develop techniques, products, modules, or building systems that incorporate prefabricated elements and on-site installation. In construction, there are five categories of IBS in what is described as the structural classification: precast concrete framing, panel and box systems, steel framing systems, prefabricated timber framing systems, and block/brickwork systems [42]. In 2019, a study about awareness and prevalence of IBS in Iran [43] was conducted applying the mean index and average ranking method. Prefabricated elements like steel formwork systems, prefabricated forms for walls, sandwich panels, permanent forms, prefabricated frames, load-bearing wall panels, ceiling and floor panels, and prefabricated forms for beams and columns were examined. The study expressed that one of the construction problems in Iran is that there is not enough IBS work experience among construction practitioners. According to this research, only 2% of respondents are fully informed about IBS, and approximately 95% of respondents do not have acceptable information about this construction method. The average index of prefabricated component prevalence in Iran is 2.72, and the sandwich panel is the most prevalent IBS component with a mean index of 3.42 [43]. In 2015, a questionnaire survey was conducted to recognize the risks and required measures for obtaining successful application of offsite construction in Iran. 300 questionnaires were distributed among Iranian architects working at consulting companies, which were selected randomly from registered architectural practices; about 100 returned, and 88 were reliable [44]. Table 1 shows that

100% of respondents in the study of Hashemi (2015) were very experienced designers or architects in comparison with the study of Taherkhani & Saleh (2019).

Table 1. General Information in references [43, 44].

Distribution of respondents' general information			
Profile		Taherkhani & Saleh (2019)	Hashemi (2015)
Gender	Male	64%	53%
	Female	36%	47%
Age	Min	24 years	20 years
	Max	60 years	50 years
Occupation	Employer	26%	0
	Contractor	26%	0
	Designer/Counselor	30%	100%
	Academics	19%	0
Work experience	Less than 10 years	76%	60%
	More than 10 years	24%	40%

The study by Hashemi (2015) illustrates that most Iranian architects (56%) are familiar with offsite techniques; nearly 100% of those who were experienced in offsite methods had used panel systems, and about 75% had not used any other systems by the panel system. As a result, except for the panel systems, in general, about 86% of Iranian architects are not experienced in any other offsite methods. In both studies, the panel system is the most prevalent IBS component in prefabricated systems in Iran.

3.5. Lightweight Steel Frame Construction

This construction methodology has received technical confirmation from the building and housing research center and has been officially introduced as one of the new construction technologies in Iran. In this regard, the Office of National Building Regulations prepared and published a regulation titled Industrial Design and Implementation of Buildings (Topics/Code 11) in 2003. According to this standard (Topics/Code 11), using LSF is only a gravity load-resisting system, up to 5 floors or 15 meters high. Also, other standards and books are published for designing and implementing Lightweight Steel Frames, such as standards (publication No.613, 612) and Guidelines for the design and implementation of light steel construction systems [45, 46, 47, 48].

Table 2. Comparison of Different Types of Construction

Construction Types	Construction Speed	Building Weight	Seismic Base Shear	Wasting Materials
Concrete Frame	195 days	318 ton	36 ton	150 kg/m^2
Steel Frame	180 days	210 ton	26 ton	100 kg/m^2
LSF	60 days	87 ton	16 ton	2 kg/m^2

Table 2 is a summary of Ref. [49], which shows the advantages of LSF building in comparison with other kinds of construction. The table illustrates that LSF, apart from building construction speed and less weight, can have suitable resistance against earthquakes.

Furthermore, this method yields less waste in comparison with other common methods of construction in Iran and leads to a more environmentally friendly method. Employing this system provides an economical dwelling for all walks of life.

3.6. Prevalence of Employing IBS in Various Construction

Since, Iran is a great source of oil and gas, marine structures such as offshore platforms and jackets have key roles in oil and gas extraction from the seabed. Because, these structures should be prepared in a short period because of their higher production of wealth, and they should be installed in the depth of the sea also the cost of construction in the sea is very high. As a result, offsite construction methods can be beneficial for these kinds of structures because of higher construction speed; enhanced health and safety; better quality; lower waste and energy consumption; enhanced control conditions; less weather dependence; improved value for money and cost predictability. Figure 13 shows IBS methods in the construction of marine structures in Iran, these structures are built in the factory, and even all equipment is installed on the platform, then after completion, should be carried with a vessel into position, furthermore using advanced cranes are placed in their position. Apart from marine structures and residential buildings, IBS methods have been used in other construction in Iran such as; commercial buildings, bridges, ports, dams, and transportation.

In 2015, an examination was conducted on the prevalence of utilizing prefabricated elements in different sorts of projects in Iran. As a consequence, the most prevalent project category that is implemented using IBS is related to marine structures with a mean index of 3.89 (RI=0.78), followed by bridges (3.32), ports (3.23), and airports (2.62). Continuing this movement, commercial and residential units by 2.13 (RI=0.43), transportation by 1.89 (RI=0.38), and lastly, dam projects by 1.74 (RI=0.35) mean index are at the lowest rate of using IBS implementation [43].

3.7. Reasons for the Failure of Modern Methods of Construction in Iran

From an engineering standpoint, architectural and construction factors such as improper thermal design, bad condition of the roof, uninsulated walls, unprincipled insulation of heating systems, cracks or seams in doors and windows, also lack of use of heating controllers bring about energy loss in the dwelling sector. As a result, reaching to Modern Method of Construction (MMC) is needed for advanced products and materials, since most residential houses are built by individuals' builders, one of the main barriers to extensive applications of MMC in Iran is the Higher prices of advanced materials products.

According to CABE (2004), the mean price of MMC in the United Kingdom is currently 8–15% greater compared to traditional practices [50]. Additionally, it is reported that similar materials and products could be up to four times more costly in Iran in comparison with other countries [51].

4. MODERN METHOD OF CONSTRUCTION IN EUROPE DUE TO ENVIRONMENTAL CONCERNS

Current trends in Europe show that the main modern direction in structural and architectural design is oriented towards construction and renovation, which place high demands on reducing energy consumption, sustainability, decarbonization, eco-design. Reducing the carbon footprint has become a priority for EU countries to achieve global environmental goals and ensure sustainability. The direction and strategy show that regardless of the climate zone of Europe, structural and architectural design in EU countries is fundamentally the same. This is despite the fact that the climate in Europe is a reflection of its location. The majority of Europe lies in the temperate zone, the south lies in the subtropical zone and the north in the subarctic zone (the farthest north is in the Arctic zone). This is a consequence of legislative and regulatory measures that are set the same for EU member states. Individual member states implement EU legislative regulations into their own legal regulations. Most countries in the world are preparing plans and implementing measures to deal with climate change. The European Union has ambitious objectives in this regard, and within the framework of the European Green Deal [52] and the European Climate Law [53], it has set a goal of lessening net domestic greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels and to become climate neutral by 2050 [54]. In consonance with the International Energy Agency, buildings account for 30-40% of energy consumption in Europe, with a supplement of 5 to 10% that is used in the processing and transportation of building components and products. This gives rise to one-third of CO_2 emissions in the area [55]. The building sector consumes approximately 40% of the total global energy. This sector is a remarkable carbon emitter as it requires large amounts of energy for building operations and maintenance, as well as for its notable material use and intensive onsite construction processes. Attitudes towards waste management have been changing in recent years, and simply following the principles of material handling on site has led to more efficient management of the construction process [56].

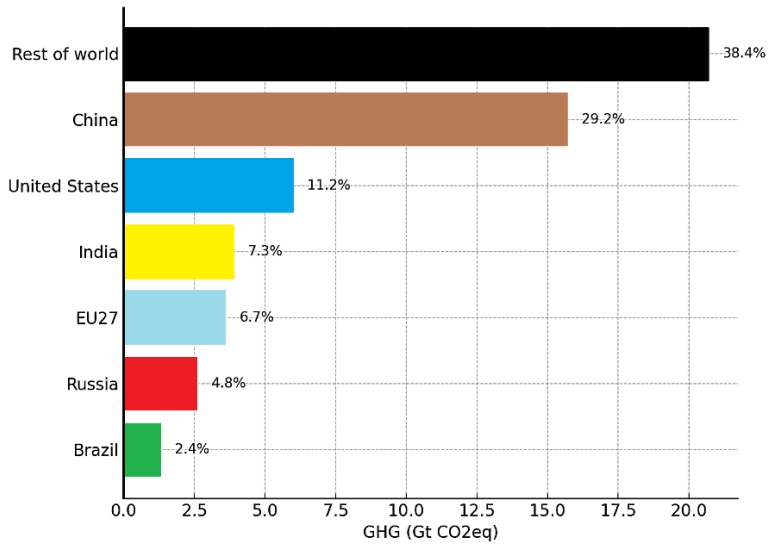


Figure 6. GHG Emissions and Contribution of the Major Emitting Economies and the Rest of the World in 2022 (figure elaborated based on [54]).

Offsite construction has been accepted as being able to address recurrent challenges like environmental sustainability, carbon, and waste through quality, process, and performance. furthermore, transitioning away from many of the obstacles usually associated with traditional construction, such as quality, cost, waste, energy, etc. [57]. In addition, the onsite construction industry and the manufacturing of construction materials also consume billions of tons of natural resources, while producing a large amount of non-recyclable waste [55]. China, the United States, India, the EU27, Russia, and Brazil were the world's six largest GHG emitters in 2022 (Figure 6). Overall, they account for 50.1% of the global population, 61.2% of global gross domestic product, 63.4% of global fossil fuel consumption, and 61.6% of global GHG emissions [56]. Outcomes show that the precast in-situ construction produces fewer GHG emissions compared to the conventional method. Buildings and infrastructure thus represent one of the most significant and cost-effective selections for reducing global GHG emissions [56, 58].

Figure 7 presents a simplified mind map that describes the advantages of modular construction in Europe. It highlights the main benefits, such as sustainability, structural efficiency, design flexibility, cost-effectiveness, and reduced construction time, that help reduce global GHG emissions in the building sectors. Using advanced building technology in the EU, such as modular constructions in residential buildings, will be a primary driver in decreasing greenhouse gas emissions and conserving natural resources. Furthermore, the development of technologies and advanced materials to improve building energy efficiency is a significant instrument for achieving this purpose.

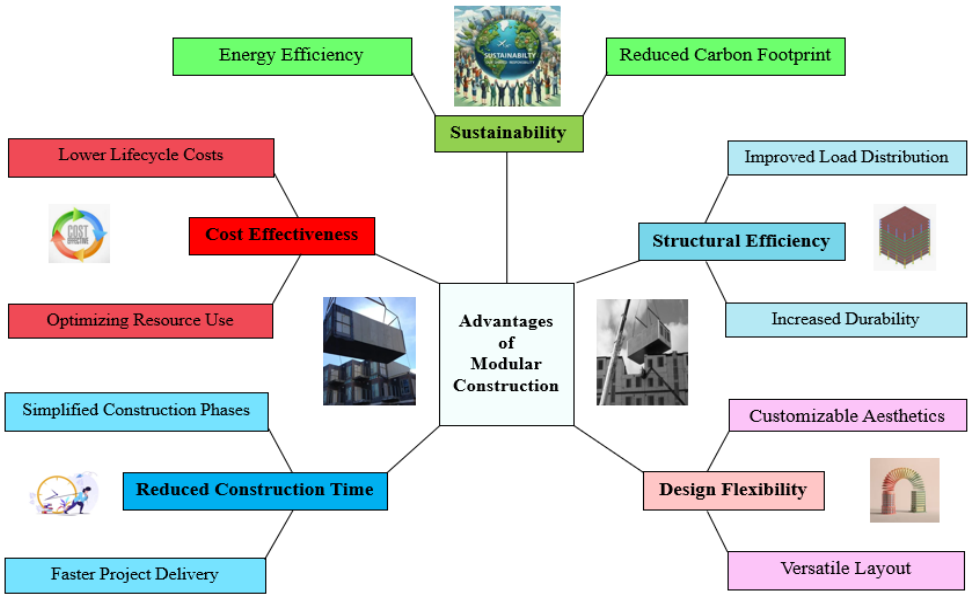


Figure 7. Simplified mind map for the advantages of modular construction (source: author) [14].

5. COMPARISON OF GHG EMISSIONS DISTRIBUTION IN THE BUILDING SECTOR BETWEEN IRAN AND EUROPE

From the knowledge gained so far, it follows that the strategies of the EU Member States emphasize the environmental assessment of structures, materials, and technologies. The same is true for new construction in Iran. In environmental assessment, we focus on the carbon footprint measurement method, which applies exclusively to greenhouse gas emissions. Or we use the Life Cycle Assessment (LCA) method, which provides a more comprehensive view of the entire life cycle of a building within the construction process. However, carbon footprint calculation tools help to identify and reduce CO_2 emissions. The Greenhouse Gas Protocol (GHG) methodology allows for the quantification of emissions, thereby strengthening strategic interdisciplinary decision-making and setting measures that lead to emission reduction. It is a powerful tool that aims to enhance the efficiency of construction and at the same time set priorities across all sectors. In the context of efforts to strengthen sustainable development, it effectively allows for the planning of sustainability strategies. According to the Emissions Database for Global Atmospheric Research (EDGAR) which provides greenhouse gas (GHG) emissions time series for all countries and all anthropogenic sectors from 1970 until 2022, in this study, a comparison of GHG in the Building Sector has been made between the Iran, Eu27 and World in Figure 8.

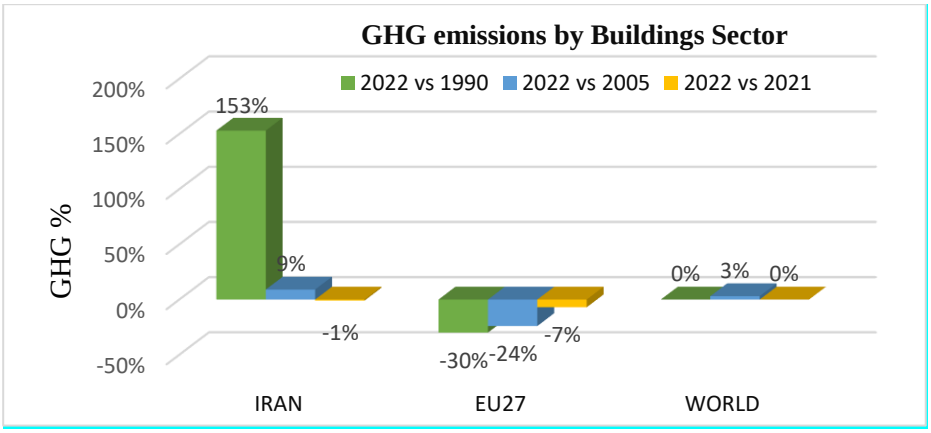


Figure 8. Comparing GHG Emissions of Iran, EU27, and the World by Building Sector (bar chart elaborated based on [54]).

Figure 8 illustrates that the EU27 is preparing plans and implementing actions to cope with climate change in the building sector because it has experienced negative growth (-30%) in GHG emissions from 1990 to 2022. Iran has had a negative growth (-1%) of GHG emissions from 2021 to 2022 in comparison with the world. It can be documented that strategic measures are demonstrable across countries not only on different continents, in different climate zones, but also in different geopolitical arrangements.

6. CONCLUSION

Since Iran has a long history in construction, structural and architectural aspects of ancient buildings such as Kolah Farangi and Abarkuh show that designers try to apply natural lighting and ventilation in their designs. Although, some codes and standards are published related

to industrial design and implementation of buildings in Iran, unfortunately, the construction of prefabricated and industrial buildings is not common in Iran because there are no required factories for the production of advanced material for this large volume of construction in Iran, and importing this material into the country increases the cost of construction. On the contrary, the construction sector is supported by European governments to enable it to address both environmental and social challenges. Further, efforts have been made through cooperation across disciplines in academia and business to develop new types of building materials with prominent properties: environmentally friendly, more secure, solid, durable, recyclable, and energetically efficient. Using advanced methods of construction and advanced materials can help less waste and more recycling of materials, speed of installation, higher productivity, reduced disruption during construction, fewer transport movements, and more reliable thermal performance in comparison with more traditional construction; thereby increasing profitability and overall, favourably impacting the environment which leads to reduces GHG emissions.

A comparison of construction processes and structural and architectural creation in Europe and Iran shows that modern trends in accordance with sustainability are similar. Modern architecture on both continents often has the character of modularity and prefabrication, with a strong emphasis on sustainability. Modern construction in Iran has elements of differentiation and relates to traditions. A number of new and modern buildings in Iran reflect the tradition of historical construction (for example, the building of the New Construction Authority in the city of Mashhad, which reflects the tradition of Iranian bridges, i.e., the creation of shaded terraces and community support).

Europe emphasizes sustainability, low-energy standards, eco-design, the use of modular elements, and prefabrication.

The paradigm of contemporary construction processes, which relates to the basic principles and approach to construction, is similar in both continents. It focuses on technological innovation and sustainability, social needs. The adaptation of buildings focuses on the needs of the relevant cultural community. Innovative processes and flexibility are an integral part.

REFERENCES

[1] Islam, M.: **Evaluation and Comparison of Building Construction Technologies in Two Major Cities of Bangladesh**. *International Journal of Structural and Civil Engineering Research*, vol. 1, no. 1, 2012.

[2] Mustafizur, R.: **One Platform-Different Cities: An Automated Plug and Play Modular Building Construction & City Planning System**. *International Council for Research and Innovation in Building and Construction, Laboratory of Building Realization and Robotics Technische Universität München (TUM), Germany*, 2014.

[3] Grisales Pachon, A. and Jacob, J.: **Necessity of a Disruptive Change in the Construction Industry – Analysis of Problematic Situation**. *International Council for Research and Innovation in Building and Construction, Laboratory of Building Realization and Robotics Technische Universität München (TUM), Germany*, 2014.

[4] Patil, S & Choudhary, A & Pawar, M, & Patil, K, & Pawar: **An Overview of Study on Smart Construction Materials and Advanced Construction Techniques**. *International Journal of Engineering Science, Advanced Computing and Bio-Technology*. 12. 29574 -29576, 2022.

[5] Kawahata, J., Murayama, K., & Akagi, K.: **Advanced Construction Technologies and Further Evolution Towards New Build NPP Projects**. *International Atomic Energy Agency (IAEA): IAEA*, 2011.

[6] Abdilahi, H., Chara, A. H., Prova, N. B. F., & Naher, N.: **A Systematic Analysis on Adaptation of Modern Construction using Advanced Technology: The Perspective to Bangladesh**. *International student symposium*, 2023.

[7] Krupík, P.: **Advanced building materials - prefabricated and modular designs as part of Construction 4.0 with a focus on transport constructions**. *IOP Conference Series: Materials Science and Engineering*, 2021.

[8] Kubečková, D., Kubenková, K., Afsoosbiria, H., Musenda, O. K., & Mohamed, K.: **External Thermal Insulation Composite Systems—Past and Future in a Sustainable Urban Environment**. *Sustainability*, 16(19), 8500. https://doi.org/10.3390/su16198500, 2024.

[9] Afsoosbiria, H., Kubečková, D., Musenda, O. K., & Mohamed, K.: **Variability of Material Solutions for the Perimeter Walls of Buildings in Post-Industrial Settlements as Part of Energy Rehabilitation and Achieving Carbon Neutrality**. *Energies*, 17(24), 6236. https://doi.org/10.3390/en17246236, 2024.

[10] **Modern Methods of Construction, Construction Industry Federation**. Report-*v4*, 2021. https://cif.ie/wp-content/uploads/2022/01/1271-CIF-Modern-Methods-of-Construction-Report-v4.pdf. (4/8/2025)

[11] **Global Advanced Building Materials**, *Market Research Report*, 2023.

[12] Uddin, M.: **An Automated Approach for Installing Building Modules**. *Proceedings of the CIB W119 CIC 2013 Workshop Advanced Construction and Building Technology for Society***,** November 2013, Munich, Germany.

[13] Hashemi, A.: **Modern Methods of Construction (MMC) in the UK housing industry**. *Second Research Student Conference held at the Welsh School of Architecture*, Cardiff University, 2006.

[14] Afsoosbiria, H.: **Structural Aspects of Building Conversions in Industrial Areas, Doctoral State Exam**, *Dissertation Thesis, VSB - Technical University of Ostrava, Faculty of Civil Engineering*, Department of Building Construction, 2025.

[15] Ross, K.: **BRE Construction Division. Modern methods of house construction: A surveyor's guide**, 2005.

[16] **Hybrid building design and its advantages**, https://constrofacilitator.com/, 2020. Available online 01.04.2025

[17] **Modern methods of construction: Views from the industry**. *Published by IHS BRE Press on behalf of the NHBC Foundation*, 2006.

[18] National Audit Office. **Using modern methods of construction to build homes more quickly and efficiently**, London: National Audit Office, 2005.

[19] Khan, H., Khan, M.: **Modern methods of construction**, IJARIIE-ISSN(O)-2395-4396, vol-5 issue-4, 2019.

[20] Mashhadifarahani, S.: **Lightweight Steel Frames vs. Common Building Structures - Structural Performance Evaluation**, *American Academic Scientific Research Journal for Engineering, Technology, and Sciences*, 2015.

[21] Rajanayagam, H., Upasiri, I., Poologanathan, K., Gatheeshgar, P., Sherlock, P., Konthesingha, C., Nagaratnam, B., Perera, D.: **Thermal Performance of LSF Wall Systems with Vacuum Insulation Panels**. *Buildings*, 11, 621. https://doi.org/10.3390/buildings11120621, 2021.

[22] Tung Vy, S., Mahendran, M.: **Experimental study of load-bearing LSF wall panels made of built-up CFS channel studs at ambient and elevated temperatures**. *Proceedings of the Cold-Formed Steel Research Consortium Colloquium*, 17-19 October 2022 (cfsrc.org), 2022.

[23] Jelcic Rukavina, M., Skeji´c, D., Kralj, A., Ščapec, T., Milovanovi´c, B. **Development of Lightweight Steel Framed Construction Systems for Nearly-Zero Energy Buildings**. *Buildings*, 12, 929. https:// doi.org/10.3390/buildings12070929, 2022.

[24] Vicente, A., Flôres, E., Vicentini, A., Zadorosny, L.: **Design Modeling and Dimensioning of A Building In Light Steel Framing Construction System**. *Unifunec Científica Multidisciplinar*, ISSN 2763-5783, 2023.

[25] Burwood, S., Poul, J.: **Modern Methods of Construction: Evolution or Revolution: A BURA Steering and Development Forum Report**. *London: British Urban Regeneration Association*, 2005.

[26] Shah, S., Jain, M., Mehta, R.: **Report of Precast Building System**, 2016.

[27] Ely, A.: **Modern Methods of Construction compatible with best practice urban design**, *Waterfront Conference on MMC*, 2005.

[28] Somesh, M. Shivani, G. Raskshita, K.: **Twin Wall Technology**, 2023.

[29] **A Short Guide To Modern Methods Of Construction (MMC)**, https://www.hlnengineering.co.uk/. Available online 01.04.2025

[30] **Thin-Joint System, H+H Product Datasheet**: https://www.hhcelcon.co.uk/, 2023. Available online 01.04.2025

[31] Jangid, Y., Khan, A., Mohite, G., Narvekar, A., Gurav, K.: **Mivan Formwork in Construction**, *International Research Journal of Engineering and Technology (IRJET)*, Volume: 10 Issue: 04, 2023.

[32] Patekar, N., Shaikh, A.: **Assessing the impact of conventional formwork and Mivan formwork on construction productivity and efficiency**, *World Journal of Advanced Engineering Technology and Sciences*, 09(01), 240–247, 2023.

[33] Kazarnovskiy, V., Hadavi, M.: **The Main Factors Affecting the Character of Housing Construction in Iran,** *International Scientific Conference Environmental Science for Construction Industry, Sustainable Strategies of Urban Planning*, https://doi.org/10.1051/matecconf/201819301021, 2018.

[34] Ashtiany, M., Motamed, H.: **Earthquake Insurance in Iran: Solvency of Local Insurers in Light of the Current Market Practice,** *Natural Hazards, and Earth System Sciences*, DOI: 10.5194/nhess-2023-81, 2023.

[35] Financial Tribune. First Iranian English economic daily. https://financialtribune.com/articles/economy-business-and-markets/79384/iran-5m-new-homes-needed-by-2027. Available on-line 01.04.2025

[36] Tap Persia Travel Around Persia, https://www.tappersia.com/mohtasham-garden/. Available online 03.04.2025.

[37] https://www.pinterest.com/pin/372109987934243427/. Available online 03.04.2025.

[38] Saadatian, O., Haw, L., Sopian, K., Sulaiman, M.: **Review of windcatcher technologies**. *Renewable and Sustainable Energy Reviews*. 16 (3): 1477–1495. doi:10.1016/j.rser.2011.11.037, 2012. Available online 01.04.2025.

[39] https://www.dreamstime.com/editorial-stock-photo-old-kharanagh-village-yazd-iran-photo-was-taken-city-july-th-virtually-deserted-crumbling-mud-brick-image59666338. Available online 03.04.2025.

[40] Iran Tourism and Touring Organization (NGO), https://itto.org/iran/attraction/rasht-municipality-square/. Available online 01.04.2025.

[41] Al-Awag, A., Alaloul, W., S. Liew, M., Baarimah, A., Musarat, M.: **The Potential Role of Industrialized Building Systems (IBS) in Malaysian Sustainable Construction: Awareness and Barriers**. *The 2nd International Recent Trends in Engineering, Advanced Computing and Technology Conference (RETREAT) AIP Conf. Proc*. 2608, 020015-1–020015-9; https://doi.org/10.1063/5.0128035, 2021.

[42] Akah, E., Bassey, L., Oguike, M.: **Industrialized Building Systems (IBS) Algorithm: Merits, Demerits and Implementation Barriers in Nigeria**, *The Artist Journal (TAJ) Volume*. 6, no. 1, 2023.

[43] Taherkhani, R., & Saleh, A. L.: Awareness and prevalence of industrialized building system (IBS) in Iran. J. Teknol, 81(6), 13-23, 2019.
[44] Hashemi, A.: **Offsite manufacturing: a survey on the current status and risks of offsite construction in Iran**. *Journal of Civil Engineering and Architecture*, 9, 141-152, 2015.
[45] **Design and industrial implementation of buildings (topic 11)**. *Second edition, National building regulations (language, Persian)*, 2013.
[46] **Code of design and implementation of cold-rolled steel structures (non-structural part of the structure).** *Publication No. 613. Building and housing research center. Vice President of Planning and Strategic Systems.* (language, Persian), 2012.
[47] **Code of Design and Implementation of Cold Rolled Steel Structures (Section of Structures)**. *Publication No. 612. building and housing research center. Vice President of Planning and Strategic Systems* (language, Persian), 2014.
[48] Ghaderi, R., Karimian, M., Khorasani, M.: Guidelines for the design and implementation of light steel construction system, (language, Persian), 2014.
[49] Ghasemzadeh, H.: **Lightweight (Light gauge) Steel Frame**. *K.N. Toosi: University of Technology*, (language, Persian), 2015.
[50] **Design and modern methods of construction**, CABE, Research outcomes: 5, Commission for Architecture & the Built Environment, London, 2004.
[51] Hashemi, A., Noguchi, M., Altan, M.: **Feasibility of Application of Modern Methods of Construction in Iran**, *ZEMCH 2015 International Conference*, 22-25 September 2015, Lecce, Italy.
[52] **Communication from the European Commission on the European Green Deal**: COM (2019) 640 final.
[53] **Regulation (EU) 2021/1119 European Climate Law European** Union (2020).
[54] Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E.: **GHG emissions of all world countries, Publications Office of the European Union, Luxembourg**, doi:10.2760/953332, JRC134504, 2023.
[55] Probst, L., Monfardini, E., Frideres, L., Moujahid, S., Luxembourg, P.: **European Union,. Smart Living: Advanced building materials**. *Business Innovation Observatory Contract No 190/PP/ENT/CIP/12/C/N03C01. Coordination: Directorate-General for Enterprise and Industry, Directorate B "Sustainable Growth and EU 2020*", Unit B3 "Innovation Policy for Growth", 2014.
[56] Yingbo, J., Kaijian, L., Guiwen, L., Asheem, S., Jinxi, J.: **Comparing greenhouse gas emissions of precast in-situ and conventional construction methods**, *Journal of Cleaner Production*, Volume 173, Pages 124-134, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.07.143, 2018.
[57] Ashayeri, I., Goulding, J., Heesom, D., Arif, M., Moore, N., Obi, L., Ahmed, N, and Saini, M.: **Implementation of a novel data-driven approach to optimise UK offsite housing delivery**, *IOP Conf. Ser: Earth Environ*. Sci. 1101 042029, DOI 10.1088/1755-1315/1101/4/042029, 2022.
[58] Robert, H.: **Greenhouse Gas Emissions of Global Construction Industries, Crawford**, *IOP Conf*. Ser..: Mater. Sci. Eng. 1218 012047, 2022.

doi.org/10.62683/SINARG2025.011

Research paper

AUTOMATED SYSTEM FOR GEODETIC CONTROL IN BUILDING OF BRIDGE SUPERSTRUCTUTE CONSTRUCTIONS USING THE CANTILEVER CONCRETE OR ASSEMBLY METHOD

Ani Stefanova[1]

Abstract

The article presents an automated system for geodetic control in building of bridge superstructure constructions using the cantilever construction method. The system includes two modules: an observation module consisting of a robotic total station and a portable laptop-tablet with special software and an assembly module connected via a radio interface. During construction, precise geodetic measurements are done to control the spatial status of the cantilever facility and the constructed bridge segments. The correction data are being registered into the total station and then transmitted to the assembly module. This procedure is repeated until the completion of the bridge construction. The author emphasizes the importance of precise measurements and proposes the development of a system with high-precision geodetic tools and means of communication thus providing fast and reliable data preparation for spatial orientation and automated preparation of executive documentation.

Key words: *Automated system, Geodetic control, Bridge superstructure construction, Cantilever method*

[1] Ani Stefanova, Chief Assist. Prof. Dr Eng., Department of Applied Geodesy; Faculty of Geodesy, University of Architecture, Civil Engineering and Geodesy, Bulgaria, email: stefanova_fgs@uacg.bg, ORCID: 0009-0008-4879-6665

1. INTRODUCTION

One of the most common technologies for bridge construction in difficult terrain conditions is the cantilever construction technology which is implemented in two ways: monolithic, also called “cantilever concrete method” and assembling – “cantilever assembly method” [1], [2].

Throughout the entire construction period, construction and assembly works are accompanied by precise geodetic measurements in order to perform an executive survey of the already constructed parts of the bridge and setting out works during the construction of its subsequent parts. The scarce literature on this issue [3], [4] mentions that measurements are carried out with a total station, and for each stage of the implementation of the cantilevers, depending on the geometry of the project, relevant preparatory calculations are carried out – mainly coordinate transformations and setting out data.

Given the exceptional importance of geodetic measurements in cantilever bridge construction, reliable control of the computational work and geodetic setting out for spatial orientation (so-called navigation) of the cantilevers must be carried out at each stage of implementation. According to the author, this implies the development of a geodetic control system, including at least a high-precision geodetic device for defining spatial coordinates, a portable field computer with special software for calculating the setting out data and a means of communication between them.

This idea is the basis of a research project developed at the University of Architecture, Civil Engineering and Geodesy aiming to create a working model of a geodetic control system for building of bridge superstructure construction using the cantilever method. The main idea, the functional block diagram, the equipment involved and the functional model of the system are discussed in this article.

2. PROJECT FOR A GEODETIC CONTROL SYSTEM IN BUILDING OF BRIDGE SUPERSTRUCTURE CONSTRUCTIONS USING THE CANTILEVER CONCRETE AND ASSEMBLY METHOD

The project was developed under a contract with the Center for Scientific Research and Design at University of Architecture, Civil Engineering and Geodesy aiming to create a working model of a geodetic control system in building of bridge superstructure constructions using the cantilever concrete or assembly method. The project was realized by a design team including the author.

2.1. Purpose of the geodetic control system:

The geodetic control system is designed to provide:

- fast and reliable preparation of the necessary data for spatial orientation of the cantilever concrete facility or correction of the assembled cantilever segment at each stage of construction in compliance with the facility design project.
- providing the necessary graphic and textual information to the operator of the cantilever concrete facility or the assembly crane;
- reliable two-sided control of the location of the cantilever concrete facility;
- two-sided connection with the facility designer via Internet;
- automated preparation of executive documentation for each stage of construction.

2.2. Necessary prerequisites for the functioning of the geodetic control system:

- A laid, measured and adjusted bridge geodetic network, providing the necessary accuracy in plan and height for setting out and control when building bridges using monolithic method and/or assembly method of supporting structures.
- Results (files) from the dimensioning of the bridge's supporting structure with special software – SOFISTIK [5] and the elements defining the local coordinate system of the bridge used in the software.
- Construction working schemes (files) of the abutments, pillars and supporting structure; longitudinal profile of the linear object (road, railway line, etc.); coordinates of the peg pints of the axis of the linear object within the scope of the bridge, in a geodetic coordinate system.
- Results of the executive measurements of the constructed elements of the substructure: abutments and pillars.

The following presentation covers a variant of the geodetic control system using a robotic total station as a measuring system module.

2.3. Functional block diagram of the geodetic control system

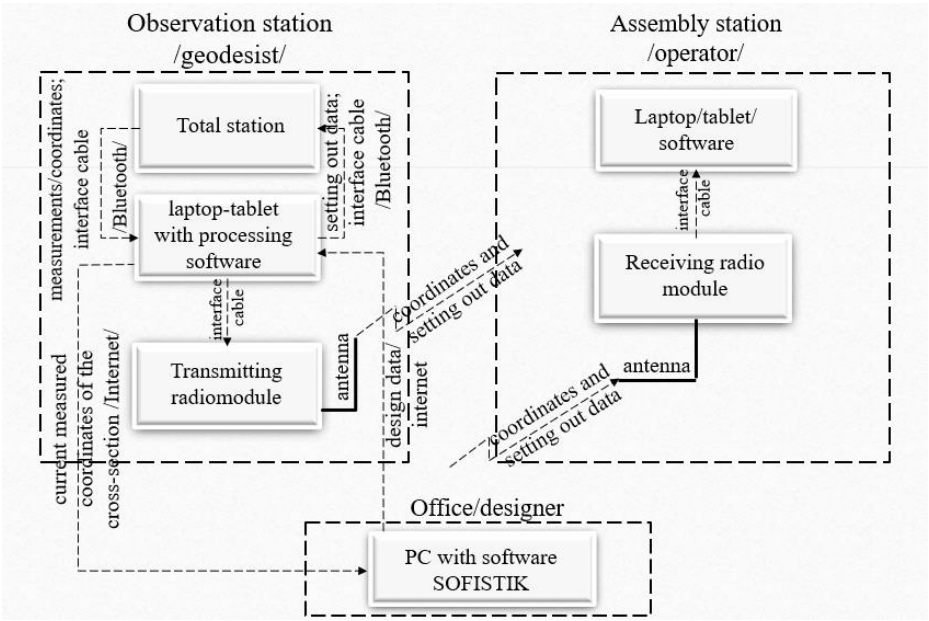


Figure 1. Functional block diagram of the geodetic control system

2.4. Equipment

The system equipment has been determined taking into account the geodetic tools, special software and computing devices available at the University - UACEG.

The requirement to provide graphic and textual information to the operator of the cantilever concrete facility or the assembly crane to support their work in locating the facility

or the assembled segments implies the presence of two system modules: observation and user.

2.4.1. Observation module (observation station)

The module includes the following components (Figure 2):

- Total station (preferably robotic or at least with the ability to measure distances up to 150-200 m without a prism) with appropriate angular and longitudinal accuracy and interface - RS232/USB, Wi-Fi.
- 10.4" laptop-tablet controller Panasonic CF-19 convertible (outdoor use-sunlight readable, 3G-module), attached to the tripod of the total station; operating system – Windows 7 Pro.
- Transmitting radio module 2.4 GHz with directed antenna (600/750) connected to the control laptop with an interface cable.
- Special software for processing the measured information, preparation of setting out data, visualization, communication and data transfer from and towards the total station to the tablet of the assembly station via radio interface and towards the designer's computer via Internet.



Figure 2. Oservation station

In this particular case, the use of a robotic total station is suggested Topcon IS 203 [6], [7] which can measure distances up to 250 m without a prism with an accuracy of 3 mm and angular accuracy on both circles 3″; interface – USB, Bluetooth, Wi-Fi; operational system – Windows CE NET 4.2.

2.4.2. Assembly module (assembly station – Figure 3)

- 10.4" laptop-tablet Asus 104tm, operational system Windows 7;
- Receiving radio module 2.4 GHz with non - directed antenna;
- Special software for receiving and visualizing setting out data from the observation module.



Figure 3. Assembly station

2.4.3. Office/Designer

- Personal computer with installed SOFISTIK software and Internet connection.

2.5. Model of functioning of the geodetic control system

The functional model presented here was developed based on the general technological plan for the implementation of the supporting structure and the corresponding stages of the computational model used in SOFISTIK.

2.5.1. Computational model

The geometric axis of the bridge's supporting structure is part of the axis of the linear object (road, railway line) which is defined by its main and detailed points in a geodetic coordinate system. In SOFISTIK the axis of the facility is represented by a series of points (nodes) but in a local coordinate system for the facility OXYZ (Figure 4).

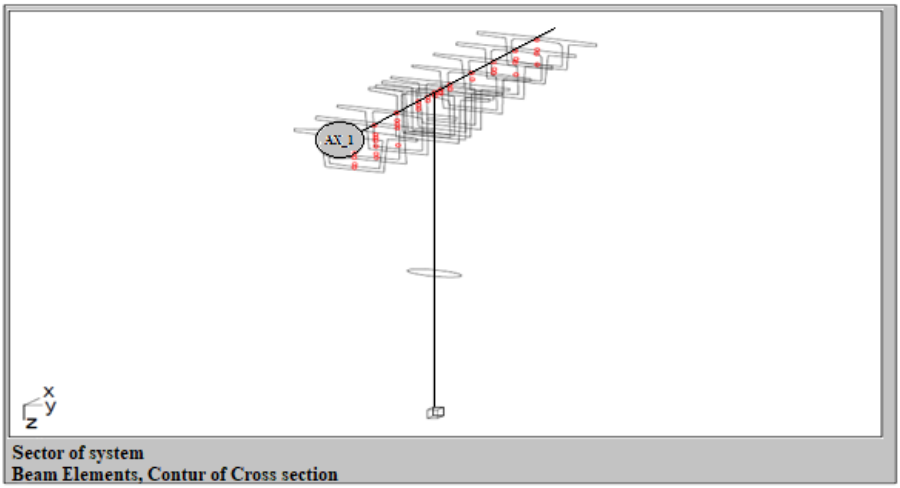


Figure 4. Axis of the facility

The beginning of the coordinate system can be chosen at any node but it is preferable to coincide with a peg pint of a straight section before the initial abutment or in the center of the abutment itself. The direction of the X axis is in the direction of the axis of the facility, if it is

straight and, respectively, in the direction of the common tangent, if it is curved. The directions of Y and Z axes are visible in the figure above.

Each pair of consecutive cross-sections closes the so-called “beam end element” which physically represents a construction element (block or segment) of the cantilever. From a computational point of view, the element is defined by two consecutive cross-sections “attached” to the axis of the facility with the center points (Figure 5).

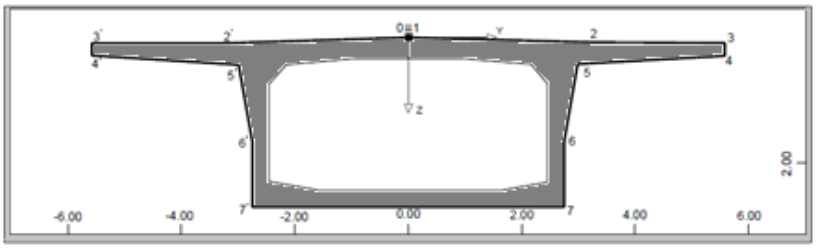


Figure 5. Cross-section

The design of the structure is carried out for each node, in successive steps, called loadcases, corresponding to the stages of construction.

As a result of the calculation of the construction with SOFISTIK software, the following files are obtained:

- A file containing the three-dimensional coordinates of all nodes of the bridge axis in the local coordinate system of the facility.

Nodal Coordinates and Supports

Number	X[m]	Y[m]	Z[m]
101	0.000	0.000	0.000
102	0.350	0.000	-0.021
103	1.350	0.000	-0.081
104	2.550	0.000	-0.153

- File containing a list of all loadcases from the calculation of the bridge support structure.

Loadcasenumber	Title
4001	Piers
4005	Creep 50 days
4010	Pier table

- A file containing the coordinates of the contour points of each section but in a local coordinate system for the section itself, starting at the corresponding node (Figure 4), arranged in ascending order by cross-section type number.

node / *cross-sec.* /	y;z т.1	y;z т.2	y;z т.3	y;z т.4	y;z т.5	y;z т.6	y;z т.7
101 / 5 /	0.000;0.000	3.500;0.000	5.580;0.000	5.580;0.300	3.000;0.300	2.750;0.300	0.000;0.300
102 / 5 /	0.000;0.000	3.500;0.000	5.580;0.000	5.580;0.300	3.000;0.300	2.750;0.300	0.000;0.300
102 / 3 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
103 / 3 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690

- Files containing the values of the translations of the central point of each section (pt. O – Figure 5) and the rotations of its axes, for each loadcase, relative to the local coordinate bridge system.

Nodal Displacements
Loadcase 4001: Piers

Node. Nr	UX [mm]	UY [mm]	UZ [mm]	PHIX [mrad]	PHIY [mrad]	PHIZ [mrad]
1138	21.902	0.0000	-3.9790	0.0000	0.1108	0.0000
1165	-18.188	0.0000	-4.2420	0.0000	-0.3585	0.0000
2138	0.000	0.0000	0.0000	0.0000	0.0000	0.0000
2165	0.000	0.0000	0.0000	0.0000	0.0000	0.0000

2.5.2. Preparation of the geodetic control system

1) The preparation of the geodetic control system for operation on a specific site (bridge) begins with the creation of a project in a special software[2] for management and procession of measurement data installed on the observation module.
2) The project directory gets the files from the constructional decision of the bridge with SOFISTIK software and a file containing the coordinates of the points from the bridge setting out network.
3) At the site, the operator centers the total station over the point selected as the observation station, sets the control laptop on the device tripod, connects the transmitting radio module to the antenna and the laptop, turns on the control laptop and starts the control software. Similarly, in the cantilever concrete facility, the components of the assembly module are connected.
4) Transfer of the file with the coordinates of the points from the bridge network from the control laptop to the total station memory.
5) Performing the necessary measurements towards points of the bridge network in order to initially establish or to control the coordinates of the observation station with the option „Free Station“.

2.5.3. Working with the geodetic control system during the cantilever construction

It is assumed that over-the-pillar block has been built and the cantilever concrete facility has been assembled to build the first block of the cantilever but it is not located according to the design, but only approximately.

Work with the geodetic control system during the cantilever construction is as follows:

1) determination of the three-dimensional geodetic coordinates of the points from the outer contour of the cross-section (front) of the formwork
2) comparison of the determined coordinates with the design coordinates
3) calculation of the necessary corrections along the three coordinate axes
4) adjustments in the orientation of the installation so that its front takes the design position.

All these operations are described in detail in the author's dissertation [8].

The described functional model essentially includes the generalized algorithm for processing information at each stage of the construction of the supporting structure.

2.5.4. Information processing algorithm

It processes the output data and geodetic measurements in order to provide the construction process with the necessary setting out data and performing geodetic control at each stage of the construction and installation works.

[2] The software was developed by a professional programmer (a member of the design team) in the algorithmic language C++ under Windows 7 Pro operating system. The program is designed for management and procession of measured information, preparation of setting out data, visualization, communication and data transfer from and towards the total station, to the tablet of the assembly station via radio interface and towards the designer's computer via Internet.

- **Registering output information:**
  - Entering the coordinates of the bridge setting out network – text file **Network.kor**.

For example: Coordinate system: 1970, Height system: Baltic.

File structure:

Site name, Coordinate system, Height system

№ X, m Y, m H, m mx my m_H

.....

  - Registering the necessary text files from the bridge dimensioning with SOFISTIK:

File with loadcases in facility calculation **Loadcases.txt**.

File structure:

Loadcasenumber Title - execution step

4001 Piers

4005 Creep 50 days

4010 Pier table

4011 Prestress

4015 Creep 50 days

4020 dead load CS #20

4030 dead load CS #30 20

4031 Prestress CS #31

.....

File with nodes coordinates (the points from the bridge axis) **Nodes.kor**.

Coordinate system – Spatial, local to the facility, set in SOFISTIK.

File structure:

Table 1

Nodal Coordinates and Supports			
Number	X[m]	Y[m]	Z[m]
101	0.000	0.000	0.000
102	0.350	0.000	-0.021
103	1.350	0.000	-0.081
104	2.550	0.000	-0.153
105	3.150	0.000	-0.189
106	7.250	0.000	-0.435
107	11.350	0.000	-0.681
108	15.450	0.000	-0.927
109	19.550	0.000	-1.173
110	23.650	0.000	-1.419
111	27.750	0.000	-1.665
112	31.850	0.000	-1.911
113	35.950	0.000	-2.157
114	40.050	0.000	-2.403
115	44.150	0.000	-2.649
116	48.250	0.000	-2.895
117	52.350	0.000	-3.141
118	54.150	0.000	-3.249
119	55.350	0.000	-3.321
120	56.550	0.000	-3.393

File with translations and rotations in the nodes from the facility axis for all loadcases **displacements.txt.**

Coordinate system – local to each node

File structure:

Table 2

Nodal Displacements
Loadcase 4001: Piers

Node. Nr	UX [mm]	UY [mm]	UZ [mm]	PHIX [mrad]	PHIY [mrad]	PHIZ [mrad]
1138	21.902	0.0000	-3.9790	0.0000	0.1108	0.0000
1165	-18.188	0.0000	-4.2420	0.0000	-0.3585	0.0000
2138	0.000	0.0000	0.0000	0.0000	0.0000	0.0000
2165	0.000	0.0000	0.0000	0.0000	0.0000	0.0000

Nodal Displacements
Loadcase 4005: Creep 50 days

Node. Nr	UX [mm]	UY [mm]	UZ [mm]	PHIX [mrad]	PHIY [mrad]	PHIZ [mrad]
1138	21.902	0.0000	-2.6914	0.0000	0.1108	0.0000
1165	-18.188	0.0000	-2.9544	0.0000	-0.3585	0.0000
2138	0.000	0.0000	0.0000	0.0000	0.0000	0.0000
2165	0.000	0.0000	0.0000	0.0000	0.0000	0.0000

Cross-section schemes files in format dxf.
File name: **Node №.dxf.**
A **file describing the contour of the sections** with a series of points with coordinates Node №*txt (half of the cross section is given, see the following scheme).

Coordinate system: local in the cross-section plane
File structure

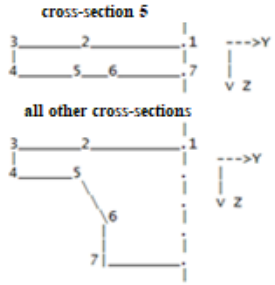


Figure 6. Cross-section

Table 3

node / cross-sec./	y;z т.1	y;z т.2	y;z т.3	y;z т.4	y;z т.5	y;z т.6	y;z т.7
101 / 5 /	0.000;0.000	3.500;0.000	5.580;0.000	5.580;0.300	3.000;0.300	2.750;0.300	0.000;0.300
102 / 5 /	0.000;0.000	3.500;0.000	5.580;0.000	5.580;0.300	3.000;0.300	2.750;0.300	0.000;0.300
102 / 3 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
103 / 3 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
104 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
105 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
106 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
107 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
108 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
109 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
110 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
111 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
112 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
113 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
114 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
115 / 1 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690
116 / 2 /	0.000;0.000	3.500;0.090	5.580;0.090	5.580;0.290	3.000;0.430	2.750;1.690	2.750;2.690

- **Pre-processing of the output information:**
  - Calculating the coordinates of the right part of the cross-sections from a file **Node №*txt** in the same coordinate system, recording the coordinates for each section in a separate file **SecNoLS.txt** with structure:

Node № Cross-section№, date
Point № У, m Z, m
1 0.000 0.000
2 3.500 0.000
.....
13 -5.580 0.000

- Transforming the coordinates from file SecNLS.txt into the bridge coordinate system (**B**ridge **S**ystem), record in file **SecN№BS.txt.**
- Transforming coordinates from file **SecN№BS.txt** into the geodetic coordinate system, record in file **SecN№GS.txt**.

- **Ongoing procession of the cantilever construction**

  - **Beginning of a cycle**
  - Entering the cross-section (node) number **SecNumber** and **Loadcase** number;
  - File transfer **SecN№GS-date.kpt** from the total station to the control laptop; registering the file into the processing software;
  - Coordinate transformation from file **SecN№GS-date.kpt** in the local coordinate system of the cross-section; record in file **SecN№LS-date.kpt**;
  - Recalculation of the design coordinates of the cross-section (file **SecN№LS.txt**) with the translations and rotations of the cross-section after the execution of the corresponding stage of the cantilever construction (file **displacements.txt**);
  - Calculation of corrections (translations) **dy, dz** which must be used to adjust the front of the cantilever concrete facility so that it takes its design position. Used files coordinates SecN№LS.txt and **SecN№LS-date.kpt**;
  - Drawing schemes of the design and actual cross-section, displaying the values of the corrections **dy, dz** and their directions;
  - Sending data to the assembly module via radio interface;
  - File transfer **SecN№GS.txt** in the total station. This file will be used by the total station operator for setting out and control;
  - File transfer **SecN№GS-date.kpt** from the front control measurement in the control laptop and sending to the designer's office via Internet;
  - Entering the next loadcase and repeating the same operations;
  - **End of cycle** (after depletion of all loadcases for the given cross-section);
  - **Beginning of a new cycle** – entering the next cross-section and loadcase, etc.

The accuracy in building superstructure bridge constructions using the cantilever concrete or assembly method is a subject of another article by the author [9].

CONCLUSION

The developed system for geodetic control in cantilever bridge construction significantly improves the reliability and efficacy of construction processes by providing accurate and fast setting out data and automated documentation. The current model of the system operates with the help of a robotic station Topcon IS 203, laptop-tablets Panasonic CF 19 and Asus 104TM as well as a set of radiomodules with range of about 200 m which allow integration of

different total station models, including those without Bluetooth and Wi-Fi. The ability to use total stations with advanced communication options (like Long Range Wi-Fi) is also provided which increases the flexibility of the system. Prospects for improving the system include the implementation of modern technologies and software platforms to increase its functionality and convenience which will contribute to even greater accuracy and efficacy when building bridge constructions.

REFERENCES

[1] Ivanchev Iliya: **Bridges. History and Modernity**, Sofia, 76-86, 2015
[2] Nikolov Petar: **Reinforced concrete road bridges**. Design guide, 2013
[3] Bankov, Borislav: **Geodetic works in bridge construction via cantilever concreting method**. *Geodesy, Cartography, Land Management*, vol.4, 15-22, 1997
[4] Topurov, Kostadin: **Reinforced concrete road and railway bridges**, vol. 1, 2012
[5] https://www.sofistik.com/
[6] Topcon. Instruction Manual. IMAGING STATION IS series IS201,203,205, 2007
[7] Topcon Link, Reference Manual, 2006
[8] Stefanova, Ani: **Geodesic assurance problems in bridge construction**, Dissertation, UACEG, Sofia, 62-71, 2019
[9] Stefanova Ani, Kostadinov Todor: **Accuracy of the geodetic activities in bridge construction**, *Geodesy, Cartography, Land Management*, issue 1-2, 28-32, 2019

doi.org/10.62683/SINARG2025.012

Review paper

PRESERVATION POLICY OF HISTORICAL CITY CORES: COMPARATIVE ANALYSIS NOVI PAZAR – NOVI SAD

Merisa Tarhaniš[1]

Abstract

This paper focuses on the preservation of historical city cores in two culturally and historically significant cities of Serbia – Novi Pazar and Novi Sad. The preservation of these areas is vital for maintaining cultural identity, historical continuity, and promoting multicultural heritage. The main aim of this research is to explore how political decisions, economic factors, and social circumstances have influenced the preservation and revitalization of these areas. A specific focus is placed on the Old Bazaar in Novi Pazar, a symbol of Ottoman heritage, and the historical core of Novi Sad, representing Austro-Hungarian architectural traditions. The methodology includes a comprehensive analysis of legal frameworks, urban planning documents, and existing preservation strategies. A comparative analysis is conducted between the two cities, considering cultural, political, and economic factors that shape their preservation policies. The comparison emphasizes the influence of multicultural heritage in Novi Pazar and post-Austro-Hungarian heritage in Novi Sad, differences in financial investment in preservation efforts, and challenges posed by urbanization and tourism. The paper identifies specific challenges faced in the preservation of historical cores, such as limited funding, the impact of urbanization, and the difficulties in maintaining authenticity amid commercialization and tourism. The comparative analysis reveals differences in the preservation strategies between the two cities, particularly in relation to the cultural traditions that shape each city's approach, as well as the financial and political support for these initiatives. The findings underscore the need for better integration of preservation efforts into broader urban development plans, increased financial investment, and public education on the importance of cultural heritage. The research suggests that for both cities, preserving their historical cores is crucial not only for safeguarding physical structures but also for preserving their cultural identities and fostering sustainable development.

Key words: preservation policy, historical cores, Novi Pazar, Novi Sad, cultural heritage, Old Bazaar, urban revitalization, multiculturalism, heritage protection law, authenticity preservation.

[1] MSc, PhD student, Faculty of Technical Sciences, University of Novi Sad, Serbia, tarhanis.dc7.2023@uns.ac.rs , https://orcid.org/0009-0003-6093-0939

1. INTRODUCTION

Architecture is one of the most important and influential areas of human creativity, with its rich material heritage preserved to this day [1]. Architectural heritage refers to everything that was built in the past and has specific monumental values that justify its protection and preservation. This includes monumental buildings, well-preserved structures, examples of folk architecture, buildings with artistic values, and those constructed from expensive and durable materials such as marble, as well as ruins that are subjects of archaeological research. Architectural heritage also encompasses significant technical achievements such as fortifications and bridges, as well as all cultural-historical spaces and immovable objects in the country that are part of archaeological sites [1]. Modern urbanization, driven by industrial development, population growth, and the demands of modern society, presents us with the challenge of preserving architectural heritage. The issue of the deterioration of cultural assets has become serious, leading to the need for legal regulations for protection. While European countries adopted laws for the protection of material culture as early as the 19th century, the Balkan countries only did so in socialist Yugoslavia, after World War II [1]. The protection of architectural heritage stems from a range of historical, cultural, scientific, national, social, economic, aesthetic, and other important aspects. The aim of this protection is to preserve significant objects and environments for future generations. This process is complex, as it includes research, evaluation, legal protection, documentation, spatial and urban planning, and care for the condition of cultural assets. On the other hand, technical protection involves a wide range of activities, from project design to the execution of conservation-restoration and other construction works, as well as full restoration, protection, revitalization, and presentation of immovable cultural assets [2]. Architectural heritage is crucial for the identity of a community and represents a source of its spiritual wealth. Novi Pazar, as the subject of this research, is a good example of a city with rich cultural heritage that nurtures cultural diversity as an invaluable treasure. Throughout history, the city has been attractive to various conquerors, which is reflected in changes in architecture and urbanism, and this evolution is manifested in its multiculturalism and different forms of life and business through the centuries [3]. Novi Sad carries layers of historical, cultural, and architectural heritage that testify to the dynamic past of the city and its cultural diversity. Developing at the crossroads of different cultures, the city has become home to a unique combination of architectural styles and urban solutions, making it rich in multicultural heritage [4]. The preservation of architectural heritage depends on many factors, and today's fast-paced life presents various challenges. The system of heritage valuation, as well as our awareness of its importance, are key to its preservation and to ensuring cultural identity and diversity for future generations [1]. However, there remains a significant gap in the existing preservation policies, particularly in their failure to effectively integrate heritage conservation into broader urban development plans. The challenges of modern urbanization and economic development in both cities have yet to be fully addressed within preservation frameworks. In this context, the research focuses on identifying these gaps and suggesting solutions for enhancing preservation strategies.

Novi Pazar and Novi Sad are ideal case studies for this research due to their distinct yet intertwined historical, cultural, and architectural trajectories. Novi Pazar's Ottoman heritage offers a unique perspective on the preservation of non-European cultural assets, while Novi Sad's Austro-Hungarian influences provide a contrasting example. The cities' shared multicultural heritage and contrasting political and historical experiences make them particularly valuable for comparative analysis.

This research introduces a new approach by comparing the preservation policies and their effectiveness in these two cities. It seeks to explore the impact of governance, political influences, and economic challenges on preservation efforts, offering a fresh perspective on the complexities of safeguarding architectural heritage in rapidly evolving urban environments.

2. LEGAL FRAMEWORKS FOR THE PRESERVATION OF CULTURAL HERITAGE

Architectural heritage, which is an important part of cultural heritage, requires a holistic approach. It is defined as buildings and architectural groups on different scales that must undergo a conservation approach, considering all of their values. The first term used to represent architectural heritage was "monument." Until the late 17th century, this term was closely associated only with archaeology, but later it became correlated with memory and aesthetics. The need to protect cultural heritage arises from its scientific, aesthetic, and natural values, as well as its sociocultural, symbolic, economic, and spiritual values. However, the protection of cultural heritage is often limited by factors such as insufficient financial resources, natural disasters, wars, neglect, and disinterest, which negatively affect and lead to the loss of historical buildings [5]. The objectives of protecting and preserving architectural heritage are numerous. Some of the goals include discovering, recognizing, collecting, documenting, studying, interpreting, evaluating, presenting, raising awareness about the importance of cultural heritage, integral preservation, and protection of cultural heritage through protective measures, as well as managing cultural heritage resources and the risks to cultural heritage [6].

2.1. National Legal Frameworks

Cultural monuments in Serbia are protected by the Institute for the Protection of Cultural Monuments of Serbia, which was established by a decree of the Government of the People's Republic of Serbia in 1947. In 1960, the name was changed to the Republic Institute for the Protection of Cultural Monuments. In Novi Sad, the Institute for the Protection of Monuments has been operational since 1983, while in Novi Pazar, the responsibility for the protection of cultural and historical heritage lies with the Institute for the Protection of Monuments in Kraljevo. In 2009, an initiative was launched by the Novi Pazar City Council to establish a local Institute for the Protection of Cultural Monuments, but despite the recognized need for such an institution, the project has not yet been realized [7]. A cultural monument is defined as an individual immovable object of cultural, historical, architectural, archaeological, artistic, ethnological, technical, paleontological, or other social significance. Cultural monuments can include: architectural works, their remains, recognizable parts, objects with related immovable properties, archaeological objects or structures, works of applied arts, paintings or sculptures, inscriptions, geological sites, works or remains of technical culture, old industries, infrastructure, and other goods permanently associated with a particular architectural object or site, as well as memorials or other commemorative monuments [8].

2.2. Local Legal Frameworks and Strategies

Novi Pazar

Local authorities in Novi Pazar have developed several key documents and strategies for the preservation of their historical urban core. Sustainable Development Strategy of Novi Pazar (2018-2028): This strategy emphasizes the preservation of cultural heritage as a crucial aspect of sustainable development. It focuses on an integrated approach that includes community participation, infrastructure improvement, and the promotion of cultural tourism [9]. Detailed Regulation Plan for the Old Town Core: This plan defines the legal and spatial frameworks for the preservation of the historical center of Novi Pazar. It includes the protection of cultural monuments, regulation of construction, and restoration of historical buildings [10].

Law on Cultural Property: This national law provides the basis for the protection of cultural heritage in Serbia, including in Novi Pazar. It regulates the protection, use, and management of cultural properties [11].

Novi Sad

With its distinctive city core, which includes Zmaj Jovina Street, City Square, Dunavska Street, Pašićeva Street, and Katolička Porta, Novi Sad also has well-developed legal frameworks and strategies for preservation. Sustainable Development Strategy of Novi Sad: This document lays the foundation for sustainable development, including the preservation of cultural heritage. It emphasizes the importance of preserving historical sites as resources for cultural tourism and the city's identity [12].

General Urban Plan (GUP) of Novi Sad: The GUP defines spatial planning and construction regulation in the historical core, with special protection measures for significant cultural and historical sites [13]. Law on Cultural Property: As in Novi Pazar, this national law provides the basis for the protection of cultural heritage in Serbia, including in Novi Sad. It regulates the protection, use, and management of cultural properties [11].

Program for the Revitalization of the City Core: This program includes specific measures for the restoration, protection, and tourist promotion of historical sites in the center of Novi Sad. It focuses on the integration of modern technologies for the preservation and promotion of cultural heritage [14]. The preservation of historical urban cores in Novi Pazar and Novi Sad relies on integrated strategies that combine legal regulations, community participation, and international cooperation. Key documents provide guidelines and frameworks for implementing these policies, ensuring the preservation of cultural heritage for future generations.

3. THE OLD BAZAAR OF NOVI PAZAR

Novi Pazar, a city with a rich history and heritage, has endured significant destruction in the past, resulting in the loss of many monuments that once testified to its history and development. Historical sources tell us that Novi Pazar once had something that few cities in this region possessed. Due to wars and devastating events, many hammams, religious buildings, fountains, gaps, and bazaars disappeared, diminishing the presence of the oriental spirit that once adorned this city, which was also known as the "tired key of Ottoman Bosnia" [16]. Despite numerous historical challenges, Novi Pazar has preserved a significant part of its historical artifacts and architectural heritage, among which the most important is the historical city center, or the Old Bazaar.

Definition of a Bazaar – The commercial and public part of an oriental city, where trade and craft shops are located, as well as other public buildings like inns, caravanserais, covered markets (bezistan), and mosques. The word "čaršija" originates from the Persian "čaršu" and the Pahlavi "čahar-sug," meaning four sides or quadrilateral, while the Arabic word "sut" refers to a market or marketplace. The Bazaar was the hub of public life in the oriental city – business was conducted there, people gathered, and it was a place for merchants and travelers to stay [17].

3.1. Historical Context and Significance

The Old Bazaar in Novi Pazar is an important cultural and historical complex located on the right bank of the Raška River. The part of the old town situated on the left bank of the river was called "Narrow Bazaar." The first part of the Bazaar was formed on the left bank, along the Stambol Road, and was known as " Narrow Bazaar." It is believed that the Bazaar expanded to the right bank of the Raška River in the first half of the 19th century. Narrow Bazaar covered an area from the bridge over the Raška River to Potok-mahala, primarily formed in a linear system, with shops and buildings arranged along the street, as well as some cross streets near the bridge and Amir-aga's inn [17]. With the demolition of Narrow Bazaar in 1947, the name "Bazaar" was transferred to the right bank of the Raška River, where the Arap Mosque and the old shops were located. Although it functionally belonged to

the main Bazaar on the left bank, it was not a typical Oriental Bazaar in terms of its functional arrangement [19]. The development of the Bazaar followed the fate of the city: during peaceful times, it grew and gained new buildings, while during wars, it was often destroyed. The greatest destruction of the Old Bazaar occurred in 1689 during the Austro-Turkish War, when many buildings were burned or demolished, including not only wooden inns and shops but also stone structures such as the bezistan (covered market), caravanserai, and hamams. After this destruction, the Bazaar was rebuilt but became much more modest, lacking some key buildings, and its appearance changed significantly. Further damage occurred due to wars in 1737, 1809, and 1944, as well as frequent fires, which further shaped the fate of the Bazaar, which suffered its greatest destruction after the war [17]. The Novi Pazar Bazaar stretched from today's "Granata" tavern to the "Kosovo" Hotel, with a branch extending from Ćemerli Inn (today's agricultural products market) to Hrvaćanin Tavern (today's Stevan Nemanja Street) [20]. The development of the Bazaar began with Isa-beg Isaković, who built the first 56 shops. These shops were located near his mosque, along what would become the main street, Stambol-drum, which determined the direction and position of the further development of the Bazaar. The further development of the Bazaar was significantly influenced by the institution of the vakuf, whose funds were used to build many structures in the Bazaar [17]. Vakuf documents testify to the vital role these buildings played in the economy of the city. Analyzing vakuf documents shows that almost all donors (those who endowed the vakufs) in the 15th and 16th centuries, along with mosques and mesdjids, built economic structures such as inns, caravanserais, bakeries, watermills, and shops. Regarding the crafts that existed in the Bazaar, the majority of craftsmen belonged to the service sector, such as shoemakers, cobblers, hat makers, tailors, furriers, saddlers, and weavers. Additionally, there were bakers, butchers, cooks, confectioners, candle makers, barbers, and coffeehouse owners [19].

3.2. Urban characteristics

The Novi Pazar Bazaar was organized according to the classic oriental principle, with divisions based on different crafts, which allowed for the formation of separate districts for specific craftsmen. Although it was more modest than the bazaars in Skopje and Sarajevo, its organization and appearance were similar. The spirit of tradition of the Novi Pazar Bazaar is reflected in the historical memory of the built core of Novi Pazar, whose significance goes beyond its material value, representing a key element of identity and remembrance of the past [21]. The Bazaar belongs to the larger oriental bazaars where craft workshops and shops were built, while housing was not typical for this area. Typical buildings in the bazaar were single-story, while buildings with an upper floor, but without residential function, were only constructed in the part of the bazaar closest to the bridge. Residential buildings with an upper floor began to be built only in the early 20th century [22]. The Old Bazaar in Novi Pazar is one of the rare and best-preserved units in Serbia, despite the challenges of modernization, such as the construction of newer buildings in the immediate vicinity of high-value monument buildings, such as Isa-Beg Isaković's Hamam and Hasan Čelebi's Mosque (Arap Mosque) with commercial buildings. New buildings disrupt the traditional spirit and historical atmosphere of the old core with mismatched aesthetic proportions and urban character. Despite significant efforts to preserve the bazaar, its values have been compromised by numerous interventions, including the use of heavy machinery, the demolition of mosques without respect for their symbolism and tradition, as well as a lack of consultation with experts [22]. Although these challenges have impacted its appearance, the Old Bazaar remains a lively and active part of the city, leading to projects aimed at modernizing and "updating" its core. As an integral part of the modern urban center of Novi Pazar, it holds special significance, which has led to the need for the development of a Detailed Protection and Revitalization Plan, aimed at preserving its monumental values and further guiding the development of the bazaar [22].



Figure 1. Novopazar Bazaar and Fortress, (http://novipazarspomenici.mi.sanu.ac.rs/stara_carsija_opis.html)

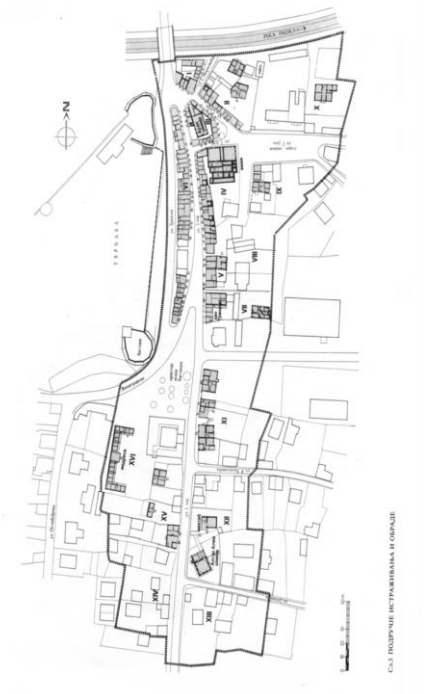


Figure 2. The Extent of the Old Bazaar, "Photograph from the book Nešković J., The Old Bazaar in Novi Pazar."

3.3. Challenges of preservation

The preservation of the authenticity of the Old Bazaar in Novi Pazar presents a significant challenge, particularly in the context of contemporary trends in modernization and urban development. The lack of adequate funding for the restoration and preservation of historical buildings further complicates the situation, while modern urbanization often threatens the integrity of historical structures. In addition, balancing tourist development with the preservation of local culture is becoming increasingly difficult, as the growth of tourism may lead to the commercialization of the space, further eroding the authenticity and identity of the Bazaar. To overcome this, it is essential to adopt sustainable strategies that will ensure the

preservation of cultural heritage while simultaneously supporting the economic development of the local community [22].

These challenges are further emphasized by the following examples:

Decay of historical buildings: One of the oldest houses in the Bazaar, the Čavić House, known for its authentic architecture, recently suffered severe damage due to neglect. The owners lack the funds for restoration, and the relevant institutions have not provided adequate support. Such cases are frequent, as many buildings remain unprotected and are left to deteriorate.

Modern urbanism and the construction of new buildings: One of the most obvious examples of pressure from modern urbanism is the construction of a business center near the Old Bazaar. This project, the Smart City Center, has raised concerns among experts and the local community due to the potential disruption of the visual identity and integrity of the Bazaar. Similar projects often ignore the historical context and contribute to modernization that endangers the traditional structure.

Commercialization of space due to tourism growth: The rise of tourism has led to changes in the function of historical buildings. For example, one of the oldest bakeries in the Bazaar, which had been in operation for nearly 100 years, has closed and been transformed into a souvenir shop, Pazarnica. This trend of turning authentic craft shops into tourist attractions threatens to erase the original character of the Bazaar, replacing it with uniform commercial contents.

4. THE CITY CENTER OF NOVI SAD

Novi Sad was founded in 1694 as a trading settlement under the name "Ratzen Stadt" (Serbian: Ratna varoš). In the following decades, the city developed as a significant commercial and craft center, thanks to its position on the Danube and its location along trade routes between the Habsburg Monarchy and the Ottoman Empire [23]. During the 19th century, Novi Sad earned the nickname "Serbian Athens" due to its leading role in the Serbian national revival. In this period, the city became a center for Serbian culture, education, and literature. The establishment of the Serbian Learned Society in 1826 and its relocation to Novi Sad in 1864 contributed to the strengthening of the city's cultural significance [24]. Since its founding, Novi Sad has been a multicultural environment, home to numerous national communities, including Serbs, Hungarians, Germans, Jews, and others. This multiculturalism played a key role in shaping the city's cultural identity and contributed to its rich heritage [25]. The city center was the focal point of many events important for the Serbian national revival. Numerous schools, libraries, and cultural institutions were established in this part of the city, making Novi Sad a crucial center for Serbian culture within the Habsburg Monarchy [26].

4.1. Historical Context and Importance

The historical core of Novi Sad, which includes Zmaj Jovina Street, City Square, Dunavska Street, Pašićeva Street, and Catholic Gate, represents a key part of the city’s cultural and historical heritage. Zmaj Jovina Street, one of the oldest and busiest streets in Novi Sad, is named after the famous Serbian poet Jovan Jovanović Zmaj. This street has been a central artery throughout the city’s history and today is a pedestrian zone that connects the main squares and historical landmarks. City Square, also known as Freedom Square, is the heart of social and cultural life, surrounded by buildings of significant architectural value, such as the City Hall and the Cathedral [27]. Dunavska Street, leading to Dunav Park and the banks of the Danube River, is an important part of Novi Sad’s urban landscape. This street is known for its unique atmosphere and well-preserved examples of 19th and early 20th-century architecture. Pašićeva Street and Catholic Gate, with their significant cultural and religious buildings, further contribute to the historical importance of the city’s core [28]. The historical center of Novi Sad represents the focal point of the city's cultural

and historical legacy. Over its rich history, Novi Sad has played a key role in the cultural and political life of Serbia. The urban structure of the historical core developed in line with European urban trends, with dominant architectural styles including Baroque, Classicism, Art Nouveau, and Modernism. These diverse architectural influences are reflected in the buildings in the city center, such as City Hall, the Bishop's Palace, and Zmaj Jovina Street, which form the heart of the historical core [29]. The construction of significant buildings with stylistic characteristics, which have been preserved to this day in the Old Core, began in the early decades of the 18th century and continued until World War II. Among the earlier built structures, which significantly contribute to the high aesthetic and architectural value of this area, the sacred buildings stand out: St. Nicholas Church (1730), the Cathedral of St. George (1741), the Assumption Church (1765–1777), the Greek Catholic Church (1820), and the Roman Catholic Church of the Name of Mary (1895). Due to significant damage to many structures during the 1849 Uprising, only rare examples, mainly secular, from the Baroque and Classical periods have been preserved. Special mention should be made of the house at Zmaj Jovina Street number 28, first recorded in 1720, as well as the one at the corner of Zmaj Jovina and Nikola Pašić Street, built in 1751, which is the only one fully preserved from that period. Stylistic and architectural similarities of these houses can be found in the Petrovaradin Suburb, with the possibility that they were built by the same masters [29]. The oldest architectural layers of the Old Core are preserved in a series of houses on Zmaj Jovina and Dunavska Streets, as well as in the blocks formed by Pašićeva, Miletićeva, Njegoševa, Grčkoškolska, Nikolajevska Streets, extending to Jovan Subotić Street. Further southwest, they are also preserved in the streets of Kralja Aleksandra and the Theater Square (City Hall block). These houses, mostly multi-story, were built in the first half of the 19th century, with many constructed immediately after the Uprising, during the period of intense city restoration. They are characterized by floor plans in the shape of the letters "L" or "P", with communicating balconies on the courtyard facades supported by vaulted constructions on Baroque-style stone consoles. The basements and ground floors of these houses are always vaulted with various constructive types. The upper floors often feature an "alcove," a niche in the corner of the house, with pseudo-Doric or later semi-columns, introduced as a functional solution during the Classicist period to provide lighting for the corner room where the two wings of the house meet. The roofs of the preserved houses are generally lower and gabled, which is also characteristic of Classicism [29]. It is common for the oldest buildings to have facades with stylistic features from later periods, the result of reconstructions carried out by the owners in accordance with the aesthetic and fashion trends of the time.

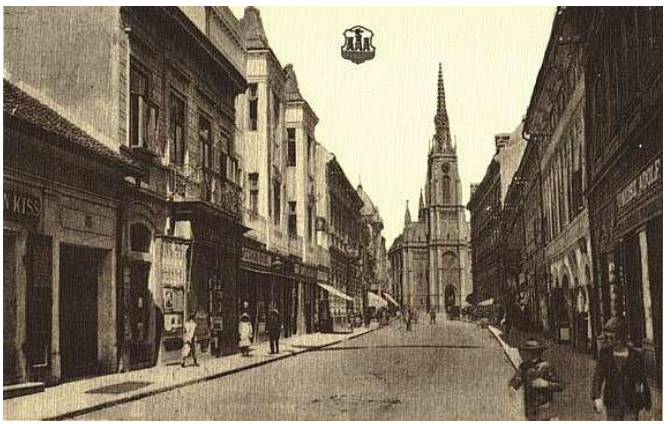


Figure 3. Novi Sad in 1920, Liberty Square, https://upload.wikimedia.org/wikipedia/commons/thumb/f/f2/Novi_Sad_1920.jpg/250px-Novi_Sad_1920.jpg

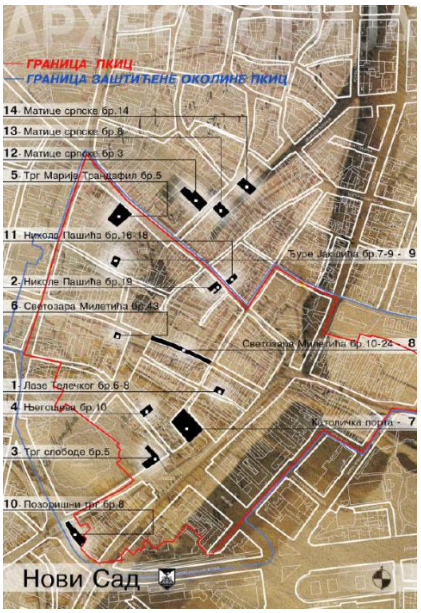


Figure 4. Photograph from the book Srbulović, Đ. The Old Town Core of Novi Sad: Catalogue of Buildings, 2017.

5. SOCIO-POLITICAL AND ECONOMIC FACTORS OF CULTURAL HERITAGE PRESERVATION

Social and economic factors have a profound impact on the life of the community and the perception of the historical center as a cultural and social hub. The different history and development of these cities have led to varying political factors that influenced the preservation of the core areas. The historical center of Novi Pazar has been protected since 1988, while the old town center of Novi Sad has been under protection since 2006 [9-12].

5.1. The Impact of Political Decisions

After World War II, Novi Pazar underwent significant urban transformation, in line with broader trends in former Yugoslavia influenced by socialist ideologies. The city received its first general urban plan in 1956, and the project for modernizing the city center began in 1968, with the aim of creating a new visual identity. This led to significant changes in the historical core of the city, where many buildings were demolished to open new roads and buildings, including the Municipal and Cultural Centers [33]. A significant milestone was 1977, when the Institute for the Protection of Monuments in the city of Kraljevo began documenting monuments and researching cultural heritage. From 1971 to 1973, a group of architects and architecture students conducted research that laid the foundation for the General Plan for the Valorization and Protection of the Historical Center of Novi Pazar from 1975. The Heritage Protection and Management Board was established in 1975 and set the foundations for a responsible approach to heritage protection planning, including the historical city center. This board was key in implementing a methodology that encompassed the protection of cultural heritage and urban planning principles with a special focus on a holistic approach to architectural heritage preservation. In that period, in 1986 and 1987, additional research was initiated, resulting in the creation of the Detailed Protection and Revitalization Plan for the Historical Center of Novi Pazar in 1988, which legally protected most of the buildings in the historical core [33]. The methodology used by the Detailed Protection Plan was based on the

protection of cultural heritage, considering urban planning principles and the importance of revitalization. The plan involved analyzing the current state of the bazaar, architecture, urban structure, the preservation of buildings and infrastructure, as well as the monument valorization of the entire space and individual buildings. Based on the research, the monument valorization included categorizing buildings according to their monumental value [22]. The state cultural heritage policy during the socialist period was oriented towards demonstrating the power of the new society through architectural and urban expression. This approach, although subject to changes due to economic dependence and shifts in political trends, was focused on modernist and international urbanism, which often led to drastic breaks with traditional architecture. However, the urban revolution in Novi Pazar, especially since the 1960s, had a specific character, as it combined the morphology of the terrain, cultural heritage, and unorthodox elements of the modernist urban matrix [33]. During the 1990s, the economic and social crisis in Serbia caused significant changes in the historical part of Novi Pazar, which mostly had negative consequences on the visual appearance and spatial values of the city. Illegal interventions, such as modernizing buildings without the approval of the Institute for the Protection of Monuments, led to a reduction in the authenticity of the historical center. Changes, such as replacing traditional wooden windows with modern aluminum or plastic windows, significantly impacted the visual identity of the city center [33]. Changes in legislation and reduced funds for cultural heritage protection after 1990 further worsened the situation in the historical center of Novi Pazar. Inconsistent planning and a weak management system created conditions for the destruction of monument values, undermining the visual-aesthetic and functional characteristics of this part of the city [34]. With the beginning of the 2000s, with the recovery of the country and the liberalization of the market, processes of development control began to be established, including the implementation of new urban concepts and tools, such as participatory planning processes and strategic plans. A key moment for the historical center of Novi Pazar was the adoption of the Detailed Regulation Plan for the Historical Center with the Park in 2017, which laid the foundations for the future development of this area, focusing on physical-spatial layout and land use [33]. However, despite efforts, the historical center of Novi Pazar still faces challenges. Mass urbanization and the influx of population from surrounding areas have created pressure on existing infrastructure systems, which has further contributed to functional obsolescence. Increased building heights, inconsistencies in material selection, and illegal interventions, such as the illegal reconstruction of the Arab mosque, represent a serious problem in the revitalization process. These changes highlight the need for better management, the enactment of appropriate laws, and raising awareness of the importance of cultural heritage preservation. In order to preserve the rich cultural heritage, a multidisciplinary approach, cooperation between institutions and the community, and continuous investment are necessary [35].

Social and economic factors have a profound impact on the life of the community, shaping the perception of the historical center as the cultural and social hub of the city.

Although significant progress has been made in preserving the architectural heritage of Novi Pazar, challenges related to the integration of cultural heritage into contemporary urban development remain. Recent studies emphasize the importance of adaptive reuse and participatory planning in the revitalization of historic cores, particularly in post-socialist contexts. For instance, a study on Belgrade highlights how the adaptive reuse of abandoned structures can contribute to the preservation of cultural identity and economic development [36]. Compared to these findings, local strategies often lack systematic support for stakeholder engagement and innovative heritage management models, indicating a need for improvement and alignment with contemporary global trends.

Novi Sad

The protection and preservation of Novi Sad’s historic city center are key elements in maintaining the city's cultural and historical identity. These policies are the result of a combination of local, national, and international efforts that ensure the preservation of the

authenticity and integrity of historical buildings and urban structures. In 2006, the city center of Novi Sad was officially designated as a Spatial Cultural-Historical Entity. This decision, made by the Republic of Serbia, recognized the historical and cultural value of this area, encompassing key buildings and streets within the city core [27]. Cultural heritage protection in Serbia is regulated by the Cultural Heritage Law, which outlines measures for the protection, conservation, and restoration of cultural assets. Local authorities, in collaboration with the Institute for the Protection of Cultural Monuments, implement these measures in Novi Sad, ensuring the preservation of the authenticity and integrity of the city center [37]. After the city center was placed under protection, strict urban planning regulations were introduced, limiting the construction of new buildings within the protected area. These restrictions are crucial for maintaining the historical character of the city and preventing the disruption of the visual identity of the core [13]. A special focus has been placed on the restoration and reconstruction of existing buildings, aiming to preserve original architectural elements. Restoration projects are often carried out in collaboration with international experts, enabling the application of modern conservation techniques [38]. Novi Sad is part of several European projects aimed at preserving cultural heritage. These projects include financial and technical support for the restoration of historical buildings, as well as the development of sustainable models for managing cultural assets [39]. As part of the preservation efforts, various educational initiatives have been carried out, engaging both the local population and tourists. The aim of these initiatives is to raise awareness about the importance of preserving cultural heritage and promoting responsible behavior in historical areas [40]. The preservation policy for Novi Sad's city center relies on a combination of legal, urban, and educational measures aimed at maintaining its historical character and cultural identity. Through cooperation at local, national, and international levels, it has been ensured that the city center remains an authentic testament to the rich history and culture of Novi Sad. The issue of new modern constructions in the Old Town has existed for some time, due to the mistaken assumption that replicas of old buildings should be created in their immediate surroundings. According to the protection service, future architecture in the Old Town should reflect the spirit of its time, both in design and shaping. Novi Sad has adopted a series of local action plans for cultural heritage preservation, which align with broader strategies at the national level. These plans define concrete steps for preserving and restoring culturally significant buildings, as well as improving cultural asset management. The plans also include measures to encourage cooperation between the private and public sectors in funding and implementing conservation projects. Novi Sad, as part of European Commission and UNESCO initiatives, has participated in programs related to the protection and promotion of cultural heritage. These programs often involve training experts and developing new technologies for conservation, as well as cultural tourism that contributes to the sustainable development of the city [41]. The local community plays a crucial role in preserving cultural heritage. Active involvement of citizens through various initiatives, such as volunteer programs and cultural festivals, helps raise awareness and foster a sense of shared ownership of cultural assets [42]. Cultural tourism has become one of the key elements in preserving and promoting the city center. Sustainable approaches to tourism, which respect cultural heritage and involve the local community, contribute to the economic development and maintenance of Novi Sad's cultural identity [43].

Despite the efforts invested in the preservation and revitalization of Novi Sad's historical core, challenges persist in achieving a balance between urban development and the protection of cultural heritage. International research points to the necessity of integrated planning approaches and sustainable tourism models for historic urban areas. For example, a study focusing on Safranbolu and Amasra in Turkey highlights the importance of a holistic planning approach to sustainable tourism to preserve both cultural and natural heritage [44].In comparison, current practices in Novi Sad show a tendency toward partial solutions and project-oriented interventions, emphasizing the need for more comprehensive and long-term heritage management strategies.

5.2. Economic Pressures and Consequences

The economic aspect refers to the commercial and trade activities that take place in the historic center, where there is a conflict between the need for modernization and the preservation of authenticity. Managing cultural heritage presents challenges that require specific financial resources. A key issue is how to develop a sustainable financing model that allows for the preservation of significant cultural monuments. The increasing number of properties requiring financing, both in Serbia and Europe, reflects a growing awareness of the importance of the past and the need to preserve national identity. This growth demands new policies and support, particularly in developing countries, so that cultural heritage can be preserved and used as a generator of economic development, especially through cultural tourism [2]. Given the upcoming financial commitments for heritage protection in Serbia, the existing European financing model raises concerns about the preservation of architectural heritage. It is necessary to improve heritage management to overcome financial inadequacy. Introducing mandatory financial subsidies for cultural monuments requires identifying incentives and capacities for financiers, as well as finding new financing models that can reduce maintenance costs. International organizations, state and local authorities, non-governmental organizations, as well as private and public donors play a key role in preserving cultural heritage. The key challenge remains how to develop an economically sustainable model for financing cultural heritage that can address contemporary challenges and prevent the loss of important cultural monuments. The economic definition of value has evolved over time, particularly in the assessment of non-market value, using methods such as CVM (contingent valuation method) and discrete choice method, which rely on direct responses from respondents in surveys [45]. In addition to these methods, travel cost and hedonic price methods are also used, although their application is considered theoretical in assessing public goods. By using these methods, researchers can estimate how much respondents are willing to pay for the protection or restoration of monuments. Practically calculating the economic value of these benefits poses a challenge. It is also important to consider the relevance of a given object in society, where nominal value (N) is often used as an independent unit of assessment. A restored historic object has a higher nominal value than a neglected one, which can lead to unexpected costs [46-47].

6. COMPARATIVE ANALYSIS OF THE PRESERVATION OF HISTORICAL CENTERS

Comparative analysis including the definition of methods and strategies for the preservation of architectural heritage in Novi Pazar and Novi Sad, comparison of preservation challenges, and recommendations for improving preservation policies.

6.1. Comparison of preservation challenges

Challenges in Novi Pazar: Balance between modernization and preservation: The need for infrastructure improvements that do not threaten the cultural heritage and historical characteristics of the city [9]. Financing: Insufficient funds for the restoration and preservation of cultural monuments [10]. Community participation: The need for greater involvement of the local community in preservation processes and decision-making [11].

Challenges in Novi Sad: Urbanization: Conflict between the interests of preserving historical monuments and the need for infrastructure modernization [12]. Tourism: Managing tourism to preserve the authenticity of historical sites and avoid the negative consequences of excessive tourist pressure [13]. Cultural heritage protection: Pressure on infrastructure and the need to balance preservation and development [14].

6.2. Recommendations for improving preservation policies

Strengthening the legal framework: Improvement and strict implementation of cultural heritage laws to ensure effective protection of historical centers [11, 14].

Financial support: Increasing investments in the restoration and preservation of cultural monuments through state and international funds [10, 13].

Community participation: Greater involvement of the local community in preservation processes through education and participatory projects [9, 12].

Sustainable tourism: Development of sustainable tourism strategies that balance the promotion of cultural heritage with the preservation of the authenticity of the site [10, 14].

Technological innovation: The application of modern technologies in preservation and restoration processes, such as digital documentation and 3D modeling [12, 13].

7. CONCLUSION

Architectural heritage represents the core of the cultural identity of each community, providing not only aesthetic and historical value but also a deep connection to the past that shapes the present and future. In the context of Novi Pazar and Novi Sad, the preservation of historical cores, especially the Old Bazaar and the city center, is of vital importance for maintaining the identity and cultural continuity of these areas. In Novi Pazar, preserving the Old Bazaar reflects the commitment of the local community and authorities to maintaining the oriental spirit and tradition, despite challenges such as a lack of funding and the impact of modern urbanization. On the other hand, Novi Sad faces pressures of modernization and commercialization, requiring a balance between preserving authenticity and developing tourist infrastructure. The key to successfully preserving these urban cores lies in the synergy between local authorities, the community, and experts, who, through appropriate urban planning and preservation strategies, must integrate the protection of cultural heritage with contemporary development needs. Through comparative analysis, it is clear that although both cities have different cultural and historical contexts, they share the common challenge of preserving identity in light of modernization. Sustainable management of cultural heritage, which considers economic, socio-political, and cultural aspects, is crucial for maintaining authenticity and strengthening cultural identity. This approach not only protects the past but also lays the foundation for the future development of cities, ensuring that cultural heritage remains alive and relevant for future generations. Ultimately, the preservation of the cultural heritage of Novi Pazar and Novi Sad represents not just the protection of architectural objects but also the preservation of the soul and identity of these cities, enabling their further prosperous and sustainable development within the contemporary social context.

REFERENCES

[1] Nenadović Slobodan: **Protection of Architectural Heritage.** University of Belgrade, *Faculty of Architecture,* 1980.

[2] Muminović Esad, Kučević Amela: **Revitalization of Architectural Heritage through a New Restoration Model on the Case Study of the Old Bazaar in Novi Pazar.** *Novopazarski zbornik,* No. 39, 2016, https://muzejnp.rs/ZBORNIK/39/index.html

[3] Aleksić Julija, Božović Jelena: **Seismic Rehabilitation Techniques for Conserving and Managing Cultural Heritage of the Old City Fortress in Novi Pazar.** *Sustainability*, Appl. Sci., 12(23), 12018, 2022, https://doi.org/10.3390/app122312018

[4] Erdujhelji Melhior: **History of Novi Sad**. Veternik, 2002.

[5] Kulekçi Akpinar Elif, Ozgeris Mustafa, Sezen Isik, Karahan Ayse, Karahan Faris: **A Research to Determine the Perception of the Tangible Cultural Architectural Heritage of Erzurum Castle and its Surroundings in Turkey.** Istanbul, Turkey, *Sustainability,* 16 (1), 34, 2024, http://dx.doi.org/10.3390/su16010034
[6] Law on Cultural Heritage, http://www.parlament.gov.rs/upload/archive/files/lat/pdf/zakoni/2021/2145-21.%20-%20lat..pdf, (2.8.2024.)
[7] Republic Institute for the Protection of Cultural Monuments – Belgrade, https://www.heritage.gov.rs/latinica/istorija_republickog_zavoda_za_zastitu_spomenika_kulture.php, (2.8.2024.)
[8] Law on Cultural Heritage. "Official Gazette of the Republic of Serbia", No. 129 of December 28, 2021, Cultural Monument, Article No. 17, https://pravno-informacioni-sistem.rs/eli/rep/sgrs/skupstina/zakon/2021/129/11, (2.8.2024.)
[9] City of Novi Pazar (2015). Sustainable Development Strategy of Novi Pazar 2015-2020, 2015, https://www.novipazar.rs/, (29.7.2024.)
[10] City of Novi Pazar (2020). Detailed Regulation Plan for the Old City Core, 2020, https://www.novipazar.rs/, (29.7.2024.)
[11] National Assembly of the Republic of Serbia (2020). Law on Cultural Goods, 2020, http://www.parlament.gov.rs/, (30.7.2024.)
[12] City of Novi Sad (2017). Sustainable Development Strategy of Novi Sad 2017-2021, 2017, https://www.novisad.rs/, (30.7.2024.)
[13] City of Novi Sad (2021). General Urban Plan of Novi Sad, 2021, https://www.novisad.rs/, (30.7.2024.)
[14] City of Novi Sad (2021). Program for the Revitalization of the City Core, 2021, https://www.novisad.rs/ , (30.7.2024.)
[15] Program for the Revitalization of the Petrovaradin Fortress
[16] Salković Avdija: **The Wall – The Tired Key of Ottoman Novi Pazar.** *Novopazarski zbornik,* No. 42, 2019, https://muzejnp.rs/ZBORNIK/42/mobile/index.html#p=1
[17] Radovanović Miloš: **Novi Pazar Bazaar, Inns, and Bridges.** *Novopazarski zbornik,* No. 15, 1991, https://muzejnp.rs/ZBORNIK/15/index.html
[18] Popadić Milan: **Architect Amir Ćorović and the Project for the City Center in Novi Pazar.** *Novopazarski zbornik,* No. 32, 2017, https://muzejnp.rs/ZBORNIK/32/index.html
[19] Premović Aleksić Dragica: **Islamic Monuments of Novi Pazar.** *Museum "Ras",* 2013.
[20] Koničanin Omer: **Novi Pazar Bazaar.** *Novopazarski zbornik,* No. 17, 1993, https://muzejnp.rs/ZBORNIK/17/index.html
[21] Nešković Jovan: **The Old Bazaar in Novi Pazar.** Belgrade – Kraljevo: Institute for the Protection of Cultural Monuments, 1988.
[22] Muminović Esad, Radosavljević Uroš, Beganović Džemila: **Strategic Planning and Management Model for the Regeneration of Historic Urban Landscapes: The Case of the Historic Center of Novi Pazar in Serbia.** *Sustainability*, 12 (4), 1323, 2020, https://doi.org/10.3390/su12041323
[23] Kostić Dušan: **History of Novi Sad and Its Suburbs.** Novi Sad: Matica Srpska, 1950.
[24] Gavrilović Živko: Matica Srpska Through the Centuries. Novi Sad: Matica Srpska, 1992.
[25] Institute for the Protection of Cultural Monuments of Novi Sad. Spatial Cultural-Historical Units, https://www.zzzskgns.rs/ , (1.8.2024.)
[26] Serbian Academy of Sciences and Arts. Collection on the Serbian National Renaissance. Belgrade: SANU, 1971, https://www.sanu.ac.rs/, (1.8.2024.)

[27] City of Novi Sad (2021). Liberty Square and Zmaj Jovina Street: Historical Overview, 2021, https://www.novisad.rs/, (1.8.2024.)
[28] Matica Srpska (2020). Landmarks of Novi Sad, 2020, https://www.maticasrpska.org.rs/en/, (1.8.2024.)
[29] Srbulović Đorđe: **The Old Core of Novi Sad: Spatial Cultural - Historical Unit.** 2017.
[30] Urban Institute of the City of Novi Sad (2020). Pedestrian Zones in Novi Sad, 2020, https://www.nsurbanizam.rs/, (1.8.2024.)
[31] City of Novi Sad (2015). City Hall: History and Significance, 2015, https://www.novisad.rs/, (1.8.2024.)
[32] Republic Institute for the Protection of Cultural Monuments (2021). Management of Urban Heritage and Tourism, 2021, https://www.heritage-su.org.rs/, (30.7.2024.)
[33] Dragović Danilo: **The Central Zone of Novi Pazar: Programmatic Foundations of Concepts from 1956 to 1968.** Faculty of Technical Sciences, *Technical Sciences Edition – Monographs,* Novi Sad, 2018.
[34] Debljović Ristić Nevena: **Historical Urban Space of Novi Pazar.** *Novopazarski zbornik*, No. 41, 2018, https://muzejnp.rs/ZBORNIK/41/NPZ%2041.html#p=1
[35] Kahrović Jerebičanin Muradija: **Historical Shaping of Urbanism and Architecture in Novi Pazar.** *Novopazarski zbornik,* No. 37, Novi Pazar, 2014, https://muzejnp.rs/ZBORNIK/37/index.html#p=4
[36] Vukmirović Milena, Nikolić Marko: **Industrial heritage preservation and the urban revitalisation process in Belgrade.** *Journal of Urban Affairs,* 45 (2), 191-216, 2021, https://doi.org/10.1080/07352166.2020.1851140
[37] Law on Cultural Goods, Official Gazette of the Republic of Serbia, https://www.paragraf.rs/propisi/zakon_o_kulturnim_dobrima.html
[38] Institute for the Protection of Cultural Monuments of Novi Sad. Report on Conservation Works in the City Core, https://www.zzzskgns.rs/, (1.8.2024.)
[39] European Union, Cultural Heritage Preservation Projects in Serbia
[40] Ministry of Culture and Information of the Republic of Serbia. Education Programs and Raising Awareness about the Importance of Cultural Heritage, https://kultura.gov.rs/, (1.8.2024.)
[41] City of Novi Sad. Local Action Plan for the Preservation of Cultural Heritage, https://www.novisad.rs/, (1.8.2024.)
[42] UNESCO. Initiatives for the Preservation of Cultural Heritage in Southeastern Europe.
[43] Urban Institute of the City of Novi Sad. Green Spaces and Ecological Sustainability in the City Core, https://www.nsurbanizam.rs/, (1.8.2024.)
[44] Janinović Jovana: **The modern and the Monster: heritage activism in the post-socialist city between performance and performativity.** *Urban Geography*, 46 (3), 481-505, 2024, https://doi.org/10.1080/02723638.2024.2376897
[45] Anon: **Economics and Heritage Conservation**. In: Los Angeles: Getty Conservation Institute, 1998.
[46] Skarin Palsson Ingela: **A Finance Model for the Built.** In: Lund, Sweden: Lund University, Faculty of Engineering, 2011, https://portal.research.lu.se/files/6416876/2203938.pdf
[47] Thorsby David: **Heritage as Asset.** In: The Economics of Cultural Policy. Cambridge, UK: Cambridge University Press, 2010, https://assets.cambridge.org/97805216/87843/frontmatter/9780521687843_frontmatter.pdf

doi.org/10.62683/SINARG2025.014

Research paper

ADAPTIVE REUSE OF INDUSTRIAL MILLS – BALANCING HERITAGE PROTECTION AND NEW USES

Ljiljana Jevremović[1], Ana Stanojević[2], Uroš Antić[3], Isidora Đorđević[4], Aleksandar Milojković[5]

Abstract

Industrial heritage is widely recognized as an essential part of the built environment, reflecting human achievements in technical culture. In sustainable development, the adaptive reuse of industrial heritage structures has emerged as a pivotal strategy for safeguarding historical edifices while seamlessly integrating them into the fabric of modern urban life. This paper examines the adaptive reuse of a specific industrial building typology—industrial mills—structures dating back to the early phases of industrialization. Characterized by their distinctive architectural forms, strategic urban placements, and the prevalent use of durable construction materials, particularly red brick façades, industrial mills have been frequently identified as prime candidates for adaptive transformation.

This study thoroughly examines multiple case studies involving successfully repurposed industrial mills, emphasizing multi-story structures constructed during the 19th and early 20th centuries, which exhibit pre-modern architectural characteristics. By analyzing these mills' urban forms, spatial configurations, and functional layouts, the research seeks to elucidate recurring models of adaptive reuse that correspond to various contemporary functions. The investigation highlights these structures' architectural and historical significance and addresses the challenges and opportunities inherent in their transformation.

The findings of this study contribute to a broader understanding of how industrial mills can be effectively repurposed, providing insights that may be particularly valuable for regions with limited experience in such transformations, such as Serbia. By bridging the gap between heritage protection and contemporary utility, this study advocates for a balanced approach that honors the historical significance of industrial mills while fostering innovative uses that enhance urban vitality and sustainability.

Keywords: *Adaptive reuse, Industrial heritage, Industrial mills, Heritage protection, Sustainable development, Urban transformation*

[1] PhD, Assistant Professor, University of Niš – Faculty of Civil Engineering and Architecture, Serbia, ljiljana.jevremovic@gaf.ni.ac.rs, ORCID 0000-0001-6877-9004
[2] PhD candidate, Teaching Assistant, University of Niš – Faculty of Civil Engineering and Architecture, Serbia, ana.stanojevic@gaf.ni.ac.rs, ORCID 0000-0003-3199-9913
[3] PhD student, Ministry of Education scholarship holder, University of Niš – Faculty of Civil Engineering and Architecture, Serbia, anticuros6@gmail.com, ORCID 0009-0004-2074-7627
[4] PhD candidate, Research Associate, University of Niš – Faculty of Civil Engineering and Architecture, Serbia, isidora.djordjevic@gaf.ni.ac.rs, ORCID 0009-0000-0012-5063
[5] PhD, Associate Professor, University of Niš – Faculty of Civil Engineering and Architecture, Serbia, aleksandar.milojkovic@gaf.ni.ac.rs, ORCID 0000-0002-0330-3627

1. INTRODUCTION

Industrial heritage represents an asset, embodying the remnants of industrialization that shaped urban landscapes and spurred societal progress [1]. It encapsulates historical narratives and collective identities that reveal socio-economic transformations and foster cultural continuity [2]. Industrial mills, for example, with their characteristic multi-story red brick façades and innovative construction techniques, serve as tangible connections to the industrial processes that once redefined urban settings [3,4]

Adaptive reuse - the process of repurposing existing structures for functions beyond their original intent - has emerged as a key strategy in promoting urban sustainability [5]. By extending the lifecycle of buildings, adaptive reuse minimizes resource consumption, reduces waste, and advances principles of economic efficiency, social inclusivity, and environmental stewardship [6]. However, despite their potential, many industrial mills remain underutilized or deteriorate, especially in regions where adaptive reuse practices are not well established [7]. Financial constraints, regulatory barriers, and the difficulty in balancing modern needs with architectural authenticity complicate these transformations [8,9,10,11]. Moreover, the absence of clear guidelines and successful case studies further exacerbates these challenges [7,12,13].

The adaptive reuse of industrial mills requires a careful balance between preserving historical value and addressing modern urban requirements. Innovative strategies that integrate social, economic, and environmental considerations are essential, particularly in regions such as Southeast Europe, where a lack of practical experience has often resulted in the neglect of these structures [14,15,16]. The current study investigates adaptive reuse strategies employed in transforming industrial mills, with the aim of identifying methodologies that harmonize heritage conservation with contemporary imperatives. By analyzing a range of case studies, this research seeks to develop replicable models for regions facing heritage management challenges, thereby contributing to urban revitalization and sustainable development efforts [2,5]. The distinctive historical and architectural significance of industrial mills, often situated in central urban locations, underscores their potential to stimulate urban regeneration, boost local economies, and enhance community engagement [3,17].

This investigation is guided by two principal research questions: How can industrial mills be effectively repurposed while preserving their heritage values? What recurring models of adaptive reuse have emerged for these structures? Employing a case study methodology, the study examines transformed industrial mills across diverse regions, emphasizing architectural interventions, spatial reconfigurations, and the subsequent impact on urban contexts.

The paper is organized as follows. Following the Introduction, the Theoretical Framework and Literature Review section outlines the research context and evaluates previous studies. The Methodology section details the study design and criteria for case selection. Subsequently, the Comparative Case Study Analysis chapter presents key insights and models of adaptive reuse. Finally, the Discussion and Conclusion synthesize the findings and offer recommendations for future research directions.

2. THEORETICAL FRAMEWORK

2.1 Adaptive Reuse and Industrial Heritage

Adaptive reuse involves repurposing obsolete buildings for contemporary uses while conserving significant architectural elements and cultural meaning. This approach extends the life of existing structures and fosters sustainable urban development by curbing the environmental impacts linked to new construction [18]. Its core principles include retaining key historical and architectural features, integrating modern functions, and ensuring economic viability. Over recent decades, adaptive reuse has evolved into a comprehensive strategy addressing architectural, environmental, social, and economic challenges. In post-industrial contexts, it has become a key method for reactivating obsolete structures - particularly those of historical or architectural merit—thus lowering waste and resource consumption, reducing carbon footprints, and revitalizing local economies. Such reuse is integral to combating urban sprawl and resource depletion.

Industrial heritage - a subset of cultural heritage that includes buildings, machinery, workshops, and complexes linked to manufacturing - offers prominent examples in ordinary structures like industrial mills. Once central to 19th- and early 20th-century urban fabrics, these mills are noted for their large scale, repetitive architectural systems, and robust construction designed for efficiency. Their inherent flexibility, high ceilings, and central locations make them ideal for adaptive reuse. In repurposing these sites, the process not only conserves embodied energy and historic fabric but also transforms them into catalysts for new urban development, thereby fostering sustainable and culturally enriched environments.

2.2 Heritage Protection Challenges

The process of adaptively reusing industrial heritage sites presents inherent tensions between conservation and functional modernization. Maintaining a site's original character while meeting today's requirements challenges architects, planners, and heritage advocates. Some critics argue that strict conservation can hinder necessary adaptations, while an excessive focus on modernization risks diluting the historical and cultural identity of the site [19]. Established frameworks, such as the Nizhny Tagil Charter [20] and the Burra Charter [21], advocate for sustainable preservation coupled with minimal intervention and compatible new uses. These guidelines emphasize stakeholder collaboration throughout the adaptive reuse process. Nonetheless, practical obstacles remain, as structural limitations, environmental upgrades, and regulatory demands can force changes that compromise historical authenticity. Thus, successful adaptive reuse requires nuanced, case-specific strategies that balance preservation with innovation.

2.3 Typology of Industrial Mills

Industrial mills illustrate a distinctive typology developed in the 19th and early 20th centuries in response to production needs. Characterized by robust, multi-story construction, these mills feature large open spaces, repetitive red brick façades, extensive windows, and structural frameworks - often supported by cast iron or heavy timber beams - that facilitate flexible interior layouts [22]. The design of these mills, including repetitive window bays and ancillary elements like towers and chimneys, underscores their functional efficiency and

durability. Initially located on city peripheries or along transportation routes, many mills have since become integral to urban cores, enhancing their potential for adaptive reuse. Redeveloped mill sites can transform into vibrant cultural centers, mixed-use developments, or community spaces, thereby stimulating economic activity and promoting social interaction within the urban fabric.

3. METHODOLOGY

This research adopts a qualitative case study approach to examine adaptive reuse strategies for industrial mills. The method facilitates a detailed exploration of the architectural, cultural, and urban transformation processes integral to repurposing heritage structures, capturing the complex interplay between preservation and modern functionality [23, 24]. Selected cases span Western, Central, and Southeast Europe, and North America, thereby offering a broad comparative analysis of regional approaches to adaptive reuse. The cases, mostly late-19th to early-20th-century mills constructed with masonry or brick, were chosen for their typological consistency and documented success in reuse projects. In selecting these examples, special attention was given to notable architectural contributions and their integration into urban fabrics.

A combination of methods was used to develop a comprehensive understanding of each case. Archival research provided historical context, original design intentions, and details about the mills' previous functions [23]. Meanwhile, on-site analysis yielded insights into current conditions, spatial organization, and the status of material preservation. Detailed examination of architectural drawings and project documentation facilitated an assessment of interventions and spatial modifications. Where available, interviews with architects, urban planners, and other stakeholders enriched the study with qualitative perspectives and practical insights [25].

The analysis employed a comparative framework focusing on four dimensions:

- Spatial configuration, examining changes in interior layout, circulation, and zoning;
- Architectural interventions, assessing façade treatments, structural adaptations, and the introduction of new materials or technologies;
- Functional outcomes, evaluating the sustainability and effectiveness of the new uses introduced;
- Heritage conservation, exploring how historical authenticity was maintained, negotiated, or reinterpreted [26].

This structured framework enables the identification of best practices, context-specific solutions, and common challenges across varied adaptive reuse projects, thereby contributing to a nuanced understanding of sustainable urban regeneration.

4. COMPARATIVE CASE STUDY ANALYSIS

4.1 Overview of Selected Case Studies

Table 1 presents 16 case studies of adaptive reuse featuring industrial mills and warehouses from the 19th and early 20th centuries. It showcases a variety of approaches to heritage conservation and highlights innovative transformations.

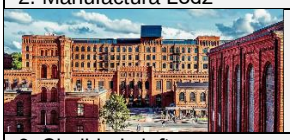
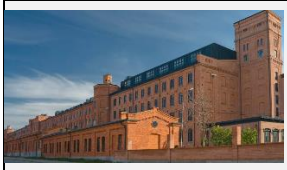
Table 1. Comparative Overview of Adaptive Reuse Projects: Industrial Mills and Warehouses (19th–20th Century)

Case Study	Year Built	Original Use	Typology
Location / Country	**Year Reuse**	**New Use**	**Heritage Status**
Richard Adam Gallery [27]	1865–1920	Foundry & Engineering Works	One-story workshop building
Brno, Czech Republic	2005	Gallery	Protected Cultural Monument
Manufaktura Łódź [28]	1872–1892	Cotton Textile Factory	Multi-Story Industrial Mills
Łódź, Poland	2006	Mixed-Use (Retail, Cultural, Hotel)	Listed Historic Monument
At Sheibler's loft [29]	1855	Textile Factory	Multi-Story Industrial Mills
Łódź, Poland	2007-2010	Residential	Protected Cultural Monument
Special Economic Zone – SEZ [30]	1890	Textile Factory	Multi-story factory building
Łódź, Poland	2010-2012	Office Spaces, Museum	Protected Cultural Monument
Salts Mill [31]	1853	Wool Textile Mill	Multi-Story Industrial Mill
Saltaire, UK	1987 onwards	Cultural Centre + Offices + Shops	UNESCO World Heritage Site
Zeche Zollern Workshops [32]	1898	Coal Mine Workshops	Industrial Courtyard Complex with Multifunctional Workshop Buildings
Dortmund, Germany	1999	Industrial Heritage Museum + Offices	Protected Monument (National)
Tobacco Factory [33]	1901	Tobacco Mill	Multi-Story Industrial Processing and Storage Block
Bristol, UK	1998	Mixed-use (Offices, Theatre, Café)	Locally Listed
The Loom [34]	1889	Wool Mill	Urban Multi-Story Warehouse and Workshop
London, UK	2015	Creative Office Hub	Locally Listed
De Lakfabriek [35]	1925	Leather factory	Multi-Story Industrial Mill
The Netherlands	2018	Residential	Protected
La Minoterie [35]	19 c.	Flour factory	Multi-Story Industrial Mill
Roubaix, France	2008	Residential	Protected
60 Atlantic Avenue [35]	1898	Factory	Multi-story warehouse
Toronto, Canada	2014	Business centre	Protected
St. Ann's Warehouse [35]	1860	Tobacco Warehouse	Multi-story warehouse
Brooklyn, USA	2015	Theatre	Protected
Business Incubator [35]	Late 19th C.	Paper factory	Multi-Story Industrial Mill
Pont-Audemer, France	2013	Business incubator	Protected
Adaptation of Former Granary [35]	1892 - 1914	Grain Storage	Multi-story warehouse
Gliwice, Poland	2008	Residential + Retail	Listed Monument
Gouda Cheese Warehouse [35]	19th Century	Cheese Storage	Multi-story warehouse
Gouda, Netherlands	2017	Residential	Not Protected
Old Mill Rigot [35]	1928	Cotton Spinning Mill	Multi-Story Industrial Mill
Dunkirk, France	2014	Business + Day care unit	Protected

4.2 Comparative Analysis

Table 2 analyses key architectural interventions and layouts in 16 case studies, offering insights into the strategies and challenges of adapting industrial mills.

Table 2. Comparative Matrix of Architectural Interventions and Outcomes in Adaptive Reuse of Industrial Mills

Case Study	Preserved Features Key Architectural Interventions	Façade Modification Layout Reconfiguration	Outcomes Challenges & Issues
1. Richard Adam Gallery 	red brick façade, large factory windows	brickwork restoration, preservation of historic character	cultural promotion, contribution to the local economy
	no external interventions	adapted for open-plan double-height exhibition space	lack of greenery and open spaces, unsafe neighborhood
2. Manufactura Łódź 	red brick façade, large factory windows	brickwork restoration, preservation of historic character	Heritage tourism boost; urban regeneration, social cohesion
	rooftop single-volume addition	adapted for shopping stores, cinemas, hotels, museums, restaurants	activation of open spaces, ongoing maintenance
3. Sheibler's loft 	red brick façade, factory windows	preservation of historical character highlighted edges of closed openings' holes	urban regeneration, increase in residential space in the urban matrix
	internal interventions, vertical rooftop extension	subdivision into apartment units, open-plan loft apartments	adapting deep-plan industrial spaces for residential use
4. SEZ Łódź 	red brick façade, factory windows	preservation of original articulation and character	urban regeneration boosted the local economy
	internal interventions, vertical extensions	adapted for offices, conference spaces, meeting rooms	balance between historical and contemporary
5. Salts Mill 	stone façade, window rhythm, internal column structure	light façade cleaning, preservation of historic character	Heritage tourism boost, key part of UNESCO World Heritage Site
	no major external additions or demolitions	adapted for open-plan exhibitions and retail spaces	conservation restrictions, balancing tourism with local needs
6. Zeche Zollern 	brick façades, Art Nouveau entrance hall, steel structure	restoration of the entrance hall and original decorative features	heritage attractions, education, and heritage highlights in Dortmund
	no significant structural additions	adapted for open-plan exhibition space, interconnected halls	maintaining large structures, ongoing conservation costs
7. Tobacco Factory 	red brick façade, large industrial windows	increased openings for natural light	key in Bristol's Cultural Quarter regeneration
	external courtyards created from service yards	corridor layout adapted for flexible working spaces	environmental remediation, retained industrial character
8. The Loom 	brick façade, industrial window design, timber beams	sensitive façade restoration	contributed to East London's creative economy
	opened courtyards for circulation, new public entrances added	adaptation for hybrid workspace with breakout zones and event spaces	upgrading services in historic structures without compromising the fabric

9. De Lakfabriek 	brick façade, large factory windows	window modifications for improved daylight and entrances	added residential units in a historical context
	rooftop pavilion addition, retained industrial footprint	subdivision into residential units, loft-style apartments with open-plan design	energy performance, preserving external historic features
10. La Minoterie 	brick façades, large factory windows	minor alterations for residential access	urban regeneration, residential revitalization
	addition of new rooftop volume and balconies	subdivision into residential units, open-plan loft apartments	ensuring daylight access, maintaining façade authenticity
11. 60 Atlantic Avenue 	heavy timber frame, brick walls, industrial windows	façade cleaning and repointing	office hub in Liberty Village, adaptive reuse precedent
	entrance glass volume addition	open-plan co-working and event space with a common entrance hall	upgrading structural capacity and respecting heritage fabric
12. St. Ann's Warehouse 	brick walls and openings	restoration of brickwork	cultural destination in Dumbo, NY, revitalized historic structure
	creation of an inner courtyard; rooftop pavilion added	adaptation for open-plan theatre with flexible seating	acoustic challenges, integrating modern theatre functions
13. Business Incubator 	brick façades, factory windows	window modifications for improved daylight and entrances	boosted local entrepreneurship, model of rural adaptive reuse
	minor volume subtractions to enhance articulation	corridor layout adapted for flexible modular workspaces	balancing high-tech needs with heritage restrictions
14. Former Granary 	brick façades, gable roofs, and window frames. timber beams	restoration of brickwork	urban revitalization in Gliwice's city center
	vertical comm. towers and entrance volume introduced	subdivision into residential and retail adaptable units	adapting deep-plan storage spaces for residential use
15. Gouda Cheese Wareh. 	brick façade, hoist doors, industrial windows	window alterations for residential needs	residential regeneration within historical urban fabric
	no significant site changes	restructuring into loft apartments with mezzanines	thermal efficiency, integrating new functions, kept exterior character
16. Old Mill Rigot 	red brick, chimney, gabled roof, wooden roof structure	façade restoration, window alterations for new needs	local services enhancement, industrial memory preservation
	interconnecting ground volume addition	adaptation into business & day-care units around the inner courtyard	meeting modern safety and accessibility standards

5. DISCUSSION

The comparative analysis of adaptive reuse projects reveals diverse architectural interventions and urban impacts, shaped by each site's historical context, original use, and

adaptive strategies. The case studies—ranging from industrial mills and warehouses to factories and workshops—demonstrate a careful balance between conserving historical identity and reconfiguring spaces to meet modern functions. Three principal types of interventions emerge: modifications to urban morphology, alterations to façades, and reconfigurations of spatial layouts. These measures are chosen to retain the industrial character of the buildings while integrating new uses that stimulate urban revitalization.

Despite notable successes, projects frequently face challenges related to conservation standards, structural integrity, and the integration of modern functionalities without compromising historical authenticity. For instance, residential adaptations may require improved insulation, additional interior layers, and enhanced daylight access, while public or cultural uses often need larger, more open spaces that can conflict with the building's original design. Successful projects employ innovative strategies—such as incorporating new architectural elements within existing massing (exemplified by SEZ Łódź and St. Ann's Warehouse), minimal façade interventions that preserve aesthetic authenticity, and open-plan spatial reconfigurations that support flexible, multifunctional use. The adaptive reuse of facilities like Salts Mill and Zeche Zollern Workshops illustrates the potential to transform industrial spaces into accessible public areas while retaining their core architectural essence.

Different approaches result in varied urban impacts. Models emphasizing minimal intervention preserve a site's historic ambiance but may limit contemporary functionality. In contrast, balanced approaches, as seen in the Tobacco Factory and Manufaktura Łódź, create synergies between heritage and modern needs that enhance urban vitality. Extensive adaptations—while sometimes compromising historical authenticity—can also drive urban regeneration when they introduce dynamic new functions, as demonstrated by. Old Mill Rigot and St. Ann's Warehouse. Table 3 summarizes this comparative spectrum of adaptive reuse approaches along dimensions such as urban morphology, façade treatment, spatial reconfiguration, new uses, urban impact, and associated challenges.

Table 3. Comparative Spectrum of Adaptive Reuse Approaches

Key Aspect	**Minimal Interventions (Preservation-Oriented)**	**Moderate Transformations (Balanced Approach)**	**Extensive Adaptations (Contemporary Reinterpretation)**
Urban Morphology	Retaining original building mass and footprint	Introducing new volumes while preserving context	Significant new additions or demolitions altering the original mass
Façade Modifications	Preserving original brick and windows	Cleaning and minor modifications to enhance usability	Replacing or extensively altering façade elements
Spatial Reconfiguration	Maintaining the original spatial structure	Open-plan integration with preserved elements	Complete reconfiguration to suit new uses
New Uses	Cultural exhibitions, museums	Mixed-use developments combining residential and commercial	High-density residential or commercial uses
Impact on Urban Context/Outcome	Preserving historical ambiance	Enhancing urban interaction with adaptive functions	Urban renewal with new identity and function
Challenges	Conservation regulations, funding	Balancing modern needs with heritage value	Public acceptance, loss of historical integrity

5.1 Balancing Heritage Protection with Contemporary Needs

The adaptive reuse of industrial mills represents an opportunity to integrate historic preservation with modern functionality. This process requires careful negotiation between maintaining architectural integrity and accommodating contemporary demands like accessibility and energy efficiency. Evidence from various case studies indicates that preserving the original structural grid and materials is an effective means of upholding a site's identity. However, excessive modifications—whether to spatial arrangements or façade treatments—may undermine the historical value and authenticity of these structures. By balancing these factors, urban spaces can be revitalized in a manner that honors their industrial heritage.

5.2 Architectural and Urban Implications

Adaptive reuse is essential for the enhancement of urban vitality and spatial integration, particularly in areas undergoing socio-economic transitions. The conversion of industrial mills frequently acts as a catalyst for the renewal of nearby neighborhoods, attracting residents, businesses, and cultural initiatives. Interventions in urban morphology, such as the introduction of new structures or the selective demolition of outdated elements, improve connectivity and accessibility. Similarly, context-sensitive façade modifications and open-plan spatial reconfigurations enable the preservation of the original character while accommodating contemporary functions.

5.3 Lessons for Emerging Contexts

The analyzed cases provide significant insights for regions like Serbia, where the adaptive reuse of industrial heritage is still developing. Transferable strategies include minimal façade interventions that maintain authenticity alongside flexible spatial configurations to support new functions. Establishing public-private partnerships is critical for securing funding and ensuring long-term maintenance. In contexts with limited adaptive reuse experience, clear guidelines that balance conservation with innovation—as well as educational initiatives to promote the value of industrial heritage—are essential for sustainable outcomes.

5.4 Sustainability Considerations

Environmental, economic, and social sustainability are core to effective adaptive reuse. Many successful projects emphasize energy efficiency, via improved insulation and the adoption of sustainable energy sources, while blending residential, commercial, and cultural functions to achieve economic resilience. Social sustainability is enhanced by creating accessible, multifunctional public spaces, which foster community engagement and maintain a narrative of industrial heritage. In this way, adaptive reuse not only preserves historical legacies but also contributes significantly to a sustainable urban future.

6. CONCLUSION

The analysis of adaptive reuse cases shows that historic industrial buildings can be transformed into vibrant urban spaces. Preserving key architectural elements—such as structural frameworks, masonry façades, and original layouts—combined with targeted

spatial modifications (like open-plan designs and selective façade treatments) enables the integration of these buildings into modern urban fabrics. Such interventions safeguard architectural identity, rejuvenate neighbourhoods, and stimulate cultural, social, and economic growth.

Case studies of adaptive reuse of industrial mills illustrate that repurposing historic structures while maintaining their heritage is both feasible and beneficial. Successful transformations preserve essential features while introducing thoughtful modifications that support new functions. These changes contribute to cultural continuity, enhance social engagement, and drive economic revitalization. The observed models are particularly instructive for regions with limited experience in adaptive reuse, such as Southeast Europe, where industrial heritage is often underutilized and lacks robust regulatory frameworks.

To address these challenges, it is crucial to build institutional capacity, foster interdisciplinary collaboration, and implement policies that promote reuse while protecting historical value. Policymakers should establish adaptive reuse frameworks that include heritage-sensitive zoning regulations, financial incentives like tax relief and grants, and streamlined administrative processes. Designers, meanwhile, should view adaptive reuse not only as a technical challenge but as a cultural initiative that emphasizes respectful transformation, narrative continuity, and integration into the urban context. Engaging stakeholders and local communities in planning and execution is essential to ensure the long-term relevance and vitality of such projects.

Industrial mills, representing significant elements of industrial heritage, serve as more than relics of past economic systems—they form an integral part of the architectural and urban identity of cities. Whether repurposed as cultural institutions, residential complexes, or mixed-use developments, these buildings offer spatial and structural opportunities for innovation that address contemporary urban challenges. Their adaptive reuse emerges as a strategic approach to harmonize heritage conservation with future urban growth, aligning with the global agenda for sustainable, inclusive, and resilient development.

In summary, the cases analyzed underscore that preserving historic elements together with strategic, context-sensitive interventions provides a replicable blueprint for adaptive reuse. This approach not only maintains historical significance but also fosters urban revitalization, cultural enrichment, and socio-economic development over time.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] Kolehmainen, L. and Sivula, A. **The linguistic heritage of industry**. *Tekniikan Waiheita*, 37(4), 33-54, 2020, https://doi.org/10.33355/tw.88909

[2] Yin, J. **Designing pathways for the revitalization of industrial heritage**. *AD*, 5(2), 40. 2022, https://doi.org/10.31058/j.ad.2022.52006

[3] Illéš, J., Joklová, V., & Jaszczak, A. **Traces of former mill races in Krnov: possibilities of revitalization and interpretation**. *Architecture Papers of the*

Faculty of Architecture and Design STU, 28(1), 36-46, 2023, https://doi.org/10.2478/alfa-2023-0004

[4] Gregorio, S., Vita, M., Berardinis, P., Palmero, L., & Risdonne, A. **Designing the sustainable adaptive reuse of industrial heritage to enhance the local context.** *Sustainability*, 12(21), 9059. 2020, https://doi.org/10.3390/su12219059

[5] Chen, J., Judd, B., & Hawken, S. **Adaptive reuse of industrial heritage for cultural purposes in Beijing, Shanghai and Chongqing**. *Structural Survey*, 34(4/5), 331-350, 2016, https://doi.org/10.1108/ss-11-2015-0052

[6] Piacentíni, M. **Rationale and policies for the green growth of cities and regional economies.** *International Economics and Economic Policy*, 9(2), 129-146, 2012, https://doi.org/10.1007/s10368-012-0209-4

[7] Antić,U., Jevremović, Lj., Stanojević, A., Milojković**, A., Potencijali i ograničenja kompleksa industrijskog nasleđa u centralnim gradskim zonama – slučaj Beogradskog pamučnog kombinata** (In Serbian), *International Conference 19th Summer School of Urbanism and Sustainable Development*, Vrnjačka Banja, Serbia, 183- 191, 2023

[8] Stanojević A., Milošević M., Milošević D., Turnšek B., Jevremović Lj., **Developing multi-criteria model for the protection of built heritage from the aspect of energy retrofitting**, *Energy and Buildings*, 250, 2021, 111285, 2021, https://doi.org/10.1016/j.enbuild.2021.111285.

[9] Yung, E. and Chan, E. **Implementation challenges to the adaptive reuse of heritage buildings: towards the goals of sustainable, low carbon cities**. *Habitat International*, 36(3), 352-361, 2012, https://doi.org/10.1016/j.habitatint.2011.11.001

[10] Šimić, I., Stupar, A., Grujičić, A., Mihajlov, V., & Cvetković, M. **The transformation of dorćol power plant: triggering a sustainable urban regeneration or selling the heritage?.** *Sustainability*, 14(1), 523, 2022, https://doi.org/10.3390/su14010523

[11] Hassanain, M. and Hamida, M. **AEC/FM performance in adaptive reuse projects: investigation of challenges and development of practical guidelines***. Facilities*, 41(7/8), 477-497, 2023, https://doi.org/10.1108/f-04-2022-0053

[12] Winata, D., Tobing, R., & Herwindo, R. **Adaptive reuse guidelines on warenhuis medan and urban heritage environment**. *Idealog Ide Dan Dialog Desain Indonesia*, 8(1), 80-102, 2023, https://doi.org/10.25124/idealog.v8i1.5508

[13] Meng, F., Zhi, Y., & Pang, Y. **Assessment of the adaptive reuse potentiality of industrial heritage based on improved entropy TOPSIS method from the perspective of urban regeneration**. *Sustainability*, 15(9), 7735, 2023, https://doi.org/10.3390/su15097735

[14] Bian, X. and Brown, A. **Establishing the potential for the application of digital storytelling to support Chinese industrial heritage**. *Acta Horticulturae Et Regiotecturae*, 26(2), 147-156, 2023, https://doi.org/10.2478/ahr-2023-0019

[15] Conejos, S., Langston, C., & Smith, J. **Enhancing sustainability through designing for adaptive reuse from the outset**. *Facilities*, 33(9/10), 531-552, 2015, https://doi.org/10.1108/f-02-2013-0011

[16] Zhang, J., Cenci, J., Becue, V., Koutra, S., & Liao, C. **Stewardship of industrial heritage protection in typical western European and Chinese regions: values and dilemmas**. *Land*, 11(6), 772, 2022 https://doi.org/10.3390/land11060772

[17] Niu, X., Liao, F., Liu, Z., & Wu, G. **Spatial–temporal characteristics and driving mechanisms of land–use transition from the perspective of urban–rural transformation development: a case study of the Yangtze river delta**. *Land*, 11(5), 631, 2022, https://doi.org/10.3390/land11050631

[18] Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., … & Tukker, A. **Solid waste and the circular economy: a global analysis of waste treatment and waste footprints**. *Journal of Industrial Ecology*, 21(3), 628-640, 2017, https://doi.org/10.1111/jiec.12562

[19] Patiwael, P., Groote, P., & Vanclay, F. **Improving heritage impact assessment: an analytical critique of the icomos guidelines**. *International Journal of Heritage Studies*, 25(4), 333-347, 2018, https://doi.org/10.1080/13527258.2018.1477057

[20] **The Nizhny Tagil Charter for the Industrial Heritage**, *The International Committee for the Conservation of the Industrial Heritage (TICCIH)*, Nizhny Tagil, 2003

[21] **The Burra Charter: the Australia ICOMOS Charter for Places of Cultural Significance***, International Council on Monuments and Sites,* Australia, 2013

[22] Tenzer, M. and Schofield, J. **Using topic modelling to reassess heritage values from a people-centred perspective: applications from the North of England**. *Cambridge Archaeological Journal*, 34(1), 147-168, 2023, https://doi.org/10.1017/s0959774323000203

[23] Medici, S., Toro, P., & Nocca, F. **Cultural heritage and sustainable development: impact assessment of two adaptive reuse projects in Siracusa, Sicily**. *Sustainability*, 12(1), 311, 2019, https://doi.org/10.3390/su12010311

[24] Arbab, P. and Alborzi, G. **Toward developing a sustainable regeneration framework for urban industrial heritage**. *Journal of Cultural Heritage Management and Sustainable Development*, 12(3), 263-274, 2021, https://doi.org/10.1108/jchmsd-04-2020-0059

[25] Li, Y., Zhao, L., Huang, J., & Law, A. (2021). **Research frameworks, methodologies, and assessment methods concerning the adaptive reuse of architectural heritage: a review**. *Built Heritage*, 5(1), 2021, https://doi.org/10.1186/s43238-021-00025-x

[26] Dorado, M. and Oliveira, E. **Advances in the design of a methodology for the identification, characterization, and assessment of and intervention in the industrial landscape**. *City Territory and Architecture*, 9(1), 2022, https://doi.org/10.1186/s40410-022-00180-3

[27] https://www.em.muni.cz/student/4976-studentsky-festival-propoji-svet-techniky-a-umeni (4.3.2025.)

[28] https://architectuul.com/architecture/manufaktura#:~:text=The%20original%20industrial%20buildings%20were%20designed%20by%20the,services.%20The%20service%20sector%20extends%20over%2012%2C000%20m2. (5.3.2025.)

[29] https://lodz.travel/en/tourism/what-to-see/industrial-heritage/k-scheiblers-industrial-empire/ (6.3.2025.)

[30] https://lodz.travel/en/convention/venues-and-conference-facilities/postindustrial/lodz-special-economic-zone/ (6.3.2025.)

[31] https://mills-transformed.com/salts-mill (25.2.2025.)

[32] https://zeche-zollern.lwl.org/ (15.1.2025.)

[33] https://www.expedia.com/Tobacco-Factory-Theatre-Southville.d6084225.Vacation-Attraction (3.3.2025.)

[34] https://theloom-e1.com/ (27.2.2025.)

[35] Jevremović, Lj. **Nova namena kao determinanta u tretmanu industrijskih braunfilda – modeli obnove i klasifikacija** (In Serbian). Doctoral dissertation, *Faculty of Civil Engineering and Architecture*, Niš, Serbia, 2022. https://nardus.mpn.gov.rs/handle/123456789/21002

doi.org/10.62683/SINARG2025.016

Research paper

MODELING THE EXPANSION OF URBAN GREEN INFRASTRUCTURE: A GIS-BASED APPROACH TO PARK ACCESSIBILITY IN NIŠ

Petar Vranić[1], Ivana Petkovski[2]

Abstract

Provision of equitable access to urban green spaces available is one of the key elements for promoting environmental justice as well as well-being among the population in urban areas. This research introduces a spatial model for park-network extension in Niš, based on an analysis of accessibility focused on network-based methodologies and GIS-based spatial decision support. The paper considers three scenarios of service area estimation for: 1) existing parks, 2) parks defined by the General Urban Plan 2010-2025 (GUP), and 3) identified free parcels that could become grounds for developing new parks. Accessibility analysis is conducted for two cases: 1) considering built-up areas, and 2) population distribution. An 800-meter walking distance is accepted as a threshold boundary, the standard threshold measure for park accessibility considering maximization of environmental and socio-cultural ecosystem services. The findings indicate that existing and GUP-planned parks offer considerable potential for the improvement of urban life since almost 60% of the built-up area in the study area contains a park in proximity of 800 m, however, even though physical coverage reveals considerable beneficial change, the accessibility analysis about population points to social inequality in the planned spatial distribution of parks, where a significant share of the population remains without a park >1.5 hectares within 10 minutes' proximity. The outcome is a replicable model of analysis for park accessibility and expansion, which offers a systematic framework to urbanists for strategic augmentation of their green infrastructure systems.

Key words: *Urban Green Infrastructure (UGI), Park Accessibility Optimization, GIS-Based Spatial Analysis, Environmental Justice, Network-Based Accessibility Modeling, Spatial Decision Support Systems*

[1] PhD, Research Associate, Mathematical Institute SANU, Serbia, petarvvv@mi.sanu.ac.rs, ORCID 0000-0002-9671-992X

[2] PhD, Research Associate, Mathematical Institute SANU, Serbia, ivana993@turing.mi.sanu.ac.rs, ORCID 0000-0001-7692-8436

1. INTRODUCTION

Despite occupying less than 3 percent of the Earth's land area, urban regions are accountable for approximately 71% of worldwide energy-related carbon emissions [1]. With this in mind, the United Nations identified three primary challenges for sustainable urban development in 2010: 1) enhancing the living conditions within cities; 2) minimizing their environmental impact; and 3) preparing them for climate change [2], which were later reflected in the 11th Millennium Development Goal - Sustainable Cities and Communities [3].

Natural habitats within cities are becoming more susceptible to their own causes; with urbanization and the extension of impervious surfaces, it is imperative to integrate nature into urban planning for the improvement of public health. Different eco-oriented urban concepts have been developed to meet these challenges, e.g., Nature-based Solutions (NbS) [4-6], Ecosystem-based Adaptation (EbA) [7,8], Urban Green Infrastructure (UGI) [9], and Blue-Green Infrastructure (BGI) [10,11]. All these terms describe approaches to city planning that hold together care, management, and restoration of natural ecosystems within urban areas. Other commonalities, which are, however, not exhaustive, tend to revolve around a general reliance on urban green spaces (UGSs) as a basis for sustainability, as well as nature-based decision-making [12].

UGS offers a wide spectrum of environmental and social ecosystem services contributing to environmental protection, improvement of public health, and climate change adaptation. They can offset urban heat island effects (UHI) by decreasing air temperature, improve air quality by filtering pollutants from the air, contribute to urban water management by enabling infiltration of rainwater into the soil, decreasing risk from flooding and relieving drainage systems, and supporting biodiversity in urban centers. [13,14].

On the other hand, the existence of urban parks encourages physical activity, decreases stress, and improves the general well-being of citizens. Also, serving as a meeting point it encourages social interaction and joint activities among citizens, affirming social cohesion [15].

To maximize expected ecosystem services, the size of and proximity to parks play a key objective in UGS planning. The size of the park directly influences the capacity for the environmental ecosystem services like microclimate regulation and reduction of UHI effects [16]. Using Land Surface Temperature (LST) Landsat 8 OLI/TIRS satellite imagery, the study found that parks larger than 1.55 hectares with dense vegetation and water bodies significantly reduced ambient temperatures by up to 8.28 °C. Furthermore, the study reveals that park cooling effect was significantly influenced by park size, plant density, and the presence of water bodies, with larger parks, denser vegetation, and water bodies exhibiting increased cooling capacity. These findings emphasize the significance of including green areas in urban development as critical infrastructure for increasing urban resilience, lowering heat-related health risks, and assuring equal access to public health benefits.

On the other side, the proximity to parks is crucial for harvesting benefits for social and cultural ecosystem services they provide. Parks that are in greater proximity to citizens are more likely to be visited. The study presented in [17] shows that people tend to visit parks closer to them. This also emphasizes the need of resolving socioeconomic discrepancies in park accessibility, since these have significant consequences for equitable urban development. While World Health Organization (WHO) suggests 300 meters as a minimum standard, many cities and planning frameworks extend this up to 800 meters (~10 minutes

walking) as a more desirable threshold [18]. Thus, the optimal combination of size and proximity of urban parks can maximize the potential benefits for urban dwellers.

Therefore, in planning the spatial distribution of parks optimizing their size and proximity to residents should be considered as a priority. A Geographic Information System (GIS) proximity analysis is regarded as a significant tool in urban planning for determining the types, geographical distribution, connectivity, and role of UGS in the UGI at various urban sizes. Although this planning method is widely applied in other countries, it is underutilized in Serbian urban planning practice.

This paper builds on the work of Vranić and Vasilevska [19]. Their research evaluates the spatial proximity to 1) extensive urban parks, neighborhood/residential parks and pocket parks) and 2) riverbank green, linear parks or urban corridors which are identified on the territory of the urban settlement Niš, and examine their accessibility from the aspect of the ‘’15-minute city’’ urban planning concept [20-22]. In line with the abovementioned the main objective of this paper is to move forward previous findings introducing a spatial model for the optimization of park-network extension in Niš, considering only parks above 1.5 hectares that can offer meaningful environmental services and simultaneously satisfy social and cultural ecosystem services with an 800-meter threshold proximity. The study integrates data of the General Urban Plan (GUP) for Niš for 2010-2025, compatibility with an analysis of accessibility focused on network-based methodologies and GIS-based spatial decision support.

2. MATHERIALS AND METHODS

This study utilizes network-based analysis in the QGIS environment to assess accessibility, i.e., park service areas, to identify underserved urban areas and potential locations for new parks. Using real network distances provides more precise insight into the spatial distribution of UGS. This section describes the selection of data, description of the study area, and application of the Time Travel plug-in for QGIS for the definition of isochrones and proximity analysis.

2.1. Study area

With an area of 596.73 km2 and 178,976 inhabitants in the urban area and 249,816 inhabitants in the administrative territory, the City of Niš is the third most populous city in Serbia [23]. Since 2004, the city of Niš has been administratively divided into five city municipalities: Medijana, Palilula, Pantelej, Crveni Krst and Niška Banja. Besides the urban settlements of Niš and Niška Banja, there are also 68 rural settlements on the administrative territory. This study focuses on chosen parks which are identified on the territory of the urban settlement Niš (which represents the central part of the administrative territory of the city of Niš), with high population density and a well-developed transportation system, so it can accurately represent the context (Fig. 1).

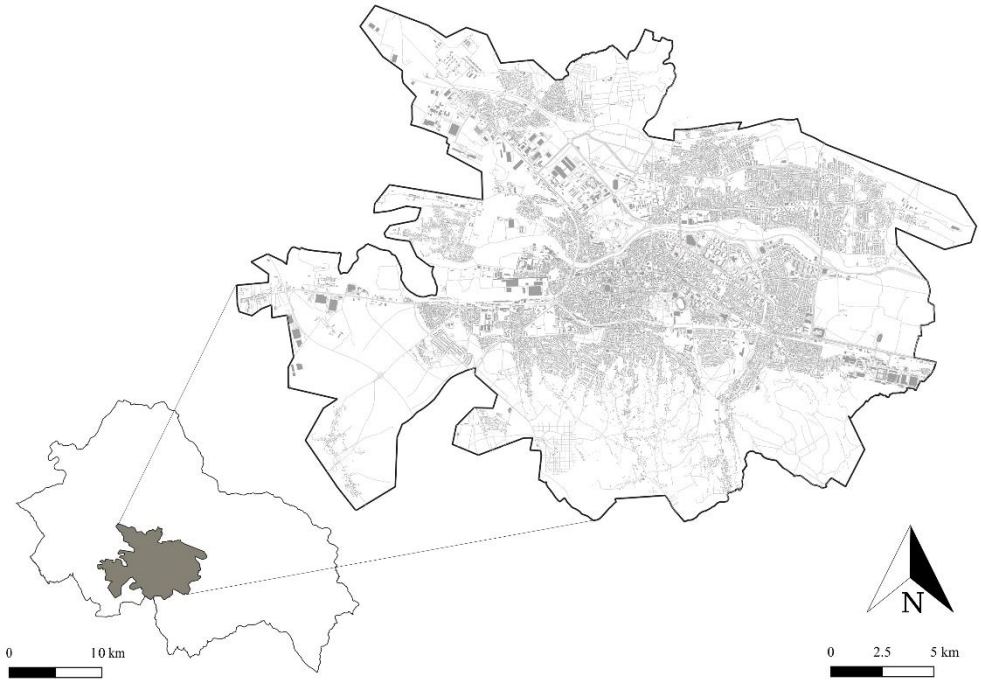


Figure 1. Study area

2.2. Data

Table 1. shows sources of input data for network analysis. Data are generated within the boundaries of urban settlement Niš as presented in Figure 1. All data used in this research are open access.

Table 1. Data

Data	Rationale	Type of data	Source
The road network	Necessary for calculating proximity and accessibility using network-based distances. Highways are omitted from the network since they are not used by pedestrians.	Vector	Data derived from OpenStreetMap (OSM) using Overpass API through QuickOSM - a QGIS plugin.
Buildings inventory	In this research all buildings are included, since the primary focus of the paper is to model expansion of parks in relation to its environmental services not only recreational that are more relevant in residential neighborhood. Thus, this	Vector	Data derived from OpenStreetMap (OSM) using Overpass API through QuickOSM - a QGIS plugin.

	feature is used for calculation of the efficiency of expansion of park service area in relation to building spatial distribution.		
Existing parks	Present destination layer or supply points in network analysis.	Vector	GUP and Google Maps Satellite image in QGIS environment.
Planed parks	Present destination layer or supply points in network analysis.	Vector	GUP and Google Maps Satellite image in QGIS environment.
Potential locations for new parks	Present destination layer or supply points in network analysis.	Vector	GUP and Google Maps Satellite image in QGIS environment. Only locations that falls in category of public areas according to GUP are considered.
Population data	Used for calculation of the efficiency of expansion of park service area in relation to population density	raster	Joint Research Centre (JRC) [24].

OpenStreetMap (OSM) is an open-source, collaboratively contributed geospatial database holding freely accessible geographic data for a variety of spatial objects and can be used as an alternative to commercially procured datasets in the context of spatial information up to date via web-based services. OSM has certain limitations but is an inexpensive, flexible, and scalable method of obtaining spatial data. It is increasingly utilized in scientific research, particularly in disciplines such as GIS, urban planning, environmental studies, and transportation analysis.

2.3. Network-based analysis

For modeling the expansion of the park network in Niš, the Time Travel plugin is used. The Time Travel plugin for QGIS is a powerful network analysis tool, especially in time travel estimation and transport system access. It enables the user to simulate and analyze movement along a network based on various transportation modes using real-time or historical traffic data.

This plugin ordinarily uses OSM data for street networks or General Transit Feed Specification (GTFS) data for public transportation. It implements routing algorithms that calculate travel time considering speed limits, traffic congestion, road conditions, and public transport schedules. The plugin uses network-based distances instead of Euclidean distances, so it offers more realistic travel estimations. In contrast to Euclidean distances, which measure straight line speed, network distances consider real roads, pedestrian routes to support practical accessibility or connectedness analysis. Also, it supports the generation of Isochrones, enabling visualization of the reachable area for the given time. It can support the identification of underserved areas, optimize transport routes, and improve the accessibility of public assets. In this way, it offers insights into equitable infrastructure distribution, enhancing decision-making in transport planning and urban mobility.

To quantify accessibility of the parks, an 800-meter cut-off is isochrone is generated for each park. This threshold is applied since the empirical studies showed that the cooling effect is strongest within the park but can extend up to 650 meters into the surrounding urban fabric, depending on park size and wind conditions [25,26]. Given that the origins of network analysis should be park access sites rather than centroids in order to replicate where people enter and depart parks, the authors conducted on-site surveys of all access points and compared them to satellite imagery. For the new park location author assumed logical entries in relation to the surrounding street network. The algorithm is run from every park entry. Isochrones created for one group of parks are merged into a single isochron to provide a final service area for examination. Features within that distance to any park are regarded as being well accessible, while those outsides are considered underserved sites.

The analysis considers two aspects service area in relation to 1) the built environment, and 2) the population. The first aspect looks at building proximity to all park categories, while the second aspect calculates population coverage within the service area for each park category. For the latter zonal statistics is used to extract the number of citizens that who within each service area.

The results are then integrated into a spatial analysis framework to quantify the efficiency of the current park location and identify potential locations for new parks that have the maximum accessibility considering the territory of the urban settlement Niš.

4. RESULTS

Through inventory 43256 buildings are identified, 9 existing parks >1.5ha, 11 parks planned by GUP >1.5 hectares, and 5 new public areas >1.5 hectares for potential extension of park network. The service area for each category is shown in Figure 2. The figure shows the expansion of the service area for two scenarios b) implementation of planned parks defined by the existing GUP, and c) implementation of additional park areas. In the initial scenario, underserved pockets were identified based on the service area generated. In the final scenario, an empty parcel was selected within each pocket, where it was possible, to achieve a more equitable distribution of urban parks.

The analysis of the expansion of parks concerning the spatial distribution of buildings, as shown in Table 2, suggests how each analyzed category influences accessibility through the number of buildings that fall within the service area of 800 m network distance. Within the service area of the existing parks, 12192 buildings are identified (28.2%). With the full realization of planned parks by GUP, the city can benefit from an additional 12228, or 28.8% of buildings within the same range. And finally, by incorporating newly identified parcels as parks, an additional 4783 (11.1%) can be covered.

Table 2. Proximity analysis in relation to buildings

Parks	Number of buildings that falls within service area of 800m	%
Existing parks >1.5 hectares	12192	28.2
GUP planned parks >1.5 hectares	12228	28.3
New parcels for parks >1.5 hectares	4783	11.1

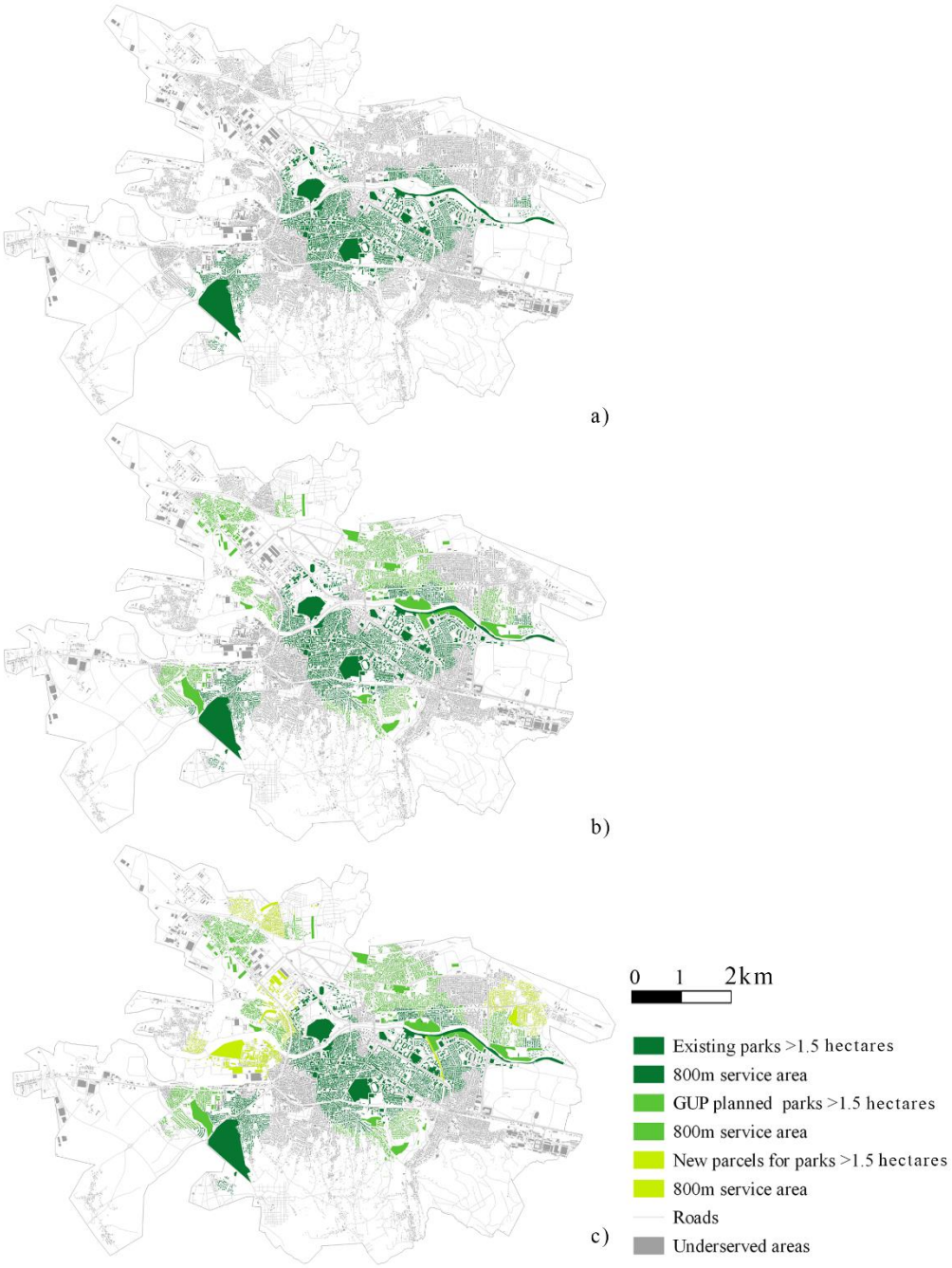


Figure 2. Service area of the urban park network: a) existing parks service area of 800m, b) expansion of service area for GUP-planned park, c) expansion of service area for newly identified parcels for parks

This result reveals that the expansion of parks by realizing GUP-planned green areas will have a significant influence on the general accessibility of parks in a physical sense since

their coverage is almost as much as the existing ones. However, planned locations for parks have certain constraints. They are largely allocated in the less densely populated areas of the city. Thus, their effects might remain limited. The same applies to the potential new location for parks. With the realization of the planned parks, the proximity to buildings can expand up to 51.4%, while with the addition of the suggested location, up to 61.4%, meaning that 38.6% of the built-up area will remain underserved, i.e., it will not have a park within a range of a 10-min walk.

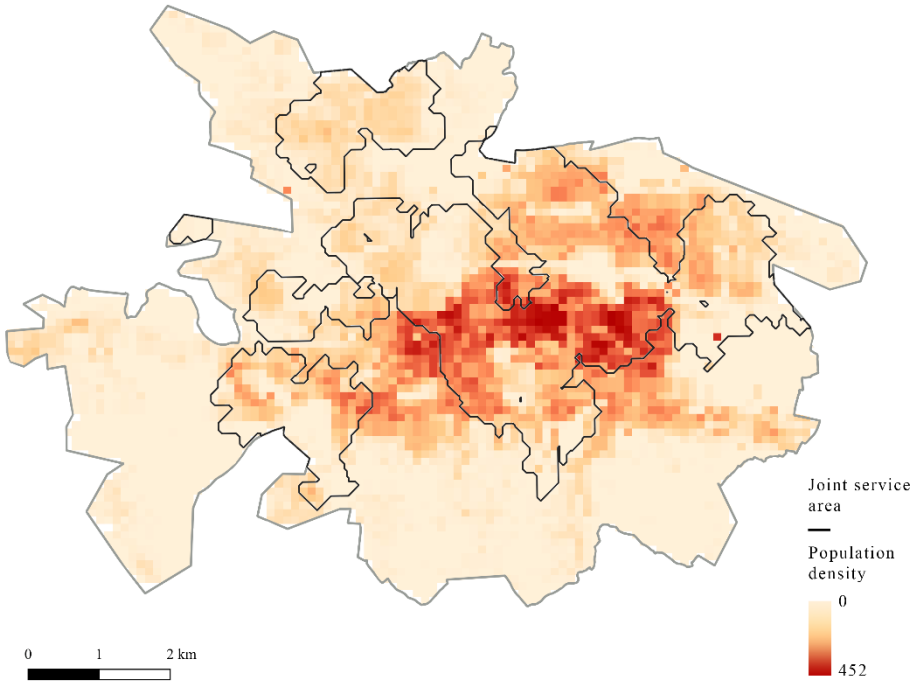


Figure 3. Grided population data resolution 100m with joint service area of existing, planned and suggested parks [25]

Table 3. Proximity analysis in relation to population

Parks	Population that falls within service area of 800m	%
Existing parks >1.5 hectares	77833	30.5
GUP planned parks >1.5 hectares	29156	11.4
New parcels for parks >1.5 hectares	11366	4.4

On the other hand, when service area coverage is analyzed using the population proximity, we found a different ratio (Table 3, Figure 3). 77833 citizens (i.e., 30.5%) are in 800m proximity to existing parks, which is relatively proportional to the building coverage. However, the GUP-planned parks will exert a far smaller effect on the population since only 29156 (11.4%) citizens will benefit from their realization, which is a considerable decrease compared to the number of buildings that are located within their service area. Finally, a newly recognized location may offer better proximity to the additional 11366 citizens (4.4%), which

is also significantly lower compared to the percentage of buildings covered within this service area (11.1%).

This finding reveals a potentially inequitable distribution of parks concerning demographic needs. Although planned parks promise to deliver considerable coverage, their demographic reach remains insignificant. With the realization of the planned parks, the proximity to buildings can expand up to 42% of the total population, while with the implementation of the suggested locations, up to 46.7% in total. It means that even with the full realization of potential parks, 53.3% of the population will have to walk more than 10 minutes to the nearest park.

5. CONCLUSION

In park proximity analysis, often the population that has access to it is put forward. However, the number of buildings that are located within the park service area is an equally relevant indicator, especially from the perspective of the environmental ecosystem services. The built environment defines the spatial pattern and influences the functioning of an urban ecosystem. The more buildings in greater proximity to urban parks, the better the chance for urban green spaces to deliver spectrum of ecosystem services and microclimate benefits to urban environments. This aspect is particularly highlighted in highly urbanized, i.e., densely built city areas with limited possibility for the expansion of green infrastructure. In that sense, demonstrated analysis indicated that existing and GUP-planned parks offer considerable potential for the improvement of urban life since almost 60% of the built-up area in the study area contains a park in proximity of 800 m. On the other hand, GUP-planned parks, with the addition of suggested alternative locations, do not contribute to the proportional benefit in densely populated city blocks. Even though physical coverage reveals considerable beneficial change, the accessibility analysis about population points to social inequality in the planned spatial distribution of parks, where a significant share of the population remains without a park >1.5 hectares within 10 minutes' proximity.

Presented findings point out the need for more detailed analysis in planning the expansion of urban parks, including the qualitative aspects of selected parks, maximization for park demographic coverage, and implementation of advanced or hybrid multicriteria GIS analysis for modeling different spatial distribution scenarios for accessibility optimization.

ACKNOWLEDGMENTS

This work was supported by the Serbian Ministry of Science, Technological Development and Innovation through the Mathematical Institute of the Serbian Academy of Sciences and Arts.

REFERENCES

[1] IPCC, **Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change**. IPCC, Geneva, Switzerland 2014. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf (15.01.2025.)

[2] UN-HABITAT**: UN-Habitat Annual Report 2010**. 2011.

[3] UNDP, 2015. **Sustainable Development Goals 2030**. https://www.undp.org/sustainable-development-goals/nopoverty?gclid=EAIaIQobChMIws63t4NwIVlM3Ch1xHwZIEAAYAiAAEgI4KDBwE (4.12.2024.)

[4] Balian Estelle, Hilde Eggermont, Le Roux Xavier: **Nature-based solutions in a BiodivERsA context**. L-Outcomes of the strategic foresight workshop*. BiodivERsA Report*, Brussels, Belgium, 2014. https://www.biodiversa.eu/wp-content/uploads/2022/12/strategic-foresight-workshop.pdf (12.02.2025.)

[5] Doswald Nathalie, Osti Matea: **Ecosystem-based approaches to adaptation and mitigation – good practice examples and lessons learned in Europe.** BfN-Skripten. Bundesamt für Naturschutz, Bonn, Germany. 2011.

[6] Niki Frantzeskaki: **Seven lessons for planning nature-based solutions in cities**. *Environmental Science & Policy*, Vol. 93, 101-111, 2019. doi.org/10.1016/j.envsci.2018.12.033

[7] Ebba Brink et al.: **Cascades of green: A review of ecosystem-based adaptation in urban areas.** *Global Environmental Change* Vol. 36, 111-123, January 2016. doi.org/10.1016/j.gloenvcha.2015.11.003

[8] Richard Munang, et al.: **Climate change and ecosystem-based adaptation: A new pragmatic approach to buffering climate change impacts.** *Current Opinion in Environment Sustainability*, Vol. 5 No. 1, 67–71, 2013.

[9] Benedict, Mark A., Edward T. McMahon: **Green infrastructure. Linking landscapes and communities.** Washington, DC: Island Press, 2006.

[10] **MEA (Millennium Ecosystem Assessment): Ecosystems and human well-being: Synthesis. Millennium assessment report.** Washington, DC: Island Press, 2005.

[11] Erik Gómez-Baggethun, David N. Barton: **Classifying and valuing ecosystem services for urban planning.** *Ecological Economics*, Vol. 86, 235–245, 2013. doi.org/10.1016/j.ecolecon.2012.08.019

[12] Dagmar Haase, Niki Frantzeskaki, Thomas Elmqvist: **Ecosystem Services in Urban Landscapes: Practical Applications and Governance Implications**. *AMBIO,* Vol. 43, No. 4, 407–412, 2014. doi: 10.1007/s13280-014-0503-1

[13] Pandey, Bhanu, Annesha Ghosh: **Urban ecosystem services and climate change: a dynamic interplay.** *Frontiers in Sustainable Cities*, Vol. 5, 1281430, 2023. doi.org/10.3389/frsc.2023.1281430

[14] Wang Dong, et al.: **Urban green infrastructure: Bridging biodiversity conservation and sustainable urban development through adaptive management approach**. *Frontiers in Ecology and Evolution*, Vol. 12, 1440477, 2024. doi.org/10.3389/fevo.2024.1440477

[15] Ge Yipeng, et al.: **Ecosystem Services and Public Perception of Green Infrastructure from the Perspective of Urban Parks: A Case Study of Luoyang City, China**. *Sustainability*, Vol. 16, No. 17, 7657, 2024. doi.org/10.3390/su16177657

[16] Jha, Priyanka, Md Saharik Joy, Pawan Kumar Yadav, Shehnaz Begam, and Taruna Bansal: **Detecting the role of urban green parks in thermal comfort**

and public health for sustainable urban planning in Delhi. *Discover Public Health*, Vol. 21, No. 1, 1-21, 2024. doi.org/10.1186/s12982-024-00368-7

[17] Orstad Stephanie L., et al.: **Park proximity and use for physical activity among urban residents: Associations with mental health**. *International Journal of Environmental Research and Public Health,* Vol. 17, No. 13, 4885, 2020. 10.3390/ijerph17134885

[18] Cardinali, Marcel, Mariëlle A. Beenackers, Arjan van Timmeren, Uta Pottgiesser: **The relation between proximity to and characteristics of green spaces to physical activity and health: a multi-dimensional sensitivity analysis in four European cities.** Environmental research, Vol 241, 117605, 2024. doi.org/10.1016/j.envres.2023.117605

[19] Vranić Petar, Ljiljana Vasilevska: **The Assessment of Proximity of Urban Green Spaces in Niš: A Geospatial Analysis.** *Facta Universitatis, Series: Architecture and Civil Engineering*, (forthcoming 2025).

[20] Carlos Moreno et al.: **Introducing the "15-Minute City": Sustainability, Resilience and Place Identity in Future Post-Pandemic Cities**. *Smart Cities*, Vol. 4, No. 1, 93–111, 2021. doi.org/10.3390/smartcities4010006

[21] Allam Zaheer, Nieuwenhuijsen Mark, Chabaud Didier, Moreno, Carlos: **The 15-minute city offers a new framework for sustainability, liveability, and health**. The Lancet Planetary Health, Vol. 6, 181-183, 2022. doi.org/10.1016/S2542-5196(22)00014-6

[22] Pozoukidou, Georgia, Margarita Angelidou: **Urban Planning in the 15-Minute City: Revisited under Sustainable and Smart City Developments until 2030**. *Smart Cities*, Vol. 5, No. 4, 1356–1375, 2022. doi.org/10.3390/smartcities5040069

[23] The Statistical Office of the Republic of Serbia: **Households according to the Number of Members**. 2022.

[24] Schiavina Marcello, Freire Sergio, Alessandra Carioli, MacManus Kytt (2023): **GHS-POP R2023A – GHS population grid multitemporal (1975-2030).** European Commission, c [Dataset] doi: 10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE PID: http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe

[25] Aram, Farshid, Ebrahim Solgi, Ester Higueras García, Amir Mosavi, Annamária R. Várkonyi-Kóczy: **The cooling effect of large-scale urban parks on surrounding area thermal comfort.** *Energies*, Vol. 12, No. 20, 3904, 2019. doi.org/10.3390/en12203904

[26] Gao, Yu, Huifeng Pan, Li Tian: **Analysis of the spillover characteristics of cooling effect in an urban park: a case study in Zhengzhou city.** *Frontiers in Earth Science,* Vol. 11, 1133901, 2023. doi.org/10.3389/feart.2023.1133901

doi.org/10.62683/SINARG2025.017

Research paper

SPATIAL DOWNSCALING OF LAND SURFACE TEMPERATURE MAPS – A CASE STUDY FOR THE CITY MUNICIPALITY MEDIJANA, THE CITY OF NIŠ, SERBIA

Nikola Đokić[1], Borislava Blagojević[2]

Abstract

Urban heat islands are becoming an increasingly important challenge in the 21st century. Land surface temperature is a key factor in the urban heat island risk assessment. Its monitoring is possible through satellite land surface temperature (LST) detection. However, satellite images with insufficient spatial resolution are available to monitor temperature changes in urban areas, which arise due to the technical limitations of satellite thermal infrared sensors. Numerous algorithms have been proposed to solve the problem of the coarse spatial resolution of LST. This study explores the application of a machine learning algorithm based on a Random Forest (RF) regression model between LST and predictor variables such as aspect, digital elevation model (DEM), hillshade, normalized difference vegetation index (NDVI), building heights, digital height model (DHM), and land cover. The study focuses on the municipality of Medijana, located in the City of Niš in the Republic of Serbia. The spatial resolution of MODIS LST was improved from 1 km to 250 m. The results indicate that the applied machine learning method can predict potential temperatures at a finer scale with high accuracy, with NDVI indicating a significant local influence on LST. The results indicated that the RF approach demonstrated a robust and high-performance methodology. The Mean Square Error (MSE) values ranged from 0.730 °C² to 1.028 °C², while the Root Mean Square Error (RMSE) values varied from 0.854 °C to 1.100 °C across the 84 models generated.

Key words: *Random Forest Regression, Land Surface Temperature, Spatial Downscaling, Urban Area*

[1] M.Sc. Civ. Eng., assistant, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, nikola.djokic@gaf.ni.ac.rs, ORCID 0009-0008-3078-1473
[2] Prof. Ph.D., University of Niš, Faculty of Civil Engineering and Architecture, Serbia, borislava.blagojevic@gaf.ni.ac.rs, ORCID 0000-0002-5304-5902

1. INTRODUCTION

Urban Heat Islands (UHIs) are the regions within urban areas that are considerably hotter than the surrounding rural or urban environment [1]. The UHI phenomenon arises from the uncontrolled growth of urban areas largely from anthropogenic reasons – the modification of natural landscape due to urban expansion by replacing forests, wetlands, and grasslands with structures, roads, and other construction interventions in general [2]. UHI poses a risk because it intensifies heat exposure in cities, leading to increased health problems, energy demand, and reduced liveability, especially during extreme heat events. Therefore, UHI topic has recently attracted many researchers.

Land surface temperature (LST) is widely used in UHI research [3, 4], as it enables the quantification of temperature differences between urban and rural areas, as well as spatial variations within cities, thereby enhancing the understanding of hazard component of UHI risk. Obtaining LST data over extensive areas via ground measurement is impractical, but the improvement of satellite-based thermal infrared (TIR) sensors addresses this issue [5]. A single sensor cannot provide LST data that combines both high frequency and precise spatial resolution due to the limits of TIR technology. Spatial downscaling of LST products with poor resolution but high frequency, together with additional auxiliary data, is an efficient way to overcome this difficulty [6]. Terra/MODIS sensors can observe surface temperature twice a day in the same study area, but their spatial resolution of 1 km is low [6]. Thus, MODIS sensors provide high temporal and poor spatial resolution. Some sensors, such as the Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER), have a high spatial resolution of 300 m but a temporal resolution of 15 days. This indicates the importance of developing and using appropriate methods for scaling satellite LST data. Spatial downscaling of LST is a widely adopted approach to enhance the spatial resolution of LST products [6, 7].

There are currently two primary types of downscaling techniques for LST: models based on physical mechanisms and models based on statistics [8]. Based on the concepts of thermal radiation, physical mechanism-based models aim to establish a significant, empirically supported relationship between thermal radiance (or LST) and auxiliary data, including land cover maps. Although these models offer insightful scientific information, their complexity may restrict their usefulness [9].

The statistical correlations between LST and different land surface parameters are the foundation of statistics-based models. These relationships are usually obtained from supplementary data with relatively high spatial resolutions. The addition of adequate predictor variables and the creation of reliable regression models are the two main phases through which statistics-based LST downscaling techniques have largely developed to improve the accuracy of downscaled LST [10]. Digital elevation models (DEM), land cover maps, and the normalized difference vegetation index (NDVI) are some of the frequently used elements in these models [6]. Statistics-based models are becoming increasingly common because they are simpler to develop than models based on physical mechanisms [11].

Although one-factor models are typically simple, utilizing a single indicator is often insufficient to capture LST fluctuations. As a result, multifactor models are used in practice more frequently. Tang et al. [12], for instance, combine several variables, including topography characteristics like DEM, slope, and aspect, remote sensing spectral indices, and land surface reflectance data from the Red, Blue, Green, and NIR bands. The non-stationary relationship between LST, NDVI, and DEM was also investigated by Duan and Li [13]. To

create a correlation with LST, Bechtel et al. Also used DEM in conjunction with the normalized difference built-up index [14].

The most common algorithms used for downscaling by statistics are linear regression models. Linear regression formulas, however, sometimes cannot account for nonlinear relationships between LST and remote sensing indices. To deal with this deficiency, various models have been presented to explain linear and nonlinear relationships between LST and driving variables.

This study aims to apply the Random Forest (RF) regression model to produce detailed maps of LST in the municipality of Medijana, located in the city of Niš in the Republic of Serbia. This model was applied in many works dealing with the same issue [6, 12]. The enhanced maps of LST are useful in delivering vital information on the spatial patterns of temperature anomalies, supporting the creation of enhanced UHI mitigation strategies and urban resilience planning. With this case study, we intend to show potential applications of using spatial downscaling as a method of overcoming the gap between coarse satellite data and the need for detailed UHI mapping. The spatial resolution of MODIS LST in this research was enhanced from 1 km to 250 m by incorporating various predictor variables, including Aspect, DEM, hillshade, NDVI, building heights, the digital height model (DHM), and Land Cover. The results indicate that NDVI plays a crucial role in influencing local LST.

The paper is organized as follows. The methodology framework, the study region, datasets, downscaling approach, model development, and model validation are briefly introduced in the Methodology. Results with the discussion of the developed models and their parameters are shown in the Results and Discussion, followed by the Conclusions section.

2. METHODOLOGY

The methodology in this research comprises the following steps:

Study Area Definition - Defining the geographical boundaries of the study area.

Data Collection – Collection of remote sensing data, MODIS LST at a 1 km spatial resolution, and predictor variables.

Data Preprocessing – This part involves transforming the data to the same coordinate reference system (EPSG:3857 -WGS 84 / Pseudo Mercator), and determining the DHM.

Spatial Downscaling – Applying spatial downscaling techniques to reduce MODIS LST data from 1 km to 250 m resolution, using the collected predictor variables.

Model Development – Development of the RF regression model as the analytical tool for predicting LST.

Model Validation – Model validation is performed on out-of-bag (OOB) samples using metrics such as mean square error (MSE) and root mean square error (RMSE).

Heat Map Generation – Creation of LST map with 250 m spatial resolution, utilizing the validated RF model to predict LST across the study area.

2.1. Study Area

The City of Niš is situated nearby the confluence of the Nišava and Južna Morava rivers, and surrounded by hills in the Niš valley. It has a diverse population of approximately 250,000 residents. This study focuses on the central city municipality of Medijana of close to 90,000 inhabitants, covering 10 km² [15] (Figure 1). The City has a temperate continental climate,

with an average annual temperature of 12.4 °C and 614 mm precipitation in 1991-2020. The warmest months are July and August with an average temperature of 23.1 °C, and the coldest is January with an average temperature of +0.9 °C [16].

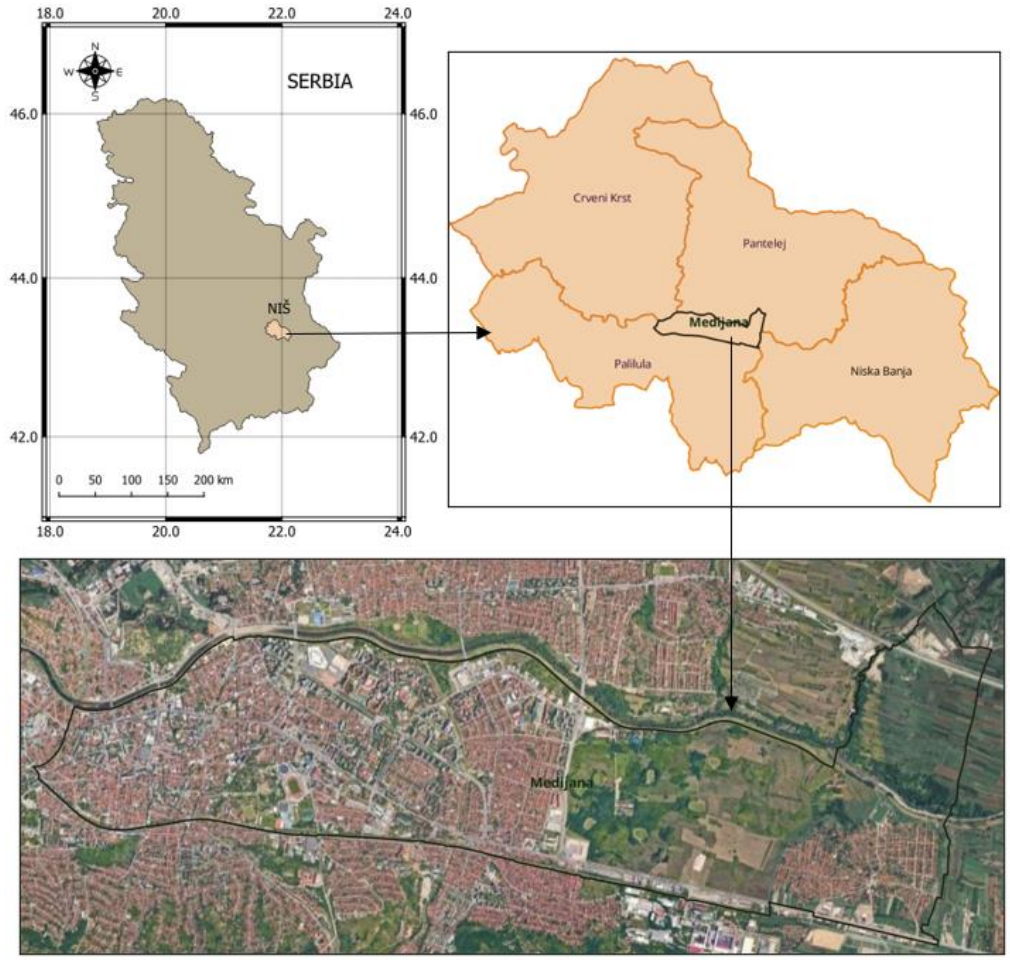


Figure 1. The location of the city of Niš in Serbia, its City Municipalities, and the study area – the Municipality of Medijana boundaries shown on a satellite map.

2.2. Data collection and preprocessing

The data collection and preprocessing stages dealt with laying a foundation for the RF regression model. Table 1 provides information regarding the data used in this research. As mentioned earlier, the MODIS LST product, with a spatial resolution of 1 km and a temporal resolution of 1 day, was used for the study area. The period of analysis in this research is from 04/08/2024 to 11/08/2024, during which exceptionally high LST were recorded, ranging from 37.7 to 41.8 °C in the study area. To enhance the resolution of the available LST product, relationships were established with the following predictors: aspect, DEM, hillshade, NDVI, building heights, DHM, and Land cover. DHM is the difference between digital surface model (DSM) and DTM [17].

DHM accounts for the volume effectively utilized for residential use [17]. In general, DHM represents building height, with a higher resolution of 30m.

Table 1. The dataset information

Dataset	Source	Spatial Resolution	Usage	Reference
MODIS/Terra Land Surface Temperature/Emissivity Daily L3 Global 1km SIN Grid V061 (MOD11A1) v 6.1	Earth Data https://search.earthdata.nasa.gov/search	1 km	Downscaling	[18]
Copernicus GLO-30 Digital Elevation Model	Open Topography https://opentopography.org/	30 m	Predictor	[19]
Aspect from Copernicus GLO-30 Digital Elevation Model			Predictor	
Hillshade from Copernicus GLO-30 Digital Elevation Model			Predictor	
ALOS Global Digital Surface Model (AW3D30)			To obtain DHM	[20]
MODIS/Terra Vegetation Indices 16-Day L3 Global 250 m SIN Grid (MOD13Q1 v006) - NDVI	Earth Data https://search.earthdata.nasa.gov/search	250 m	Predictor	[21]
GHS-BUILT-S R2023A	Copernicus https://human-settlement.emergency.copernicus.eu/download.php?ds=builtH	100 m	Predictor	[22]
CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly	Copernicus https://land.copernicus.eu/en/products/corine-land-cover/clc2018	100 m	Predictor	[23]

In the context of the RF regression model applied to LST mapping, predictor variables play a crucial role in determining the accuracy and reliability of the model's outputs. Predictor variables serve as inputs that help the model understand the relationships between different factors and how they influence LST. Figure 2 shows the maps for each of the predictors used across the study area.

2.3. Spatial Downscaling

Statistics-based models are developed by identifying statistical relationships between LST and various land surface parameters obtained from auxiliary data with comparatively high spatial resolution. If the relationships between LST and its predictors remain consistent across spatial resolutions, high-resolution LST can be estimated using these predictors. To develop the connections required to improve the LST resolution with this approach, it is

necessary to adapt the predictors to the coarse resolution of the LST (Re-sampling process). The predictive model was formed using the XLStat software [24]. The software allows building a predictive model for a quantitative response variable based on explanatory quantitative and/or qualitative variables.

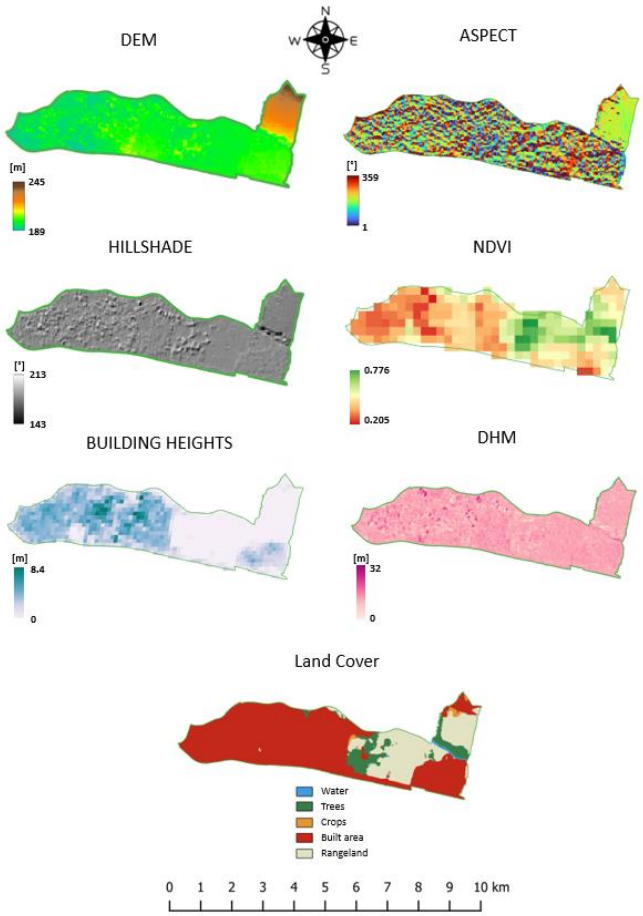


Figure 2. Thematic maps of predictors

The resolution of 250 meters is chosen because it is the lowest resolution among the predictors used. As indicated in Table 1, this 250-meter resolution corresponds to the NDVI. To work with an even finer resolution, it is necessary to utilize predictors that also have high resolutions. However, this increased level of detail demands more data, time, and memory for processing.

Furthermore, to obtain the final LST map with high resolution, a residual correction must be performed between the initial LST map (1 km) and the LST map obtained from the model (250 m), on which disaggregation is now performed to a resolution of 1 km. Figure 3 shows a schematic of the LST downscaling procedure.

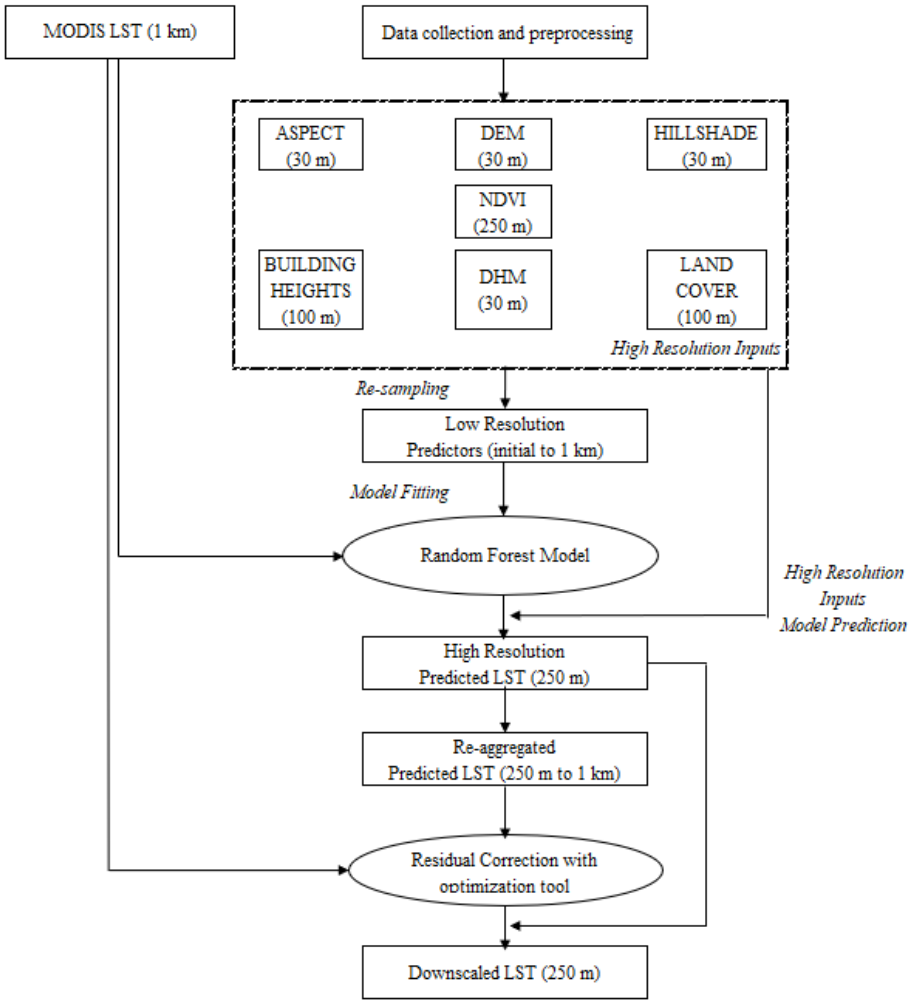


Figure 3. Land surface temperature (LST) downscaling procedure scheme

2.4. Model Development

MODIS LST products are known for their coarse spatial resolution. Regression models have been developed to enhance LST resolution by incorporating auxiliary environmental predictors. RF are ensembles of decision trees that can be used to solve classification and regression problems [25]. RF regression is a powerful ensemble learning technique used for predictive modeling. Built upon decision trees, it combines multiple individual trees to enhance accuracy and reduce overfitting. The development process involves data preprocessing, parameter selection, model training, and performance evaluation. For model development, we use the Random Input variant, an essential modification of the bagging XLstat [26]. Its objective is to increase the independence between the models (trees) to obtain a final model with better performance. XLstat requires the entry number of trees, mtry, and tree parameter values, such as minimum node size, minimum son size, and maximum depth. More trees enhance stability but increase computation time. Maximum depth restricts tree complexity to prevent overfitting. Mtry refers to the number of features randomly selected at each split when building individual decision trees. It controls the level of randomness in

feature selection, ensuring that different trees in the ensemble consider different subsets of features. To assess the predictive ability of RF regression, we use evaluation metrics Mean Squared Error (MSE) and Root Mean Squared Error (RMSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2} \quad (2)$$

where n is the number of sample data; Y_i is the observed surface temperature in °C, and $\hat{Y}_i$ is the predicted surface temperature in °C.

The following RF parameter values were used:

- Forest parameters: Sampling (Random with replacement); Method (Random Input); Sample size (40); Number of trees (100, 200, 500, and 1000),
- Stop conditions: Construction time (300); Convergence (50),
- Tree parameters: minimum node size (2); minimum son size (1); maximum depth (10, 20, and 30); mtry (1, 2, 3, 4, 5, 6, and 7); CP (0,0001).

The sensitivity of model parameters was tested by varying model parameters such as maximum depth, number of trees, and mtry.

2.5. Model Validation

When training a RF model, each tree is constructed using a bootstrap sample of the data. This means that some data points are randomly selected (with replacement) to build the tree, while those not included in this sample are referred to as OOB samples. These OOB samples serve as a means to evaluate the model predictions, offering an internal validation method that eliminates the need for separate test data. This technique is especially advantageous as it allows for the evaluation of the model during training, thus conserving both time and computational resources [27]. Also, OOB samples can be used in the model parameter tuning process, in order to choose the optimal model for LST prediction. We use OOB samples for parameter optimization and model validation.

3. RESULTS AND DISCUSSIONS

3.1. Predictor Significance and Parameter Sensitivity

To adapt the RF machine learning model to various problem domains, it is required to calibrate the model parameters accordingly. The selection of the optimal parameter configuration is crucial, as it significantly influences the overall performance and predictive accuracy of the model. Ensuring that these parameters are finely tuned can lead to more effective and reliable outcomes in a range of applications. One of RF valuable features is the ability to measure the importance of each variable (or feature) in making predictions. Mean Decrease in Impurity (MDI) – also known as Gini Importance, measures the extent to which each feature contributes to reducing uncertainty (impurity) when making splits in decision trees. Features that create significant splits receive higher importance scores. High importance values indicate features that strongly influence predictions. Features with low importance may contribute little and could be considered for removal in optimization

processes. Because in recent studies of size reduction techniques, many authors have shown that introducing a large number of predictors improves model performance [9, 28], our preliminary model concept included a variety of explanatory variables. We also included some predictors that we have not seen used in similar studies, such as building heights and DHM. However, our analysis indicated that increasing the number of predictors does not significantly affect the accuracy of the model, which was also pointed out by Bartkowiak, P. et al. [29]. This is illustrated in Figure 4, which highlights the significance of the seven variables employed to predict surface temperatures, represented by the mean increase error (MIE). MIE values indicate that DEM, NDVI, and Building Heights have a more significant role in the LST prediction process. We assumed that DHM would have a more significant influence in predicting LST, however, it did not come to this, most likely due to insufficiently good fitting of DSM and DEM.

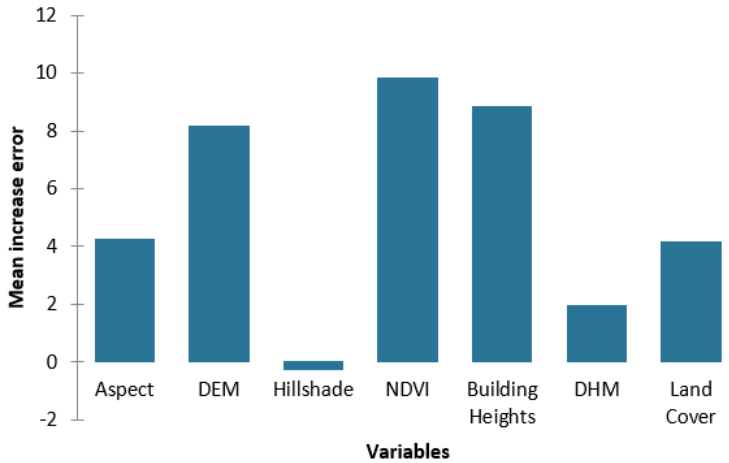


Figure 4. Variable significance in the prediction of LST

Figure 5 demonstrates the sensitivity of the developed models to varying parameters: maximum depth (3 cases) and mtry (from 1 to 7) for the fixed number of trees (4 cases), which yields a total of 84 models (3x7x4=84).

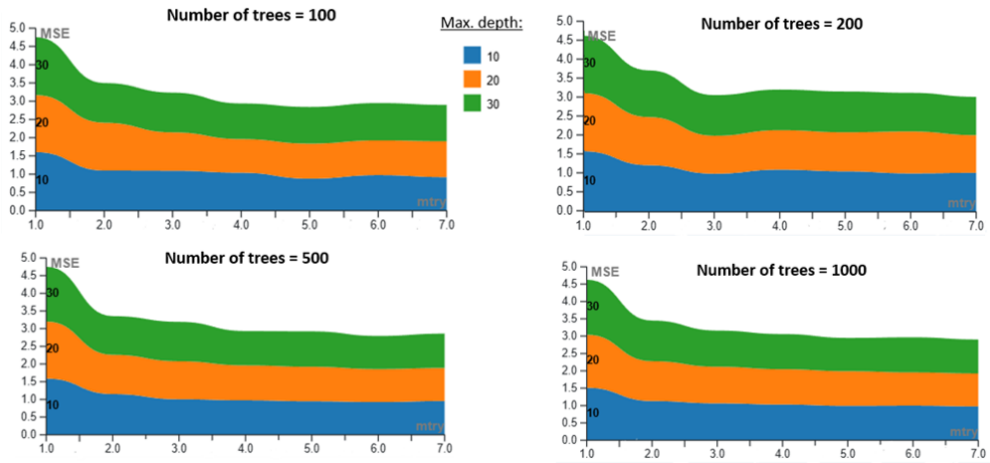


Figure 5. Sensitivity of the model to changes in the number of trees, maximum depth, and mtry (x-axis) through MSE

The highest variability, shown by the highest MSE, corresponds to the value mtry = 1. A number of trees and max depth did not cause a significant variation in model performance.

3.2. Results of Model Validation

Out-of-bag (OOB) error is a key indicator in RF models. OOB error is computed during training. It provides an internal estimate of the model's performance without the need for a separate validation set or cross-validation. For each data point, predictions are made using only the trees that did not include that point in their training set. The OOB error (MSE), is then calculated as the average error across all these predictions. The errors varied from 0.730 °C² to 1.028 °C² across the 84 models generated. Figure 6 illustrates the evolution of OOB error as the number of trees changes. The left diagram depicts the model with the smallest error, while the right diagram illustrates the model with the largest developed error.

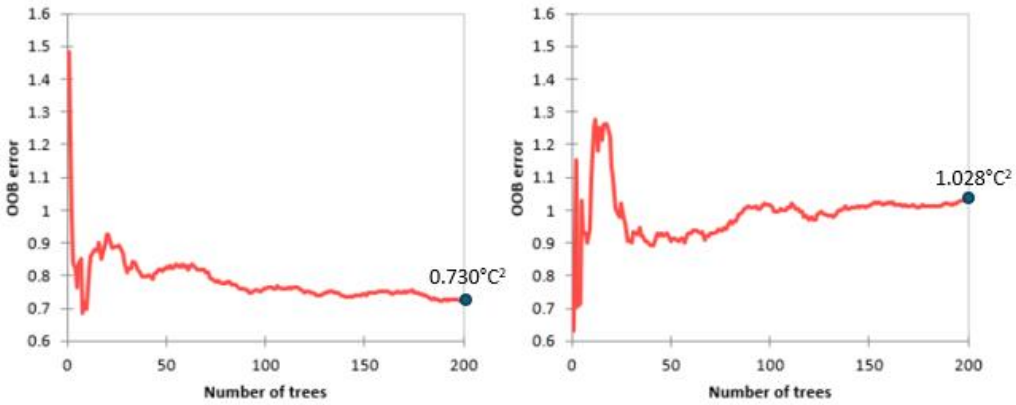


Figure 6. OOB error evolution. Left: the best performing model, Right: the worst performing model

The model selected for LST downscaling has the following parameter values: mtry = 6; number of trees = 200; max. depth = 30.

The selected model has RMSE of 0.854 °C, while in the work that also used the RF approach, RMSE of 2.2 K was obtained [29]. Hutengs & Vohland [28] applied random forest regression to MODIS LST data with RMSEs ranging from 1.41 K to 1.92 K. Similarly, good results were obtained by Maeda [30]. The mentioned RMSE values depend on the location and are greatly influenced by the topographical complexity, as well as the heterogeneity of the vegetation in the study area. Our RMSE value indicates that we have established a highly accurate model for LST prediction.

3.3. Results of Downscaling – Identifying UHI Hotspots

Spatial downscaling of LST data allows us to identify localized areas of temperature peaks, i.e., UHI hotspots. Figure 7 illustrates the temperature distribution across the municipality of Mediana at its original resolution of 1 km. It can be seen that the western part of the municipality, which is the most built-up area, is also the warmest. However, areas of 1 km² require considerable investments to mitigate the effects of UHI, which may not be justified because it is not likely that the whole area suffers from overheating. To determine if a high investment is justified or if it needs to be reduced to a smaller area, it is rational to work on

improving the resolution of the LST map. Figure 8 shows the results of spatial downscaling of LST, which is produced by the model formed using a RF.

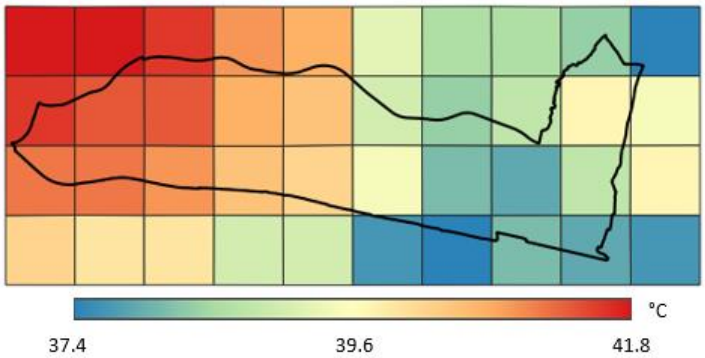


Figure 1. Original MODIS 1 km LST map over the municipality of Medijana

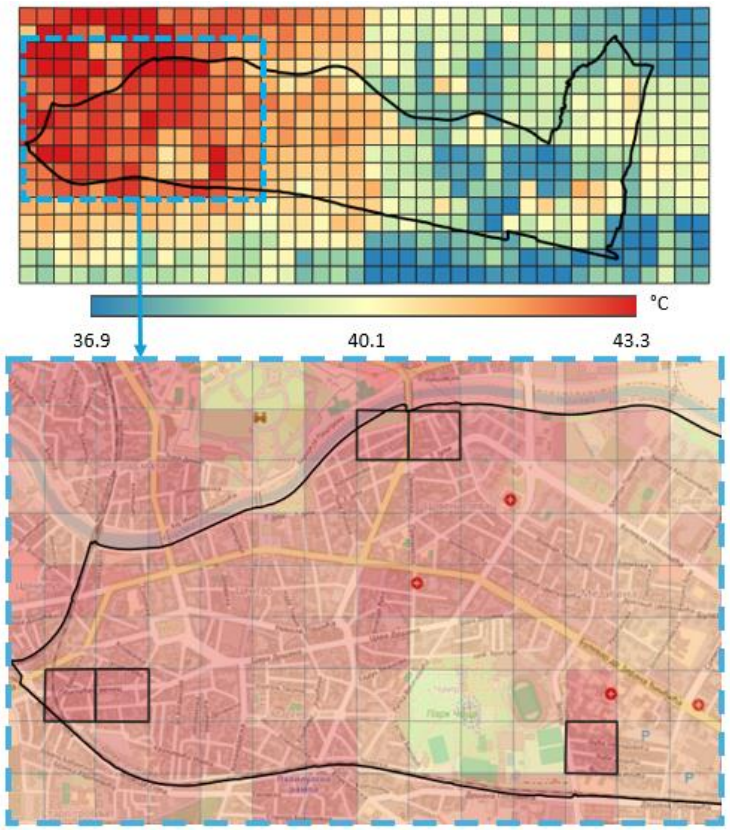


Figure 2 . Downscaled MODIS map with 250 m resolution, with zoom on the hottest part of the study area and five identified UHI hotspots (black boxes)

In the lower part of Figure 8, we highlighted five fields with a resolution of 250 m, where the highest LST values are predicted, ranging from 41.6 °C to 43.1 °C. These areas include Obilićev venac neighborhood, the street of 7. Juli (Šećer mala neighborhood) and the area around the Medical Secondary School.

4. CONCLUSION

The hazard component of UHI risk involves the assessment of LST data. In urban areas, more precise identification of UHI hotspots enables the application of targeted mitigation measures. In this research, we applied a machine learning - RF downscaling method to enhance the spatial resolution of LST data (from 1 km to 250 m), using MODIS/Terra Land Surface imagery for the central City Municipality of Niš, Serbia, during a heat wave event recorded in 2024. The following can be concluded:

1. Among the seven predictors considered in the LST prediction models, the most significant were NDVI, Building Height, and DEM; Aspect and Land Use were moderately significant, while DHM and Hillshade had the least impact.
2. The established models demonstrated robust and consistent performance, with MSE values remaining rather stable for mtry values greater than 2, regardless of the examined number of trees and the maximum depth.
3. The achieved accuracy (RMSE = 0.854 °C) of the downscaled LST model - using mtry = 6, 200 trees, and a maximum depth of 30 - outperforms similar studies that applied the RF approach.
4. Five UHI hotspots were identified in the City Municipality of Medijana, providing insights for urban planning and UHI effect mitigation. The enhanced-resolution LST dataset can support stakeholders in identifying heat stress-prone areas and implementing targeted adaptation interventions, such as green, blue and white measures.

In future research, we aim to incorporate additional predictors into the RF downscaling model, such as the Tropical Night Index, which is not only an indicator of UHI presence but is also available in future climate projections. Because climate models offer long-term simulations of this parameter until the end of the 21st century, it will be possible to assess potential shifts in UHI locations under various urban development scenarios.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] Jabbar, H. K., Hamoodi, M. N., & Al-Hameedawi, A. N.: **Urban heat islands: a review of contributing factors**, effects and data. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1129, No. 1, p. 012038). IOP Publishing, 2023.

[2] Bokaie, M., Zarkesh, M. K., Arasteh, P. D., & Hosseini, A.: **Assessment of urban heat island based on the relationship between land surface temperature and land use/land cover in Tehran**. *Sustainable Cities and Society*, 23, 94-104, 2016.

[3] Weng, Q.: **Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends**. *ISPRS Journal of photogrammetry and remote sensing*, 64(4), 335-344, 2009.
[4] Sobrino, J. A., Oltra-Carrió, R., Sòria, G., Bianchi, R., & Paganini, M.: **Impact of spatial resolution and satellite overpass time on evaluation of the surface urban heat island effects**. *Remote Sensing of Environment*, 117, 50-56, 2012.
[5] Xu, S., Zhao, Q., Yin, K., He, G., Zhang, Z., Wang, G., ... & Zhang, N.: **Spatial downscaling of land surface temperature based on a multi-factor geographically weighted machine learning model**. *Remote Sensing*, 13(6), 1186, 2021.
[6] Xinming, Z., Xiaoning, S., Pei, L., & Ronghai, H. U.: **Spatial downscaling of land surface temperature with the multi-scale geographically weighted regression**. *National Remote Sensing Bulletin*, 25(8), 1749-1766, 2021.
[7] Zhan, W., Chen, Y., Zhou, J., Wang, J., Liu, W., Voogt, J., ... & Li, J.: **Disaggregation of remotely sensed land surface temperature: Literature survey, taxonomy, issues, and caveats.** *Remote Sensing of Environment*, 131, 119-139, 2013.
[8] Pan, X., Zhu, X., Yang, Y., Cao, C., Zhang, X., & Shan, L.: **Applicability of downscaling land surface temperature by using normalized difference sand index**. *Scientific reports*, 8(1), 9530, 2018.
[9] Yang, Y., Cao, C., Pan, X., Li, X., & Zhu, X.: **Downscaling land surface temperature in an arid area by using multiple remote sensing indices with random forest regression**. *Remote Sensing*, 9(8), 789, 2017.
[10] Wu, J., Zhong, B., Tian, S., Yang, A., & Wu, J.: **Downscaling of urban land surface temperature based on multi-factor geographically weighted regression**. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 12(8), 2897-2911, 2019.
[11] Wang, S., Luo, Y., Li, X., Yang, K., Liu, Q., Luo, X., & Li, X.: **Downscaling land surface temperature based on non-linear geographically weighted regressive model over urban areas**. *Remote Sensing*, 13(8), 1580, 2021.
[12] Tang, K., Zhu, H., & Ni, P.: **Spatial downscaling of land surface temperature over heterogeneous regions using random forest regression considering spatial features**. *Remote Sensing*, 13(18), 3645, 2021.
[13] Duan, S. B., & Li, Z. L.: **Spatial downscaling of MODIS land surface temperatures using geographically weighted regression: Case study in northern China**. *IEEE Transactions on Geoscience and Remote Sensing*, 54(11), 6458-6469, 2016.
[14] Bechtel, B., Zakšek, K., & Hoshyaripour, G.: **Downscaling land surface temperature in an urban area: A case study for Hamburg, Germany**. *Remote Sensing*, 4(10), 3184-3200, 2012.
[15] GO Medijana. https://medijana.rs/o-nama/ (15/03/2025).
[16] Republic Hydrometeorological Service of Serbia: **Monthly and annual means, maximum and minimum values of meteorological elements for the period 1991 – 2020,** (14/04/2025).
[17] Tomás, L., Fonseca, L., Almeida, C., Leonardi, F., & Pereira, M.: **Urban population estimation based on residential buildings volume using IKONOS-2 images and lidar data**. *International Journal of Remote Sensing*, 37(sup1), 1-28, 2016.
[18] Wan, Z., Hook, S., Hulley, G.: MODIS/Terra Land Surface Temperature/Emissivity Daily L3 Global 1km SIN Grid V061 [Data set]. NASA EOSDIS Land Processes Distributed Active Archive Center. Accessed 2025-03-27 from https://doi.org/10.5067/MODIS/MOD11A1.061. 2021.

[19] European Space Agency. (n.d.). *Copernicus GLO-30 Digital Elevation Model* [Data set]. https://doi.org/10.5270/ESA-c5d3d65

[20] J. Takaku, T. Tadono, M. Doutsu, F. Ohgushi, and H. Kai, **"Updates of 'AW3D30' ALOS Global Digital Surface Model in Anterctica with Other Open Access Datasets"**, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*., XLIII-B4-2021, 401-408, 2021.

[21] Didan, K.: MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes Distributed Active Archive Center. Accessed 27/03/2025 from https://doi.org/10.5067/MODIS/MOD13Q1.006, 2015.

[22] Pesaresi, M., & Politis, P.: GHS-BUILT-H R2023A—GHS Building Height. *Derived from AW3D30, SRTM30, and Sentinel2 Composite*, 2018.

[23] European Environment Agency. (2020). *CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly* [Data set]. Copernicus Land Monitoring Service. https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac

[24] Addinsoft. (2025). *XLSTAT statistical software* (Version 2025). [Computer software]. https://www.xlstat.com.

[25] Liu, C. B., Chamberlain, B. P., Little, D. A., & Cardoso, Â.: **Generalising random forest parameter optimisation to include stability and cost.** In *Machine Learning and Knowledge Discovery in Databases: European Conference,* ECML PKDD 2017, Skopje, Macedonia, September 18–22, 2017, Proceedings, Part III 10 (pp. 102-113). Springer International Publishing, 2017.

[26] Breiman, L.: **Random forests**. *Machine learning*, 45, 5-32, 2001.

[27] Janitza, S., & Hornung, R.: **On the overestimation of random forest's out-of-bag error.** *PloS one*, 13(8), e0201904, 2018.

[28] Hutengs, C., & Vohland, M.: **Downscaling land surface temperatures at regional scales with random forest regression**. *Remote Sensing of Environment*, 178, 127-141, 2016.

[29] Bartkowiak, P., Castelli, M., & Notarnicola, C.: **Downscaling land surface temperature from MODIS dataset with random forest approach over alpine vegetated areas**. *Remote Sensing*, 11(11), 1319, 2019.

[30] Maeda, E. E.: Downscaling MODIS LST in the East African mountains using elevation gradient and land-cover information. International Journal of Remote Sensing, 35(9), 3094-3108, 2014.

doi.org/10.62683/SINARG2025.018

Research paper

INTERNALIZATION OF ARCHITECTURAL SPACES AS A METHODOLOGICAL NOTE IN THE DEVELOPMENT OF THE DESIGN PROCESS

Milena Grbić[1], Olivera Dulić[2]

Abstract

This paper presents the principles and outcomes of a specific methodology conceived as a teaching tool at the Faculty of Civil Engineering in Subotica. The methodology is designed to support students in developing a deeper understanding of spatial relations, applicable across all phases of architectural design education. The methodological framework is grounded in an expanded interpretation of the term internalization, defined as the assimilation of spatial relations experienced through direct perception into the individual's cognitive framework. This process aims to enrich students' personal systems of thought and behaviour, advancing their ability to apply these insights in architectural design practice.

The methodology unfolds through three key stages: 1) Perceptual Analysis as personal experience of the architectural space, documented through photographs capturing selected spatial relations; 2) Verbal Interpretation as an articulation of spatial experience through five keywords, composed into a haiku poem; 3) Visual interpretation of spatial relations as their abstract transposition into a representative pictogram transcending stylistic conventions.

The study included 20 students from the second and fourth year of undergraduate studies. Selected for the research were buildings in the architectural styles of Secession (second year) and Neoclassicism (fourth year) in Subotica. Each student independently chose a distinct building from the works of renowned architects of the period, ensuring equal research conditions within the same architectural language.

The results reveal that the methodology successfully fostered intuitive engagement and multilayered spatial understanding, expressed through a synthesis of perceptual, verbal, and visual forms. The presented works showcase the students' developing subjective perspectives, which are a key objective of the process. Future academic practice will explore how this approach guides students in generating new values within the architectural discipline.

Key words: *Architectural education, Architectural space, Critical thinking, Art Nouveau, Neoclassicism*

[1] Ph.D., Grad.Arch.Eng., Associate Professor, University of Novi Sad, Faculty of Civil Engineering Subotica, Serbia, mgrbic@gf.uns.ac.rs, orcid.org/0000-0001-6485-1478

[2] Ph.D., M.Arch., Assistant Professor, University of Novi Sad, Faculty of Civil Engineering Subotica, Serbia, olivera@gf.uns.ac.rs, orcid.org/0000-0002-9463-8659

1. INTRODUCTION

Who is the one who speaks, who is the one who thinks instead of me?

Teaching architectural design represents a complex pedagogical task due to the multilayered nature of the discipline itself, which encompasses technical, aesthetic, functional, as well as psychological and sociocultural aspects. Students are simultaneously confronted with the challenge of mastering practical design skills while also developing the ability for abstract and critical thinking. In this context, there arises a continuous need for the development and implementation of contemporary and experimental teaching methods that can enhance the learning process and enable a deeper understanding of the design procedure. Experimental approaches are particularly significant, as they reflect the very nature of the creative process, in which experimentation plays a key role in generating architectural solutions.

Architectural design requires continuous balancing between structured knowledge and creative improvisation, which enables students to explore, experiment, and develop their authorial expression. This complexity makes the search for effective pedagogical strategies a particular challenge for educators. An additional layer of complexity in the teaching process stems from the fact that design skills are acquired through direct experience, reflection, and constructive critique. This implies the necessity of constantly adapting teaching approaches to the individual cognitive styles, interests, and abilities of students.

Learning architectural design does not entail the illustration of preformulated abstract ideas through the work of a single generation of students; rather, it begins with the premise that ideas are constructed based on their intuitive insights and reflections, through dialogue and collective exploration. The fundamental intention of this methodology is to encourage and affirm interaction—within the academic curriculum—between students and architecture as a meaningfully open and dynamic structure, in the formation and interpretation of which students participate as equal contributors. Although the primary goal of this pedagogical practice is not the realization of an architectural project as a final product, the methodology does not renounce the design apparatus; instead, it employs it as a tool for reflection and discovery.

The implementation of the methodological framework was carried out within the regular coursework of the subjects *Design of Public Buildings* (second year) and *Development of Architecture* (fourth year) at the Faculty of Civil Engineering in Subotica, Architectural Engineering module, during the 2024/2025 academic year. A total of twenty students participated in the research, each selecting one building for analysis. Second-year students analysed buildings in the Art Nouveau style, while fourth-year students worked on Neoclassical buildings. Within the given stylistic frameworks, students independently selected their buildings, with no repetition of chosen examples. The selection of stylistic periods was motivated by the fact that the chosen buildings were works of relevant authors of the time and possessed pronounced spatial qualities suitable for investigation. At the same time, working within a unified stylistic context provided students with equal conditions for analysis and for recognizing spatial and experiential relationships that particularly inspired them.

It is important to note that the choice of styles had no influence on the outcome of the methodology, nor was such an outcome anticipated. In the context of interpreting architectural meaning and history, the primary stylistic functions gradually lose their

expressive effectiveness over time. Contemporary observers—i.e., recipients of meaning, in this case, the students—are often unfamiliar with the specific symbolic-stylistic language of the given epoch and therefore unable to spontaneously recognize or interpret it. Architecture as a discipline is indeed a history of forms, but at the same time, it remains open to new interpretations, regardless of the original content or the author's intent. The methodological approach employed in this study demonstrates that meaning-making processes do not end at the moment an architectural work is created; rather, the conditions under which meaning disappears simultaneously represent the conditions for its reconstruction, reinterpretation, and transformation.

2. THEORETICAL BACKGROUND

"Isn't art, as Duchamp once said, "a game among all men of all eras?"
Postproduction is the contemporary form of this game," states Nicolas Bourriaud

The theoretical foundation of the proposed methodology relies on a synthesis of the views of Henri Focillon and Nicolas Bourriaud, thereby establishing a framework for understanding architectural form as a polysemic phenomenon. In this context, architectural form is considered a central element with its internal logic and vitality, open to various interpretations and reinterpretations. Simultaneously, form is also understood as a dynamic process whose meaning is not predetermined but rather constituted through active interaction with the observer. Within this framework, architectural form becomes a space of social interaction, collective engagement, and mutual communication.[3]

Starting from an inversion of Nicolas Bourriaud's thesis that "the museum, like the city, is a catalogue of forms" [1], this paper proposes the opposite perspective—the city, like the museum, can be viewed as a catalogue of forms. In this sense, the city is defined as a collective asset available to all—and in this case, to students—not to be submitted to, but rather to be used as a tool for exploring contemporary spatial, cultural, and social phenomena. At the boundary between the use and production of space, a certain stasis emerges—one that transcends the domain of architecture and becomes evident within the broader cultural context. Students' intuitive engagement with architectural objects goes beyond the traditional framework of appropriation and approaches a culture of use and consumption of forms—a culture of the constant activity of signs. In analogy with the principles of ready-made art, in which artists find material for artistic creation in objects already present in the marketplace, the architectural work assumes a value similar to that of a scenario—it becomes a scene(scenario), not merely as an end in itself, but as a means of definition: an act through which space becomes communicative and enduringly memorable.

The actual space being observed is reflected through the collision of images, opening a pathway to perceiving the real through fiction. Although an architectural object possesses

[3] Henri Focillon focused on the concept of form as a central element of art, arguing that forms possess a life of their own, which does not necessarily depend on specific historical circumstances. Focillon emphasized that form in art is not static but dynamic, and is in a constant process of transformation. The nature of form, according to Focillon, is something that grows and changes—something open to various interpretations over time.
Nicolas Bourriaud, on the other hand, concentrates on the interaction between art and its audience, asserting that art in contemporary society should not be something passively observed, but rather a dynamic process that involves the audience in the creation of meaning. According to his definition, relational aesthetics is art that relies on social interaction and creates a space for collective action and mutual communication.

values capable of communicating within the realm of designed architectural conditions and the broader cultural context, the methodology considers only the pure object of observation to be relevant. By drawing on the French philosophical lineage between Focillon and Bourriaud, it becomes possible to read the nature of form as being simultaneously prepared to be form and to be experienced as part of one's own contemporaneity. Thus, in its ultimate methodological outcome, determinism is transformed into technique—that is, into a design tool. In attempting to define the relationship between the method and the object under investigation, it becomes necessary to abandon the secure ground of established determinacy found in architectural modes of expression and to allow for the ambiguity of its appearance to be felt [2].

The past can be seen within the context of idealized theoretical constructs, the future as a breakthrough toward other ways of living, while the present stretches between change and stability, across a range of its own necessities and freedoms. It is the present that becomes the focus—because it holds the capacity to create a perceptual field within existing circumstances. It allows for internalization—to create a personal reality that exists within one's own perception and understanding of the world. Space and time become reality within the selected frame in which they are no longer separated, or in which that separation is no longer visible.

Within the proposed methodology, let us attempt to adopt the perspective of the student as an active subject in the research process. As part of the assignment, students are placed within a predetermined—or independently selected—spatial context and are tasked with identifying a specific spatial relationship (or spatial phenomenon), guided by their own subjectively strongest perceptual impression. The contextual distinction—whether it involves an enclosed architectural object or an urban setting—is not decisive in this model, as the research is directed toward the universality of the spatial relationship, regardless of its physical location. While inhabiting the space, students analyse and become aware of the elements of that spatial relationship that initially triggered their interest, as well as the emotions that the spatial relationship evokes in them (e.g., colonnade, arcade, niche, towers…). From that moment on, such a spatial relationship—whether encountered again in real life or an image—will always be associated with the experience they had in that particular space. Through direct experience, that space has been shaped within them as an idea of that space—serving as a mnemonic association that enables them to experience a similar sensation in comparable spatial relationships [3].

Over time, the concrete experience of a real spatial relationship becomes abstracted and transformed into a general idea of that type of relationship. Such an abstract matrix functions as an internal tool for recognizing similar phenomena across different contexts. In doing so, students develop the ability to read space in a polysemic way, identifying variations of the same underlying spatial logic. The abstract model formed in this process is not conditioned by collective norms but rather represents an individual construction of meaning—one that is simultaneously created, embraced, and affirmed within the domain of personal perceptual and mental experience. In this way, the spatial relationship generates an internalized code—which constitutes the primary objective of the methodological approach—that must, whether consciously or unconsciously, be validated through the process of articulation and presentation, to be permanently remembered and potentially become a subject of communicative exchange within a broader educational and professional context.

The articulation and presentation of an abstract idea—both to the authors themselves and to others—represents an exceptionally complex task, given its polysemic nature and elusiveness within everyday forms of communication. However, it is possible to establish a strategy of visual-verbal representation that involves the creation of a personalized ideogram – a visual sign that is not generic but is individually connected to the semantic layer of the idea – as well as the selection of a set of key words that most precisely illuminate that abstract thought.

This method is theoretically grounded in Allan Paivio's cognitive theory of dual coding, which posits that the memorization process is significantly more effective when visual representations are combined with verbal information [4]. Paivio distinguishes between two cognitive systems: one that encodes images and visual data, and another that processes verbal information. By linking these two systems, parallel neural pathways are formed, thereby substantially increasing the likelihood of long-term consolidation of information in memory. In this context, the use of ideograms and carefully selected words acquires a clear methodological function. Furthermore, the decision to articulate key words in the form of haiku poetry is based on the so-called Hedwig von Restorff effect, which suggests that information that deviates from a familiar pattern—whether through form, tone, content, or expressive uniqueness—is more likely to be remembered precisely because of its distinctiveness and cognitive salience [5].

2.1. Ideogram

Within architectural education, the ideogram is recognized not merely as a graphic representation but as a cognitive and conceptual tool that condenses spatial experiences, relationships, and meanings into a single, synthetic form. As Jacek Krenz [6] emphasizes, ideograms serve as visual catalysts in the process of architectural conception, enabling the simultaneous activation of analytical and intuitive thinking by merging formal abstraction with the communication of complex, often intangible spatial ideas. Unlike sketches, which primarily depict the appearance of an object, ideograms integrate a semantic layer, functioning as symbolic condensations of essential spatial qualities. By reducing complex architectural notions into clear and evocative visual structures, ideograms allow students to preserve the coherence of architectural ideas while facilitating their reinterpretation and further development throughout the design process.

In this methodology, the ideogram also serves as a cognitive frame that supports students in constructing individualized systems of meaning. Building on Ivo Vrouwe's [7] insights, ideograms are understood as visual structures that enable students to synthesize perceptual impressions, conceptual reflections, and material intuitions within a coherent language of representation. Through this mediating role, ideograms bridge sensory perception and conceptual abstraction, fostering deeper internalization and encouraging students to develop autonomous and reflective design thinking that transcends mere technical representation.

The theoretical foundation that supports the use of ideograms in this methodology is rooted in the conceptual role of the diagram in architecture. The diagram transcends its function as a technical drawing and is affirmed as a cognitive and conceptual model capable of structuring complex spatial relationships. Shaped by contributions from philosophers, semioticians, and architects throughout the twentieth century, the diagram—as Charles Sanders Peirce defined—represents "intelligible relations in the constitution of an object," not through depiction, but through structural substitution [8–9]. In architectural practice, the

diagram becomes a means of reduction, abstraction, and synthesis—a tool for both thought and design. Fraser and Henmi [10] characterize it as a selective representation enabling interpretation; Knoespel [11] highlights its potential to both order and destabilize structures; and Bijlsma [12] positions it as a model for analysis and creative generation. Through this layered capacity, the diagram functions as an epistemological bridge between perception, reflection, and design, integrating visual and conceptual knowledge [13].

Building upon this conceptual framework, the present methodology extends the diagram's epistemological role into the realm of intuitive spatial articulation through ideograms. While the diagram structures and abstracts spatial relationships analytically, the ideogram captures their emotional and experiential dimensions, offering students a complementary means for internalizing and expressing architectural space.

Alongside the haiku-formulated key words, the ideogram thus becomes part of a broader communicative system, enabling students not only to reflect on their spatial insights but also to position them within a shared academic discourse. Through this practice, students are empowered to construct personal architectural languages rooted in perceptual authenticity, bridging immediate spatial experience with its research-oriented articulation.

3. METHODOLOGICAL FRAMEWORK

The methodological structure is situated at the intersection of theoretical reflection and pedagogical experimentation, transforming the theoretical foundation into a concrete design tool through which students become active subjects of spatial exploration. The method relies on subjective perceptual experience, mnemonic coding, and cognitive anchoring as key resources for the development of authentic perceptual mechanisms and the construction of an individual system of meaning, which can subsequently serve as a foundation for future spatial articulation in design practice.

The methodological framework, implemented within the courses *Design of Public Buildings* and *Development of Architecture* at the Faculty of Civil Engineering in Subotica during the winter semester of the 2024/2025 academic year, comprised several key methodological components:

1) Contextual Immersion: Students are placed within a concrete spatial context and encouraged to engage in intuitive perception—observing, listening, and feeling. The goal is for each student to independently identify a spatial relationship that evokes a strong personal impression. The nature of the spatial environment (interior or exterior) is not of primary importance compared to the intensity of the perceptual reaction. Each individual perceives forms, light, textures, and the arrangement of elements differently, directly influencing the understanding and interpretation of spatial relations. The same space is revisited at different times of the day to capture, through photography, the moment that most accurately reflects the experienced impression.

2) Analytical Reflection: Students deconstruct the identified spatial relationship, analysing both its formal elements (e.g., colonnades, arcades, niches, towers) and the emotional resonance they evoke. This dual analysis, formal and affective, forms the basis for constructing an internalized, abstract representation of the spatial relationship.

3) Visual-Semantic Representation: The combined use of visual and verbal expression makes the memory process more effective. The internalized spatial perception is externalized

through the creation of an ideogram and the selection of five key words, serving as a visual-semantic tool that condenses the essence of the experienced space.

4) Visual Representation: The ideogram is considered a conceptual tool and a cognitive model that enables students to structure their spatial impressions and transform them into transferable, stable forms. In this way, the ideogram becomes a cognitive bridge between immediate experience and its academic articulation.

5) Verbal Representation: In parallel with the visual component, the activation of the verbal system is required. Students are asked to identify five key words that best describe the spatial relationship they perceived as significant. These words do not necessarily represent final concepts but rather result from an initial cognitive mapping intended to articulate the intuitive impression through language. The synthesis of the five key words into the form of a haiku poem represents a deliberate methodological choice to deviate from expected patterns (in form, tone, or expressiveness), thereby increasing the likelihood of long-term memorization through cognitive salience.

Beyond the concrete methodological outputs—photography, ideogram, and haiku—the broader objective of the methodology is to develop students' individual spatial literacy and their ability to recognize and articulate polysemic spatial logics across various contexts. The abstract spatial relationships formed through this process function as mental matrices, enabling students to identify (and apply) variations of the same conceptual framework in future spatial experiences.

4. RESULTS AND DISCUSSION

The results of the methodological procedure were expressed through three interrelated and communicative representations, which enabled students to articulate, visualize, and reflect upon personally experienced spatial relationships: 1) *Perceptual analysis of space*, documented by a photograph that most strongly reflects the student's subjective impression of the selected spatial relationship; 2) *Verbal interpretation*, conveyed through five carefully chosen key words structured in the form of haiku poetry, thereby achieving a condensed and symbolic expression of meaning; 3) *Visual abstraction*, realized through an ideogram, which represents the transposition of the experienced spatial relationship into an abstract cognitive model.

Through the analysis of the obtained results (Figure 1, Figure 2), several key educational and methodological effects were identified, which are considered particularly significant for the development of architectural awareness among students. First, the concrete examples confirmed the thesis that the meaning of architectural elements is neither static nor universal but is formed through a complex interaction between the physical characteristics of space and their variable interpretations. In this way, the illusion of architecture's constancy was deconstructed, and it was understood as being subject to rapid obsolescence and the continual transformation of meaning.

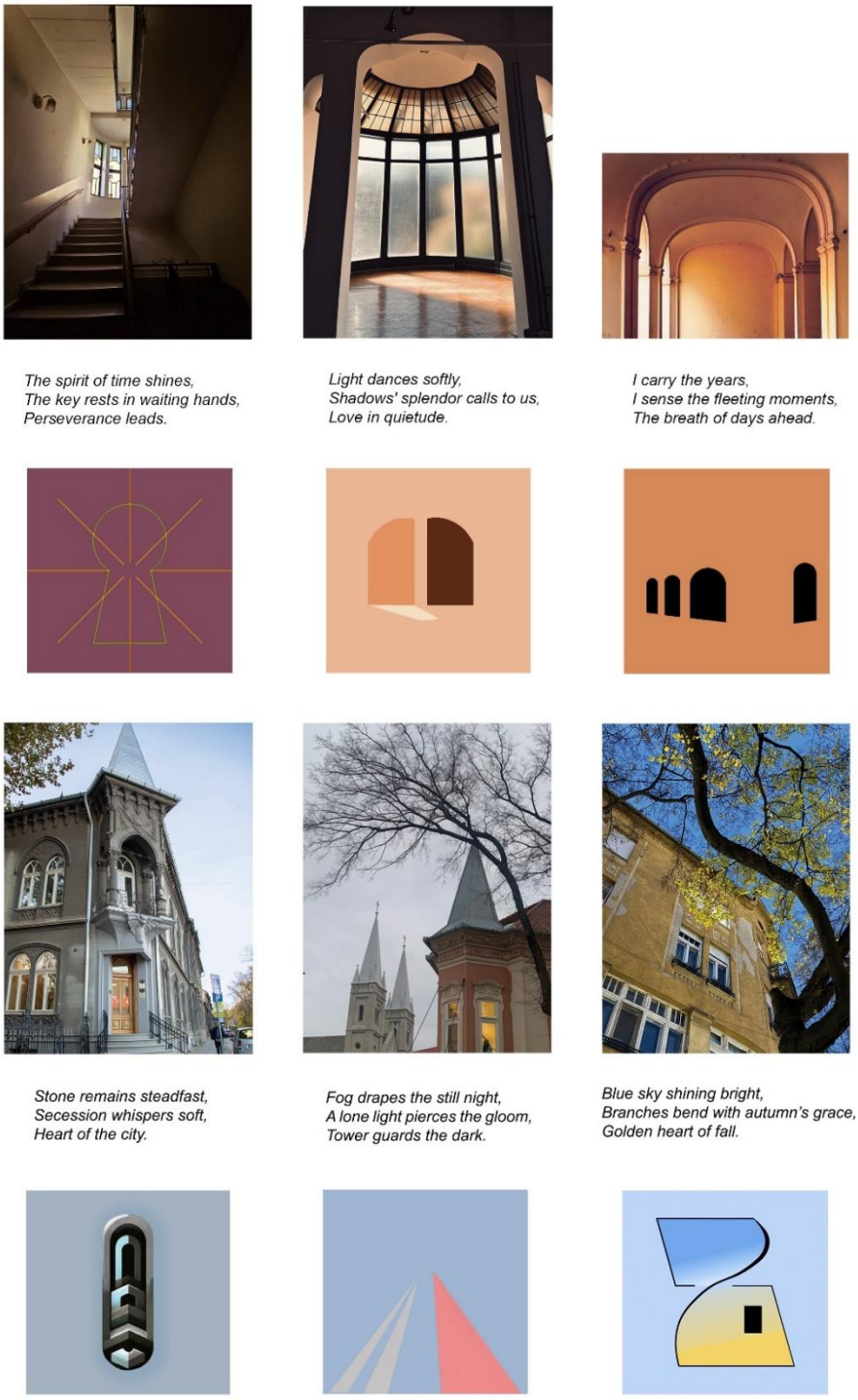
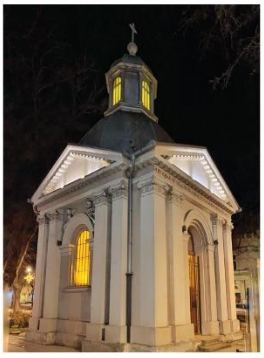


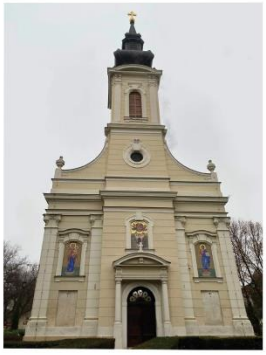
Figure 1. Overview of selected student works aligned with the applied methodological framework (second-year students)



Cornerstone lies still
calmness found within the storm
peace within the soul



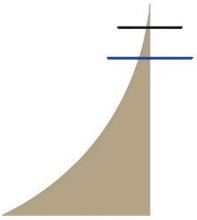
Window facing you
golden glow upon the glass
the soul travels far



Old tower shines bright
beneath the blue sky's great vault
a prayer endures

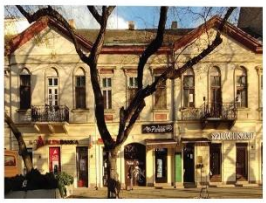








Night kisses the door
a pillar bears the great vault
silence radiates



Shadows of the trees
an old building tells its tales
holding quiet truths



Golden facade glows
Silent past begins to speak
The sky is witness



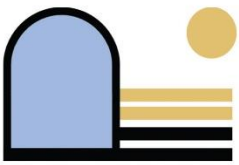


Figure 2. Overview of selected student works aligned with the applied methodological framework (fourth-year students)

From a semiological perspective, grounded in the theoretical frameworks of Ferdinand de Saussure and Roland Barthes, a second benefit emerged: the analysed spatial relationships were recognized as signs consisting of two levels of meaning: 1) *The denotative level* (signifier) – the physical dimension of the spatial relationship, which can be identified, named, and documented independently of any interpretive layer (in this case, the photograph as the primary form of evidence); 2) *The connotative level* – the semantic dimension of the spatial relationship, formed through the personal, cultural, and social experiences of the observer (articulated through haiku and pictogram/ideogram).

As a third positive outcome, the insights gained through the application of this methodology indicate the potential for students to develop the ability for conscious and critical use of these spatial relationships in their own design practice. This process evolves within a dialectic between two conceptual extremes: a) a maximum of responsibility, in which form is perceived as strictly determined by programmatic requirements, regulations, or cultural expectations. That is, through the creation of personal associative nuances related to a given spatial relationship, a path has been opened toward its fully conscious application in future architectural practices; b) a maximum of voluntariness, in which form is understood as flexible and open to subjective use and interpretation. This raised awareness of the fact that every (designed) spatial relationship is subject to interpretation—one that will depend on the culture, experience, and context of the individual (e.g., the future user).

As a comprehensive contribution to a deeper understanding of architecture, the key idea conveyed to students is that architecture, while persuasive, simultaneously remains open to interpretation. It is precisely this ambiguity that enriches its openness, creating space for avoiding typological, formal, and rhetorical rigidity. Within the framework of such a methodology, the constitutive elements of architectural form gain the right to be articulated outside of predetermined schemas, thus restoring to architecture the freedom of creation and interpretation as equal components of meaning.

Simultaneously, this methodology affirms the student as an active participant who, through experience and reflection, shapes authentic design positions beyond the confines of reproducing existing models. The educational process thereby becomes a space for creation and interpretation, rather than the reproduction of predetermined templates.

5. CONCLUSION

As indicated at the very beginning of this paper, within architectural education there are no predefined or universally applicable solutions that could serve as rigid methodological guidelines. The search for such a form of “timelessness” is not only methodologically unfounded, but also fundamentally opposed to the nature of the architectural discipline, which continuously evolves through contextual, social, and individual changes. Accordingly, contemporary methodologies of design education should strive to balance between experimentation and ephemerality, remaining open to constant questioning and transformation.

Arising from the observed discrepancy between students’ initial expectations and the complexity of cognitive processes required by architectural design, the developed methodology emerged as a spontaneous yet systematically articulated didactic unit within the teaching framework at the University of Novi Sad – Faculty of Civil Engineering in

Subotica. The aim was to make students' initial encounter with architectural thinking more immediate, intuitive, and meaningful.

First and foremost, students had the opportunity to engage in direct interaction with real space, to experience and perceive it on a personal level—an approach that remains underrepresented within the curricula of design courses. This type of engagement, still insufficiently present in standard curricula, proved to be essential for activating sensitivity and critical thinking within the learning process. Tête-à-tête discussions with students further enabled a deeper analysis of individual perceptual responses and laid the foundation for the development of personalized architectural codes.

The abstracted spatial elements, acquired through direct experience, do not remain confined to the domain of individual reflection but are reactivated in the design process, where they become connected to new contexts and scales. In doing so, students develop operative creative mechanisms that guide them toward the formation of concepts articulated through a contemporary, universal architectural language. This advancement in the understanding of spatial relationships has a positive impact on the development of critical thinking, the outcome of design projects, and, consequently, contributes to shaping future designers.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the second-and fourth-year students of the Architectural Engineering module at the Faculty of Civil Engineering in Subotica, University of Novi Sad, whose participation in the courses Design of Public Buildings (Kristina Miličić, Milica Gršić, Dragana Butorac, Boris Radak, Nikolina Stančić, Evelin Rosza) and Development of Architecture (Amina Bero, Brigita Skenderović, Aleksandar Toškov, Katarina Nikolić, Adela Mujčić, Milica Krasulja) was essential to the realization and development of the methodological framework presented in this paper. Their dedication, thoughtfulness, and willingness to explore have greatly contributed to the quality of this work.

REFERENCES

[1] Nicolas Bourriaud: **Postproduction Culture as Screenplay: How Art Reprograms the World**. *Has & Sternberg*, New York, 2002.
[2] Vladimir Milenković: **Forma prati temu - petodelni metodološki esej**. Univerzitet u Beogradu, Arhitektonski fakultet, Muzej primenjene umetnosti, Beograd, 2015.
[3] Umberto Eko: **Kultura, informacija, komunikacija**. Nolit, Beograd, 1973.
[4] Allana Paivio: **Mental Representations**. Oxford University Press, New York, 1986.
[5] Collin M. MacLeod: **Zeigarnik and von Restorff: The memory effects and the stories behind them**. *Memory & Cognition*, vol. 48, pp. 1073–1088, 2020.
[6] Jacek Krenz: **Ideograms in Architecture: Between Sign and Meaning**. *Gdańsk University of Technology*, Gdańsk, 2012.
[7] Ivo Vrouwe: **Ideograms as a tool for constructive sensemaking in architecture education.** In *Proceedings of the EAAE-ARCC International Conference on Architectural Research*, Leuven, 2013, pp. 469–477.
[8] Eleanor Kaufman and Kevin Jon Heller (Eds.): **Deleuze & Guattari: New mappings in politics, philosophy, and culture**. University of Minnesota Press, Minneapolis, 1998.

[9] Anthony Vidler: **Diagrams of Utopia**. In *The activist drawing: retracing situationist architectures from Constant's New Babylon to beyond*, C. de Zegher and M. Wigley (Eds.) Drawing Center, New York, 2001.
[10] Iain Fraser and Rob Henmi: **Diagrams**. in *Envisioning Architecture: An Analysis of Drawing*, John Wiley & Sons, New York, 1993, pp. 99–111.
[11] Kenneth J. Knoespel: **Diagrammatic Transformation of Architectural Space**. *Philosophica*, vol. 70, pp. 11–36, 2002.
[12] Luke Bijlsma, **The diagram**. *OASE Journal for Architecture.*, vol. 48, pp. 1–2, 1998.
[13] Stan Allen: **Diagrams matter**. *ANY Architecture New York*, vol. 23, pp. 16–19, 1998.

doi.org/10.62683/SINARG2025.019

Review paper

CONSTRUCTION SOLUTIONS OF THE OLD ŽEŽELJ BRIDGE IN THE SPHERE OF INNOVATIVE ACHIEVEMENTS IN DOMESTIC BRIDGE ENGINEERING

Dušan Kocić [1], Milan Gligorijević [2], Marjan Petrović[3], Nemanja Petrović[4]

Abstract

In this paper, a retrospective of the construction solutions of the old Žeželj Bridge on the Danube in Novi Sad will be presented. It was built between 1957 and 1961 and was designed by academician Branko Žeželj, a civil engineer after whom the bridge was colloquially named. The bridge consists of two arches with spans of 211 and 165.5 meters, with the roadway suspended from them. An innovative radial cable prestressing of the arch cross-section was applied, a method patented by engineer Branko Žeželj. Upon completion, and for many years afterward, it was the bridge with the largest arch span—both the largest arch in Europe and the longest-spanning arch in the world for railway traffic. The construction system of this bridge was unique in the world and was first applied in Yugoslavia, serving as a model for many bridges worldwide. For this reason, Branko Žeželj was awarded at the World Congress for Prestressing (FIP) held in Rome in 1960 for his significant innovations in prestressed concrete construction technology. As proof of the bridge's high-quality construction, it was only destroyed after six strikes during the NATO aggression in 1999. Nineteen years later, a new steel bridge, visually reminiscent of the original, was opened.

Key words: *bridge structures, radial prestressing, construction technology.*

[1] Civil engineer, assistant, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, dusan.kocic@akademijanis.edu.rs, ORCID 0009-0006-4886-0482
[2] PhD, Faculty of Civil Engineering and Architecture - Department of Constructions, Serbia, milan.gligorijevic@gaf.ni.ac.rs, ORCID 0009-0005-3538-3851
[3] PhD, lecturer, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, marjan.petrovic@akademijanis.edu.rs, ORCID N/A
[4] PhD, lecturer, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, nemanja.petrovic@akademijanis.edu.rs, ORCID 0000-0003-4010-2311

1. INTRODUCTION

The development of construction in Yugoslavia after World War II progressed rapidly. Due to swift industrial growth and the need for rapid reconstruction of a war-ravaged country, the golden era of the construction industry began. The need for mass construction of buildings forced engineers to seek new and faster construction solutions. Academician Branko Žeželj designed and patented more than 20 innovations, becoming a pioneer in the application of prestressed concrete technology in the former Yugoslavia and globally.

One of his structural solutions was the bridge over the Danube in Novi Sad. According to its structural system, this bridge belonged to the category of concrete arch bridges. It was built using prestressed concrete technology. For large-span arch bridges, the most crucial aspect of design and construction is the assembly plan [1].

The bridge consisted of two concrete arches from which the roadway deck was suspended via concrete hangers. To ensure the necessary navigable profile of the river, Branko Žeželj devised a unique method for constructing the arches, which involved building the arch in three segments. For bridges over large rivers such as the Danube and Sava, assembly from sections on the banks or using floating equipment is often employed to avoid temporary supports in the riverbed [1].

The Žeželj Bridge was constructed between 1957 and 1961. It was the world's first arch bridge built using prestressed concrete technology and a unique construction system. The main arch spanned 211 meters, making it the largest concrete arch bridge in Europe at the time, and the largest in the world to carry railway traffic. Destroyed during the NATO bombing in 1999, it was a key transportation link over the Danube in Novi Sad, connecting the city with industrial zones and the Pan-European Corridor X [2].

The Žeželj Bridge was not only a vital traffic connection linking the banks of the Danube and enabling the flow of people and goods along an important European corridor, but it also stood as a powerful symbol of Novi Sad's identity. Its recognizable silhouette was etched into the collective memory of the citizens as an architectural landmark of the city and a testament to the engineering progress of its time (Figure 1). As such, the bridge transcended its functional role and became part of the cultural and visual identity of the urban landscape. The demolition of the bridge in 1999 caused significant disruptions to both rail and road traffic, breaking the continuity of one of the most important transport links across the Danube [3].

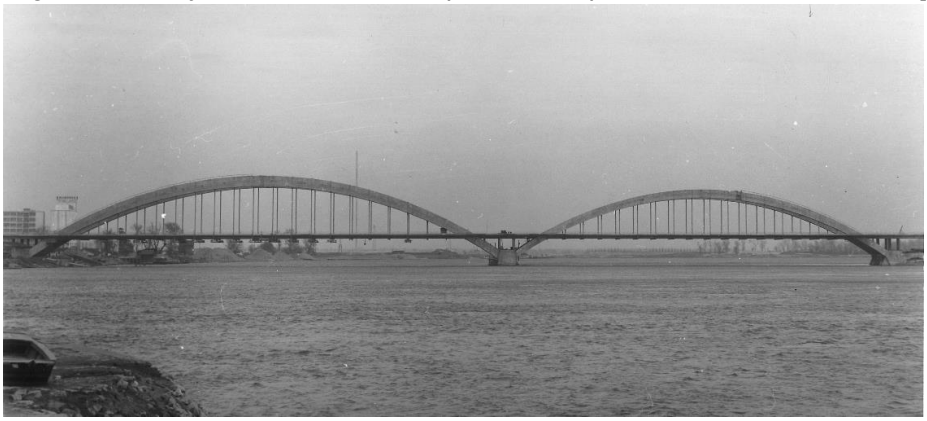


Figure 1. View of the bridge over the Danube in Novi Sad [4]

2. DESCRIPTION OF BRIDGE STRUCTURES

The road-rail bridge over the Danube in Novi Sad was located on the route of the main international thoroughfare Belgrade – Budapest, which represented the shortest connection between Central Europe and the Middle or Near East. The bridge also played a significant role in the national context, as it connected the fertile regions of Vojvodina with the rest of Serbia. Additionally, it was crucial to the transportation, economic, and industrial development of Novi Sad.

Before World War II, traffic was carried over two separate bridges – one for road and one for rail – both of which were destroyed during the war. A temporary solution after World War II was a steel truss road-rail bridge, built on the site of the demolished structure. However, its construction, adapted for combined traffic, resulted in difficult and slow traffic flow.

The construction of a new bridge was conceived as the foundation for a comprehensive solution to the railway junction and port area in Novi Sad. The bridge spanned the Danube at a location with a pronounced river bend, in the port zone, and since it was situated in the city center, it had to meet both aesthetic and urban planning requirements.

2.1. The bridge project

The total width of the regulated Danube riverbed in the area of the planned bridge, in accordance with urban planning, traffic, and industrial conditions, was 340.0 meters. The minimum navigable profile provided for a width of 190.0 meters at zero water level (elevation 71.76 m), and 210.5 meters at maximum water level (elevation 78.76 m). The vertical clearance of the navigable profile at high water levels was 6.0 meters. In addition, a secondary navigable profile of smaller dimensions was planned for upstream towing.

The bridge was designed for railway traffic, with the top edge of the deck placed at an elevation of 88.05 meters. The structure also had to span streets 15.0 meters wide on both the Novi Sad and Petrovaradin sides.

The total length of the structure between the end supports, including the river and the riverside streets with sidewalks, was 466.45 meters. It was divided into four segments: two main spans and two riverside approach structures.

The main navigable channel was spanned by an arch with a span of L = 211.0 meters, while the remaining part of the riverbed was spanned by an arch with a span of L = 165.75 meters. The floodplain structure on the Petrovaradin side was a simple beam with a span of 26.0 meters and an overhang of 2.72 meters, while the Novi Sad side had a continuous girder with spans of 10.0 + 20.0 + 10.0 meters and an overhang of 3.50 meters.

The width of the roadway slab was 20.15 meters, with pedestrian walkway expansions at the points where the bridge intersected with the arches. The clear width between the arches was 14.05 meters – of which 4.40 meters were allocated to the railway profile and 9.0 meters to the roadway. The inspection walkway had a width of 1.0 meter, while the usable width of the pedestrian paths was 5.15 meters.

2.2. Arc of span L=211.0 m

The structural system of the main span consisted of a fixed (encastre) arch with a span of L = 211.0 meters and a rise-to-span ratio of f/L = 1/6.5. The moment of inertia varied – decreasing from the crown toward the supports, where it increased sharply. The rise of the arch was 32.50 meters, while the axial spacing between the arches was 16.55 meters.

The arch had a box cross-section, with a height of 4.50 meters at the crown, tapering to 3.20 meters at the supports. The height-to-span ratio ranged from h/L = 1/47 to 1/66. The width of the arch above the roadway was constant at 2.50 meters, while below it widened to 4.70 meters. The side walls of the cross-section were 25 cm thick, while the top and bottom slabs varied from 62 cm to 1.20 meters. The section was reinforced and additionally radially prestressed.

The structural analysis included compensation of stress states in the arch using hydraulic presses at the dry crown joint to account for viscoelastic and plastic deformations, while the final closing of the crown was performed after the installation of the hangers.

Most of the roadway was suspended from the arch using hangers with an octagonal cross-section, with 15 cm sides, made of prestressed concrete (Figure 2). The transverse girders were prefabricated, also made of prestressed concrete.



Figure 2. Pre-assembled hangers at the place of manufacture [4]

The rest of the structure consisted of secondary transverse girders, four longitudinal girders, the roadway slab, and cantilevers with pedestrian walkways. Except for the walkway, all elements were constructed on site. The roadway slab was cross-reinforced, with expansion joints located above the piers and at mid-span (Figure 3).



Figure 3. Track plate and secondary supports [5]

The arches were connected by a truss bracing system made of prefabricated elements, which were prestressed and formed a unified structure (Figure 4). For stability under lateral loads, a box-shaped stiffening element was provided beneath the roadway, which, together with the lower parts of the arches, formed a closed frame.



Figure 4. The design of the arch with a lattice connection [5]

The scaffolding for the large arch had to be designed to meet navigation requirements, allowing a 100.0-meter-wide passage for ships during the bridge construction (Figure 5). On the other hand, the high speed and depth of the river, as well as the potential for significant ice flows, required scaffolding with as few supports in the river as possible. To meet these conditions, a five-span scaffolding structure was designed. Two of the spans were composed of military prefabricated steel structures with a span of 23.0 meters, and the central span of 108.0 meters consisted of four two-hinged arches made of prefabricated reinforced concrete elements, connected by transverse girders and prestressed crossed diagonals. The auxiliary supports were founded on prestressed concrete piles with cross-sectional dimensions of 35 x 35 cm and a length of 17.0 meters.

The scaffolding was designed to carry only about 40% of the weight of the arches, which required the arches to be concreted in three phases. After the first phase, the lower ring had to be prepared using hydraulic presses to carry the load of its own weight and, together with the scaffolding, the load of the subsequent phases. In this way, an economical and lightweight scaffolding system was designed.

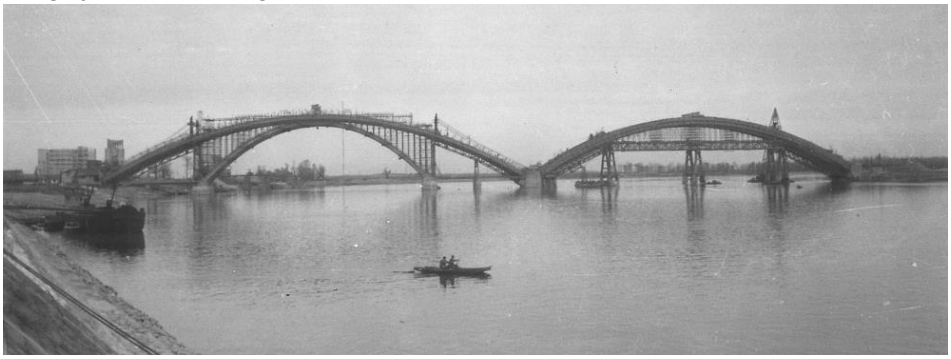


Figure 5. Scaffolding display during the construction of the arches [5]

The 108.0-meter-span arch scaffolding for the large opening was assembled using the cantilever method with a floating crane that had a lifting capacity of 50 tons and a lifting height

of up to 35.0 meters. Individual prefabricated elements, weighing between 16.5 and 24.0 tons, were hinged to one another and held in place with cables over pylons and anchors until the arch was positioned in its final design alignment. Afterward, the hinged joints were concreted, and the arch was definitively tensioned transversely (Figure 6).

The supports for the two-hinged arch scaffolding were constructed on-site as box structures reinforced with ribs.

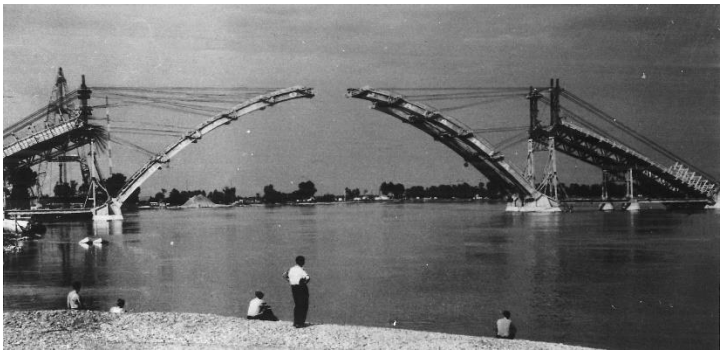


Figure 6. Installation of arched scaffolding of a large arch [5]

2.3. Arc of span L=165,75 m

The arch with a span of L = 165.75 m had the same slenderness ratio f / L = 1 / 6.5 as the larger arch. The rise of the arch was 26.50 m, and the axial spacing between the arches was 16.55 m. The arch structure was built as a closed box section of variable height – at the crown, the height was 3.63 m, gradually decreasing to 2.60 m at the supports. The height-to-span ratio ranged between h / L = 1 / 46 and 1 / 64.

The width of the arch above the roadway was constant at 2.20 m, while below the roadway it widened towards the supports to a maximum of 4.20 m. The side walls of the section had a constant thickness of 25 cm, while the thickness of the top and bottom slabs varied from 50 cm at the crown to 90 cm near the supports.

The arch was reinforced in both longitudinal and transverse directions, and the side walls were additionally radially prestressed.

The roadway structure was suspended from the arch by vertical hangers with an octagonal cross-section and 15 cm side length, made of prestressed concrete. The hangers were designed as prefabricated elements, partially prestressed at the production site and additionally prestressed during connection to the arch and the transverse girder.

A smaller portion of the roadway was supported on reinforced concrete piers with a rectangular cross-section, located above the river pier. The transverse girders were also prefabricated, made of prestressed concrete, and designed as simply supported beams. The rest of the roadway structure consisted of secondary girders, four longitudinal girders, the roadway slab, and sidewalk cantilevers. Most of these elements were constructed on site, except for the prefabricated parts of the pedestrian walkway. The cantilevers and secondary girders were made of prestressed concrete, while the remaining elements were made of reinforced concrete.

The longitudinal girders were designed as continuous girders with fixed supports, with transverse load distribution based on the grillage system. The roadway slab was cross-

reinforced, with expansion joints located above the piers of the bank structure and at mid-span.

The scaffolding for the smaller arch was designed using prefabricated “Kohn” and “Rotwagner” structures, with four spans (Figure 5). Three auxiliary supports were designed to be founded on prestressed concrete piles, with lengths of 15.0 and 17.0 m and cross-sectional dimensions of 35 x 35 cm. One foundation contained 10 and another 14 piles.

2.4. Approach inundation constructions

On the Petrovaradin side, the approach inundation structure was a simply supported beam with a span of 26.0 m and an additional cantilever of 2.72 m in length. It was constructed as a concrete slab supported by ribs, which also formed cantilevers. Installation ducts were placed beneath the slab. This structure was monolithically connected to the arch and transmitted all vertical and horizontal loads.

On the side of Novi Sad, the approach inundation structure was a continuous girder, consisting of three segments with spans of 10.0 + 20.0 + 10.0 m, and an additional cantilever of 3.50 m. In terms of structural design, it was similar to the Petrovaradin side, but it accounted for the possibility of larger thermal displacements. For this purpose, bearings allowing movement in both directions were installed at the first support, while the remaining supports were designed as sliding bearings in the longitudinal direction.

3. BRIDGE CONSTRUCTION TECHNOLOGY

Construction of the bridge began in 1957, with the organization of the construction site on the left bank of the river, which is navigable only during exceptionally high water levels. Additionally, this bank is well connected to external land and water communications.

3.1. Supports

The left riverbank pillar was constructed on-site and then lowered to the designated level through caisson excavation. Since the area near the foundation, where the slab was supposed to be placed to achieve the reactive thrust from the soil, had poor-quality soil (silty clay), a deeper excavation was carried out. After that, the slab was cast and lowered to the designated level using a hydraulic elevator. To consolidate the ground behind the slab, mechanical compaction of sand and gravel in layers was performed, and part of the natural sandy material was reinforced with "Franki" system piles.

The right riverbank pillar was constructed in a similar way to the left one. The difference was that, at the location where the support was to be placed, a stone embankment island was first created, using a mix of stone rubble and dredged sand as part of the future riverbank regulation. Then, the caisson was constructed along with the slab. After that, the caisson excavation was carried out, and the caisson was lowered to the intended level.

The middle (river) pillar was constructed about 100 meters upstream on the left bank, and, after dry excavation, was lowered to the depth of the riverbed. Then, the channel was connected to the river flow, and the caisson was transported to the pillar location using caisson barges. This construction method was adopted due to the great water depth at the river pillar (10.0 meters at average water level), ensuring safer and faster work.

The caisson was made with reduced sections and pre-stressed elements, so during the caisson transportation phase, it weighed 3200 tons, out of the 6000 tons it weighed when it was lowered to the riverbed.

3.2. Concreting of the arches

The concreting of the arches began with the creation of the first ring (phase one). Once the lower ring in the crown received the load from its own weight through hydraulic presses, the viscoelastic and plastic deformations were partially compensated. Therefore, the upper ring was concreted independently from the lower one. Once the viscoelastic and plastic deformations were similarly compensated for the upper ring, the two rings were connected (phase three). To ensure secure bonding of the concrete during all three phases, the side walls were pre-stressed with radial cables.

The concreting of the individual phases was done in slabs of 10 to 15 meters in length, with an interspace of 1.5 meters. These interspaces were later concreted to eliminate the initial deformations due to shrinkage of the concrete.

The main reinforcement for the arches, Č 37 with a diameter of 32 mm, was welded in contact up to half the length of the arches, then manually transported and placed in the formwork. The concrete was prepared on the bank or floating structures, and lifted into place by a crane. After the concreting of the arches was completed, the wind bracing was assembled using a light mobile wooden scaffold.

The joint at the crown of the arch remained under pressure for about six months, until the beginning of the concreting of the secondary transverse and longitudinal supports. During this period, a significant portion of the parasitic influences was compensated, such as viscoelastic and plastic deformations, concrete shrinkage, plastic flow, and the separation of the end supports.

3.3. Construction of pavement

The suspenders and transverse supports were made on-site as prefabricated elements, transported below the bridge by floating means, and lifted and installed using a light wooden portal crane. The attachment of the suspenders to the arch and the transverse supports to the suspenders was done using pre-stressing.

After the installation of all the transverse supports, formwork was made for the longitudinal and secondary transverse supports, and concreting was carried out. Following that, the assembly of the pedestrian path elements was completed, and finally, the road slab was concreted, with simultaneous connection of the pedestrian path elements to each other and to the grillage of the main supports.

The concreting of the roadway was carried out from the ends toward the center of the structure.

4. DEMOLITION OF THE BRIDGE

On March 24, 1999, a group of NATO member countries, led by the United States, began an aggression against the Federal Republic of Yugoslavia. Under the pretext of preventing a humanitarian disaster in the territory of Kosovo and Metohija, both military and civilian targets across the country were bombed. The aggression lasted for 78 days, with the use of cluster

bombs and bombs containing depleted uranium. The NATO member states sought the approval of the United Nations Security Council for military intervention, but it was not granted.

All the bridges in Novi Sad were destroyed during the aggression. The Brotherhood and Unity Bridge, better known as the Žeželj Bridge, was a target that long withstood attacks. It was destroyed on May 3, 1999, after being hit for the sixth time. Throughout the bombing, the target was the river pier, which was struck by several dozen GBU-27 projectiles.

The arch static system had inclined reaction supports that could be broken down into horizontal and vertical components. Since both ends of the arches were supported by the river pier, which was destroyed after being hit multiple times, the horizontal reaction components of the arch supports over the river pier remained in "balance," as shown in Figure 7. Therefore, after the destruction of the river pier, the arches leaned on each other, and it can be conditionally said that the arches were levitating. More accurately, the operation to destroy the bridge was unsuccessful.

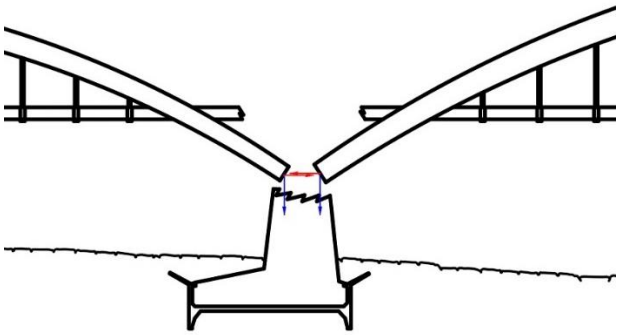


Figure 7. Schematic representation of the support of the arches after the destruction of the river column

Only after many unsuccessful hits on the river pier, the smaller arch was later targeted from the side at the crown by cruise missiles. After several consecutive lateral strikes, the smaller arch (connected by the roadway slab and tie rods) was overturned into the river as a whole, thus completing the bridge demolition mission, as shown in Figure 8.



Figure 8. Aerial photo before and after the bombing of the bridge [6]

Nineteen years later, a new steel arch bridge was built at the site of the old bridge, visually resembling the original concrete bridge.

5. CONCLUSION

The road-rail bridge over the Danube in Novi Sad was much more than an infrastructure facility – it represented a crucial point of connection not only in transportation but also in urban, economic, and strategic terms.

This bridge was the result of a carefully designed revolutionary engineering solution [7], which successfully met the complex technical, traffic, and aesthetic demands of a modern city. The method of its construction served as a model for many engineers around the world.

The construction of the bridge, made possible by the knowledge and dedication of local experts and workers, was a symbol of progress and modernization. Its existence testified to the skill, ambitions, and values of the state and society at that time.

The destruction of the bridge during the NATO aggression in 1999 not only physically interrupted vital transportation flows but also dealt a significant blow to the historical heritage of Novi Sad and Serbia.

REFERENCES

[1] Stojadinović Branislav, Bubić Nenad, Žugić Bojan: **Nove konstrukcije velikih montažnih lučnih mostova**. Savetovanje „*Savremena građevinska praksa*“, Zlatibor, 2011.

[2] Mladenović Goran, Petrović Veljko, Lukić Vesna: **Geotechnical Investigations for the Design of Foundation of the Bridge across the Danube River at Novi Sad**. *3rd International Conference on New Trends in Geoengineering, Construction and Environment*, Belgrade, 2014.

[3] Bojović Božidar, Banić Branimir, Domanović Miloš, Denić Marko: **Identification of Key Parameters in the Finite Element Model Updating Procedure for a Steel Frame Structure**. *IOP Conference Series: Materials Science and Engineering*, 419, 012032, 2018.

[4] Branimir Grujić, Ljubomir Benedetić: **Izveštaj o ispitivanju drumsko-železničkog mosta preko Dunava u Novom Sadu. Luk 211 m**. *Institut za ispitivanje materijala SR Srbije*, Beograd, 1963.

[5] Branimir Grujić, Ljubomir Benedetić: **Izveštaj o ispitivanju drumsko-železničkog mosta preko Dunava u Novom Sadu. Luk 165 m**. *Institut za ispitivanje materijala SR Srbije*, Beograd, 1963.

[6] https://commons.wikimedia.org/wiki/File:Pre_post_strike_assesment_Novi_Sad_May_3_1999.jpg

[7] Milan Gligorijevic: **Modeliranje spojeva susednih polja montažnih grednih mostova**. *Magistarski rad, Građevinski fakultet u Nišu*, Niš, 1996.

doi.org/10.62683/SINARG2025.020

Research paper

REQUIREMENTS FOR TRAIN-TRACK-BRIDGE DYNAMIC INTERACTION ANALYSIS

Nikola Mirković[1], Uroš Mirković[2], Dušan Stevanović[3]

Abstract

The analysis of the dynamic interaction between the train, track, and bridge is crucial for ensuring the performance of railway infrastructure and the safety of railway traffic, especially on high-speed rail systems. This paper examines the key requirements for analyzing the dynamic interaction between the train, track, and bridge, with particular emphasis on the guidelines outlined in UIC Code 776-2. The analysis includes the structural strength of the bridge, passenger comfort, and the overall safety of railway traffic, ensuring a comprehensive evaluation of the entire railway system. Specifically, the paper examines the impact of continuously welded rails, which are widely used in modern railways due to their improved performance and reduced maintenance needs. The dynamic behavior of the train, track, and bridge is analyzed to confirm the structural integrity of the system, mitigate vibrations, and enhance passenger comfort. UIC Code 776-2 serves as a key reference for understanding the design and performance requirements for analyzing train-track-bridge dynamic interaction, guaranteeing that safety standards are met while optimizing efficiency. By evaluating the dynamic performance of the train, track, and bridge components, potential risks can be assessed, and strategies can be developed to mitigate them. This research contributes to the development of more resilient railway systems, ensuring the safety of both passengers and infrastructure.

Key words: *Railway Infrastructure, Continuously Welded Rail, Railway Traffic Safety, Bridge Structural Strength, Passenger Comfort, Engineering Application*

[1] PhD, Research Associate, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, nikola.mirkovic@jcerni.rs, ORCID 0000-0002-5980-3049
[2] PhD, Research Assistant, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, uros.mirkovic@jcerni.rs, ORCID 0000-0001-6781-5798
[3] MSc Civ. Eng., PhD student, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, dusan.stevanovic@jcerni.rs, ORCID N/A

1. INTRODUCTION

The rapid expansion of high-speed railways has heightened the focus on the train-track-bridge dynamic interaction, attracting significant attention from researchers and engineers around the world. This growing interest highlights the importance of understanding the complex behavior of these interconnected systems to ensure the safety, performance, and durability of modern railway infrastructure.

When a train crosses a bridge, it induces vibrations that affect the bridge structure, resulting in dynamic impacts. These vibrations can, in turn, influence the safety of the train's operation and the comfort of passengers aboard, especially when the train is traveling at high speeds. This interaction between the train, track and, bridge is not only a physical phenomenon but a coupled dynamic system, where the behavior of one directly affects the performance of the other. Such interdependence highlights the need for thorough analysis to ensure both the structural integrity of the bridge and the safety and comfort of the train. Understanding this dynamic coupling is crucial for optimizing the design and operation of railway systems.

Numerous studies have focused on the development of numerical models to simulate train-track-bridge interactions. These models incorporate various factors such as train speed, bridge flexibility, track irregularities, and environmental conditions. Zhai et al. [1] presented research that investigated the evolution of dynamic interaction models, ranging from basic constant force models to advanced train-track-bridge dynamic interaction models. The paper examined key modeling elements, including the train, track, bridge, wheel-rail contact, system excitation and solution algorithm. Additionally, it discussed safety assessment and real-world applications, emphasizing the importance of detailed track modeling and outlining future research challenges in the field. Ribeiro et al. [2] conducted a comprehensive validation of a three-dimensional dynamic model for train-track-bridge interaction on a bowstring-arch railway bridge, demonstrating the effectiveness of numerical simulations in replicating experimental observations. Similarly, a study by Fedorova and Sivaselvan [3] proposed an algorithm for dynamic train-track-bridge interaction analysis. The method modeled the bridge and train separately, coupling them through kinematic constraints, with contact forces treated as Lagrange multipliers. The algorithm was validated using a differential-algebraic equation solver and accounted for wheel-rail contact separation caused by track irregularities. Zhu et al. [4] proposed a hybrid method combining the direct stiffness method and the mode superposition method for the efficient analysis of the train-track-bridge system. The train and track were modeled using multi-body dynamics and the direct stiffness method, respectively, while the bridge was modeled using the mode superposition method. Coupling between the train, track and bridge subsystems was achieved through interaction forces, significantly reducing computational complexity.

Experimental validation plays a crucial role in verifying the accuracy of numerical models. Mo, Zhuo, and Li [5] introduced an approach based on multi-sensor time-frequency analysis to identify local track irregularities using bridge acceleration data. Their findings highlighted the potential of vibration-based monitoring techniques for track maintenance and infrastructure diagnostics. Zhang, Tian, and Xia [6] analyzed the train-bridge dynamic interaction, emphasizing the need for experimental evaluation methods to ensure the safety and stability of both bridges and trains. The system is modeled using the rigid-body dynamics method for the train, the finite element method for the bridge, and Kalker's linear creep theory for the wheel/rail interaction. This interaction is investigated through theoretical analysis,

numerical simulations, and experimental research, considering excitations such as track irregularity, structure deformation, and structural damage, among others. Chang et al. [7] investigated the impact of wheel hollow wear on the dynamic interaction within high-speed train-track-bridge systems. A nonlinear rigid-flexible coupled model was developed for a high-speed train operating on a long-span continuous girder bridge. The model integrated train-track-bridge interaction theory, non-elliptical multi-point wheel-rail contact theory, and a modified Craig-Bampton modal synthesis method. Numerical results indicated that wheel hollow wear altered the wheel-rail contact geometry, exacerbating dynamic interactions and amplifying bridge vibrations at a speed of 350 km/h.

European regulatory frameworks governing train-track-bridge interaction are designed to ensure the safety and performance of railway infrastructure. Key documents include recommendations such as UIC Code 776-1 [8], which focuses on load models for railway bridges; UIC Code 776-2 [9], which provides guidelines for railway bridge design considering train-track-bridge dynamic interaction; and UIC Code 774-3 [10], which addresses rail stresses and bridge deformations caused by track-bridge interaction. Standard EN 1991-2 [11] defines actions on bridges, including dynamic effects from railway traffic. Collectively, these regulations establish design and assessment criteria to mitigate excessive stresses, deformations, and vibrations, thereby ensuring the structural integrity and operational stability of railway bridges.

In the following chapters of this paper, the relevant requirements for conducting the train-track-bridge dynamic interaction analysis, as defined in European technical regulations, will be presented and discussed, along with the criteria that ensure railway traffic safety, bridge structural strength, and passenger comfort. Additionally, distinct situations from engineering practice will be considered to illustrate when dynamic analysis is required.

2. TRAFFIC SAFETY ON RAILWAY BRIDGES

Railway bridges are critical components of transportation infrastructure, enabling the safe passage of trains over rivers, valleys, roads, and other obstacles. However, ensuring traffic safety on railway bridges presents unique challenges due to the fact that these structures are elevated. This height exposes them to various environmental conditions and makes them more susceptible to dynamic forces generated by train operations. Traffic safety on railway bridges is influenced by several key factors, including the quality of the wheel-rail contact, track stability, and the deformations and vibrations the bridge may experience during operation.

When the contact between the wheels of a train and the rail is smooth and consistent, it minimizes the risk of derailment and vibrations that can negatively affect the bridge's structure. Proper wheel-rail interaction helps distribute the load evenly, reducing the forces on the bridge's supports, which is vital for maintaining its integrity over time. Any irregularities, such as wheel wear or rail defects, can lead to uneven forces and excessive rail wear, potentially compromising traffic safety. Therefore, maintaining optimal wheel-rail contact quality is essential for the safe operation of trains, particularly when crossing bridges, as it contributes to both structural stability and overall operational reliability.

Track stability is another crucial factor in ensuring traffic safety on railway bridges. A well-aligned track minimizes the risk of derailment, particularly when trains are crossing bridges. Any irregularity, such as track misalignment or insufficient ballast support, can cause uneven

forces and vibrations that may weaken the structural integrity of the track. When the track is unstable, it can lead to excessive wear on the rail, irregular wheel-rail contact, and potentially dangerous oscillations, all of which increase the likelihood of accidents. Therefore, ensuring the track's stability is essential for the safe operation of trains, as it directly impacts both the safety of passengers and the long-term durability of railway bridge structures.

According to UIC Code 776-2 [9], the deformation of the bridge deck, in terms of distortion criteria, is calculated using the characteristic load model (LM71) [8] and appropriate load diagrams (such as SW/0 or SW/2) [8], multiplied by dynamic increment coefficient (Φ) [8] and the classification coefficient (α) [8], or the high-speed load diagram, considering the effects of centrifugal force. When the bridge deck carries multiple tracks, with one of them being loaded, it experiences torsion due to the applied operational loads. The distortion of the bridge deck (t), under operational loads, is measured on a 1435 mm wide track over a distance of 3 m, as shown in Figure 1. Total distortion due to total deformation of the bridge deck, must not exceed 7.5 mm per 3 m. As speeds increase, the allowed distortion decreases.

The limit values for distortion of bridge deck are set based on different speed domains [9]:

- for speeds up to 120 km/h, the maximum allowed distortion is 4.5 mm per 3 m of track,
- for speeds between 120 km/h and 200 km/h, the maximum allowed distortion is 3.0 mm per 3 m of track,
- for speeds over 200 km/h, the maximum allowed distortion is 1.5 mm per 3 m of track.

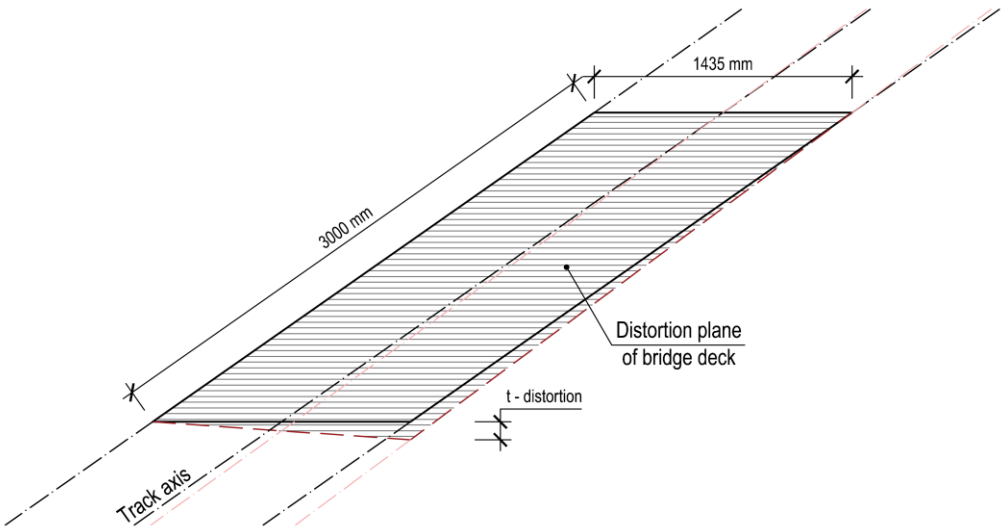


Figure 1. Distortion of bridge deck according to [9]

Horizontal and vertical displacements of the bridge deck are also important for railway traffic safety. If continuously welded rails (CWR) are used, longitudinal horizontal displacements due to vertical operating loads, including the dynamic increment coefficient, must remain below 10 mm, without considering interaction. On the other hand, when considering interaction, according to UIC Code 774-3 [10], longitudinal horizontal displacements due to vertical operating loads, including the dynamic increment coefficient, must remain below 8 mm. For displacements caused by acceleration/braking, the limit must be below 5 mm. In cases where the track has CWR and expansion joints at the end of the

bridge, the limit can rise to 30 mm. Vertical displacements at end of bridge deck should be kept below 3 mm for ballasted tracks and 1.5 mm for ballastless tracks [9].

Finally, the acceleration of the bridge deck plays a crucial role in the railway traffic safety. To ensure safe operation, the maximum acceleration of bridge deck with ballasted track must remain below 0.35g for frequencies up to 30 Hz. For bridges with ballastless tracks, the limit is set at 0.5g for frequencies below 30 Hz [9].

3. STRUCTURAL STRENGTH OF RAILWAY BRIDGES

The structural strength of railway bridges is a critical factor in ensuring the safe and efficient functioning of railway networks. The ability of a bridge to withstand dynamic loads, including the weight of trains, environmental conditions, and the repetitive stresses imposed during operation, is paramount. The guidelines for the design and assessment of the structural strength of railway bridges focus on three key aspects: strength, fatigue, and durability.

The strength of a railway bridge refers to its ability to resist applied forces without failure or excessive deformation. The design must account for the maximum load that can be exerted by trains, including both static and dynamic loads, as well as acceleration and braking forces. Requirements for calculating the structural strength of railway bridges ensure that the structure can safely support the weight of the heaviest trains operating on the line. The strength of materials used in the bridge's construction, such as steel or concrete, is also a crucial consideration, as these materials must be able to withstand the stresses they will be subjected to over the bridge’s service life.

Fatigue is the weakening of a material caused by repeated loading and unloading cycles over time. Railway bridges are particularly susceptible to fatigue due to the continuous passage of trains, which introduce dynamic loads that vary in magnitude and frequency. Fatigue analysis is essential for assessing the long-term performance of a bridge, especially in high-speed or heavily trafficked railway lines. Special attention must be given to the effects of high-frequency train passages, which can significantly reduce the lifespan of the bridge if not properly accounted for in the design. The fatigue life of railway bridges should normally be a minimum of 100 years according to technical regulations and engineering practice.

Durability refers to the ability of a railway bridge to maintain its structural integrity over time, despite exposure to environmental conditions such as moisture, temperature variations, and chemical corrosion. Also, durability is closely related to the concept of fatigue, as prolonged exposure to environmental stressors can exacerbate the fatigue process and lead to premature deterioration of the bridge.

By adhering to these guidelines, it is possible to ensure the safety, reliability, and longevity of railway bridges, which are essential components of modern transport infrastructure. Regular assessment and maintenance are necessary to preserve the structural integrity of railway bridges and to mitigate the effects of fatigue and environmental conditions over time.

In cases where it is necessary to perform a dynamic analysis of the bridge structure with appropriate load models or real trains, it is essential to determine the dynamic increment coefficient, as shown in equation (1) [9]:

$$\varphi'_{dyn} = \max\left[\gamma_{dyn}/\gamma_{stat}\right] - 1 \tag{1}$$

where:

φ'_{dyn} - dynamic increment coefficient for the real train and a track without irregularities,

γ_{dyn} - dynamic deflection of bridge deck due to load models or real trains,

γ_{stat} - static deflection of bridge deck.

The decision of whether the structural strength of the railway bridge will be analyzed using load models or real trains is based on the following flowchart in Figure 2.

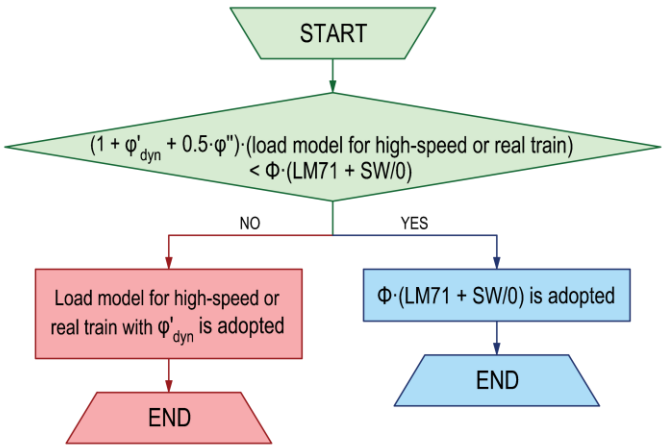


Figure 2. Flowchart for determining the loads to be considered in bridge strength calculations according to [9]

where:

φ'' - dynamic increment coefficient for the real train and a track with irregularities,

Φ - dynamic increment coefficient.

4. PASSENGER COMFORT ON RAILWAY BRIDGES

This chapter delves into the factors that contribute to passenger comfort on railway bridges, focusing on train-track-bridge interaction, the physiological effects of vertical accelerations, and the resulting passenger fatigue.

The train-track-bridge interaction is a critical aspect of railway design that significantly influences ride quality when trains cross bridges. The interaction forces between train wheels and the track are intensified on bridges as a result of their structural dynamics. Variations in bridge materials and construction conditions can have a significant impact on how vibrations and dynamic loads are transferred between the train and the bridge. These interactions cause oscillations or undulations in the train body, leading to changes in the way passengers perceive comfort. The structural rigidity of a bridge plays a role in how vibrations are propagated. On more flexible bridges, train operation can induce significant oscillations that may lead to passenger discomfort. As trains pass over these flexible structures, their motion may become more irregular, leading to a more noticeable impact on passenger comfort. Track alignment and the quality of track-bed maintenance on bridges are also crucial for minimizing unwanted vertical and lateral forces, which can lead to unpleasant jolts or bumps for passengers. Table 1 provides an overview of the key parameters of passenger comfort on railway bridges.

Table 1. Parameters of passenger comfort on railway bridges

Structural parameters	Operational parameters	Environmental parameters	Human perception parameters
Bridge stiffness and deflection; Natural frequency and resonance; Damping characteristics; Track structure and transitions.	Train speed; Axle load and suspension system; Braking and acceleration; Wheel-rail interaction.	Wind and weather conditions; Noise and vibrations.	Vibration perception; Seating orientation and comfort; Visual stability.

Vertical accelerations are one of the primary factors affecting passenger comfort when trains cross bridges. As a train transitions from solid ground onto a bridge, the change in support structure leads to increased vertical accelerations. If these accelerations are excessive, they can cause discomfort, particularly for passengers seated or standing in the aisles. To mitigate these effects, train manufacturers must focus on developing effective suspension systems and optimizing track design, both of which help absorb or minimize these accelerations, thereby improving overall ride quality. Additionally, train speed plays a significant role in comfort. While higher speeds are often linked to increased efficiency and shorter travel times, they can exacerbate the forces experienced on railway bridges. Striking a balance between speed and comfort is crucial to ensuring a smooth and pleasant journey, especially on bridge sections where dynamic interactions between the train and track are most pronounced.

Prolonged exposure to excessive vertical accelerations and vibrations can lead to physical discomfort, such as muscle strain, and increased stress on the body, especially for passengers who are seated for extended periods. This strain often manifests as fatigue, which, over time, can degrade the overall passenger experience. Understanding the connection between train dynamics and passenger health is essential for improving comfort standards. Research into human response to vertical accelerations has provided insight into the thresholds that lead to fatigue and discomfort. By integrating this knowledge into railway bridge design and train suspension systems, engineers can optimize the experience for passengers, ensuring a reduction in discomfort and fatigue.

According to UIC Code 776-2 [9], passenger comfort in trains operating over railway bridges is classified into three distinct levels based on the vertical acceleration experienced in the vehicles. The highest comfort level is considered "very good", where vertical acceleration does not exceed 1.0 m/s². This level ensures a smooth and comfortable ride with minimal vibrations. The "good" level of comfort allows vertical acceleration up to 1.3 m/s², providing an adequate level of comfort, although it is slightly less smooth compared to the "very good" level. Finally, the "acceptable" comfort level is defined by vertical acceleration of up to 2 m/s². While this level is still within safety standards, it may be perceived as less comfortable, with more noticeable vibrations during travel. These comfort levels are crucial for optimizing the passenger experience while ensuring the safe operation of trains. Also, the criteria for ensuring passenger comfort on railway bridges are based on the vertical deflection of the bridge decks, considering factors such as vertical acceleration in the vehicles, train speed, span length, the number of span sections, and the bridge configuration.

5. VALIDATION PROCEDURES FOR DYNAMIC ANALYSIS IN ENGINEERING PRACTICE

The UIC Code 776-2 [9], as well as standard EN 1991-2 [11] provide a flowchart to assist in determining the need for dynamic analysis (Figure 3). The parameters of this flowchart include:

V [km/h] - maximum traffic speed,

L [m] - bridge span,

n_0 [Hz] - first natural bending frequency of the unloaded bridge,

n_T [Hz] - first natural torsional frequency of the unloaded bridge,

v_{lim}/n_0 and $(v/n_0)_{lim}$ - defined in Tables 8 and 9 of Appendix A in [9].

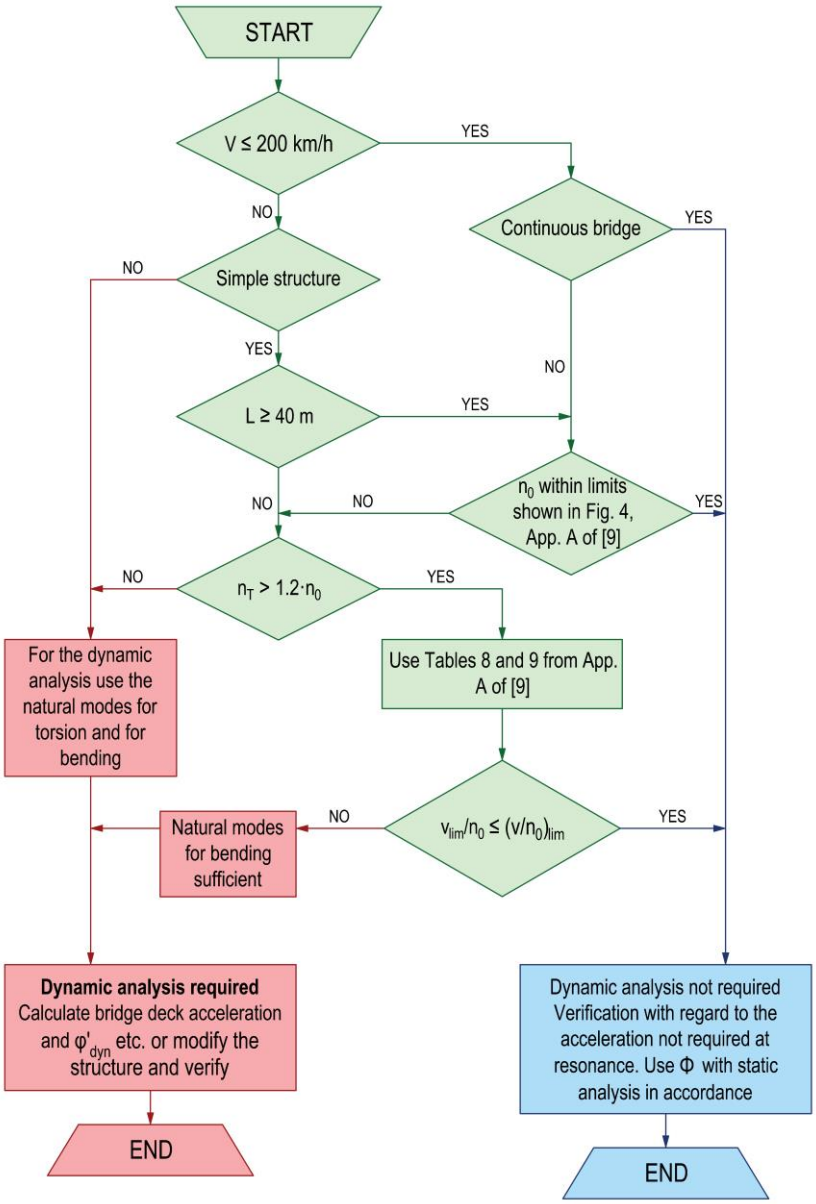


Figure 3. Flowchart for determining the need for dynamic analysis according to [9]

However, the use of this flowchart is not straightforward, as there are seven distinct situations in engineering practice where dynamic analysis becomes necessary:

1. When the maximum traffic speed is less than or equal to 200 km/h, the bridge structure is not classified as a "Continuous bridge", n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
2. When the maximum traffic speed is less than or equal to 200 km/h, the bridge structure is not classified as a "Continuous bridge", n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending;
3. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is not classified as a "Simple bridge", a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
4. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is greater than or equal to 40 m, n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
5. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is greater than or equal to 40 m, n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending;
6. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is not greater than or equal to 40 m, n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
7. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is not greater than or equal to 40 m, n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending.

The application of dynamic analysis, with particular emphasis on bending and torsional modes, is essential for accurately assessing the behavior of bridge structures under realistic operational conditions. This methodology aids in identifying potential critical points of bridge structure that may arise due to resonance, which could lead to failure. By utilizing this methodology, engineers can predict the dynamic response of bridge structures under varying loads and conditions, ensuring more robust and safer designs. Table 2 systematically presents all seven situations in engineering practice that require dynamic analysis.

Table 2. Summary of situations requiring dynamic analysis

Situation	$V \leq$ 200 km/h	Bridge type	$L \geq$ 40 m	n_0 within limits	$n_T > 1.2 \cdot n_0$	$v_{lim}/n_0 \leq (v/n_0)_{lim}$	Natural modes
1	✓	Not continuous	-	✗	✗	-	Bending + torsion
2	✓	Not continuous	-	✗	✓	✗	Bending
3	✗	Not simple	-	-	-	-	Bending + torsion
4	✗	Simple	✓	✗	✗	-	Bending + torsion
5	✗	Simple	✓	✗	✓	✗	Bending
6	✗	Simple	✗	-	✗	-	Bending + torsion
7	✗	Simple	✗	-	✓	✗	Bending

6. CONCLUSION

In this paper, a comprehensive analysis of the dynamic interaction between train, track, and bridge was conducted, with an emphasis on the requirements for ensuring traffic safety, passenger comfort, and the structural strength of railway bridges. By examining the guidelines outlined in UIC Code 776-2, the research identifies key factors influencing the train-track-bridge dynamic interaction, such as bridge deformations, vertical accelerations, and vibrations, while also highlighting the role of CWR in minimizing rail wear and enhancing the overall performance of railway bridges. Additionally, seven distinct situations in engineering practice that require dynamic analysis have been identified and are presented in Table 2. These findings contribute to the development of more resilient railway infrastructures, supporting the optimization of high-speed rail systems while ensuring compliance with international railway safety regulations.

REFERENCES

[1] Zhai Wanming, Han Zhaoling, Chen Zhaowei, Ling Liang, Zhu Shengyang: **Train–track–bridge dynamic interaction: a state-of-the-art review**. *Vehicle System Dynamics*, 57(7), 984-1027, 2019, https://doi.org/10.1080/00423114.2019.1605085.

[2] Ribeiro Diogo, Calçada Rui, Brehm Maik, Zabel Volkmar: **Train–Track–Bridge Dynamic Interaction on a Bowstring-Arch Railway Bridge: Advanced Modeling and Experimental Validation**. *Sensors*, 23(1), 171, 2022, https://doi.org/10.3390/s23010171.

[3] Fedorova Maria, Sivaselvan Mettupalayam V.: **An algorithm for dynamic vehicle-track-structure interaction analysis for high-speed trains**. *Engineering Structures*, 148, 857-877, 2017, https://doi.org/10.1016/j.engstruct.2017.05.065.

[4] Zhu Zhihui, Zhang Lei, Gong Wei, Wang Lidong, Bai Yu, Harik Issam E.: **An efficient hybrid method for dynamic interaction of train–track–bridge coupled system**. *Canadian Journal of Civil Engineering*, 47(9), 1084-1093, 2020, https://doi.org/10.1139/cjce-2019-0020.

[5] Mo Ye, Zhuo Yi, Li Shunlong: **Local track irregularity identification based on multi-sensor time–frequency features of high-speed railway bridge accelerations**. *Sustainability*, 15(10), 8237, 2023, https://doi.org/10.3390/su15108237.
[6] Zhang Nan, Tian Yuan, Xia He: **A train-bridge dynamic interaction analysis method and its experimental validation**. *Engineering*, 2(4), 528-536, 2016, https://doi.org/10.1016/J.ENG.2016.04.012.
[7] Chang Chao, Ling Liang, Han Zhaoling, Wang Kaiyun, Zhai Wanming: **High-Speed Train-Track-Bridge Dynamic Interaction considering Wheel-Rail Contact Nonlinearity due to Wheel Hollow Wear**. *Shock and Vibration*, 2019(1), 5874678, 2019, https://doi.org/10.1155/2019/5874678.
[8] **UIC Code 776-1R, Loads to be considered in railway bridge design, 5th edition**. *International Union of Railways*, Paris, France, 2006.
[9] **UIC Code 776-2R, Design requirements for rail-bridges based on interaction phenomena between train, track and bridge, 2nd edition**. *International Union of Railways*, Paris, France, 2009.
[10] **UIC Code 774-3R, Track/bridge Interaction, Recommendations for calculations, 2nd edition**. *International Union of Railways*, Paris, France, 2001.
[11] **EN 1991-2:2003/AC:2010, Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges**. *European Committee for Standardization/Technical Committee 250*, Brussels, Belgium, 2010.

doi.org/10.62683/SINARG2025.021

Research paper

ALGORITHM FOR POSITIONING CYCLING INFRASTRUCTURE WITHIN THE EXISTING CITY ROAD PROFILE

Dušan Kocić[1], Miloš Šešlija[2], Nenad Stojković[3]

Abstract

This paper presents an algorithm for positioning cycling infrastructure within the existing cross-section of a roadway. The analysis focuses on roadways in urban areas, specifically city streets. The input data consists of the geometric elements of the site plan, longitudinal profile, and cross-sections. The algorithm first classifies them according to the street category criterion and conducts different analyses depending on whether the street falls into the category of arterial, collector, or local roads. At this stage, the algorithm examines the elements of the cross-section of the city roadway. Upon completing this step, a preliminary solution for the positioning of cycling infrastructure is formed, followed by a detailed analysis of all geometric elements of the street, considering the conditions for bicycle traffic in an urban area. Additionally, an analysis of the horizontal and vertical geometry of the examined street is conducted. If all criteria are met, the preliminary solution is adopted as the final one.

Key words: *Cycling infrastructure, Algorithm, Analysis.*

[1] Civil engineer, assistant, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, dusan.kocic@akademijanis.edu.rs, ORCID 0009-0006-4886-0482
[2] Ph.D., Associate Professor, Faculty of Technical Sciences - Department of Civil Engineering and Geodesy, Serbia, sele@uns.ac.rs, ORCID 0000-0002-8857-8952
[3] Ph.D., Assistant Professor, Faculty of Civil Engineering and Architecture - Department of Roads, Serbia, nenad.stojkovic@gaf.ni.ac.rs, ORCID 0000-0002-6892-7908

1. INTRODUCTION

Due to climate change and the increasing carbon footprint caused by the high intensity of motor vehicle traffic using fossil fuels, there is a growing tendency toward alternative and environmentally sustainable modes of transportation. Cycling is a highly accessible, healthy, and environmentally friendly mode of transport. Good infrastructure must be adapted to the needs of cyclists to promote and affirm cycling as a sustainable means of transportation in urban areas.

Cycling infrastructure should be planned as a connected network at the city-wide level, providing enough space for the safe movement of all cyclists and preventing congestion, which is a common issue in cities characterized by high bicycle usage, such as Copenhagen. An analysis of Copenhagen's cycling infrastructure network has shown that, although the city generally has a well-developed network of bike lanes, there are significant inequalities in infrastructure accessibility across different parts of the city [1].

A key characteristic of a good cycling infrastructure network is its connectivity, which integrates it into the overall urban transportation system. An efficiently designed cycling infrastructure, including well-connected routes and protected lanes, is crucial for reducing detours and improving accessibility in urban areas. Cycling corridors significantly reduce deviations from the shortest path (RDR - Realized Detour Ratio), while a lack of connected lanes and physical barriers increase the distance cyclists must travel, thereby reducing the efficiency of bicycle transportation [2].

Providing cycling infrastructure is a way to encourage cycling, which can contribute to improving the urban environment and reducing the impact of traffic on climate. Although cycling infrastructure is relatively inexpensive, it still requires certain costs and occupies valuable urban space [3]. Therefore, it is important to assess its impact on the volume of bicycle traffic, considering the significance of location and infrastructure type.

A large number of cities around the world have negligible infrastructure for safe cycling. The development of urban transportation has historically been strongly oriented toward automobiles, resulting in well-connected road networks for motor vehicles, while cycling networks remain fragmented and underdeveloped [4]. Accordingly, systematic strategies are necessary to expand cycling infrastructure at the city-wide level.

The limitations of public transport and the need for physical distancing during the COVID-19 pandemic contributed to a significant increase in bicycle traffic in many cities worldwide, including London [5]. The pandemic highlighted the need for an urgent reorganization of existing city road profiles to support active transportation. The redistribution of traffic space in favor of walking and cycling should not be just a temporary measure but part of a long-term strategy for sustainable urban mobility. Identifying key transport corridors and optimizing the street network can significantly contribute to creating an efficient and resilient cycling infrastructure.

An effective cycling network should allow cyclists quick and direct access to desired destinations with minimal alternative detour routes. Although the total length of the cycling network is often measured, it does not necessarily guarantee good connectivity and functionality [6]. Strategic planning of cycling infrastructure can help optimize bicycle traffic, reduce dependence on cars, and improve the quality of life in cities. A comprehensive approach to the development of cycling infrastructure is necessary to make cycling a competitive and attractive option for daily commuting.

2. TRANSPORT INFRASTRUCTURE

The term "transport infrastructure" refers to the transportation network of a given area, encompassing all types of traffic present. For a better understanding and analysis of issues related to bicycle traffic in urban areas, it is necessary to consider all aspects that directly and indirectly influence this mode of transport.

2.1. Categorization of the urban road network

The urban road network has a dual purpose: to connect different parts of the city and to ensure the efficient servicing of facilities and locations directly adjacent to the roadway [7]. Based on these tasks, the road network of an urban area can be divided into two categories:

- Primary road network (urban)
- Secondary road network (local)

The primary road network aims to provide traffic connectivity, accommodating a larger number and variety of vehicles traveling at higher speeds. The roads within the primary network are designed for the smooth flow of motor vehicle traffic and include:

- Urban highways
- Major city arterials
- City arterials
- Collector streets

Urban highways are sections of long-distance roads that pass through densely populated urban areas. They connect the city with higher-ranking national roads as well as the international road network. Due to the high speeds of motor vehicle traffic, urban highways are constructed without the possibility of longitudinal bicycle and pedestrian traffic.

Major city arterials are roads with exceptionally high traffic capacity that pass through the city center and connect it with out-of-town connecting roads. They facilitate the flow of fast passenger traffic, public urban transport, and the routing of freight flows.

City arterials connect entire parts of the city with specific activity centers and can rely on regional roads. They are intended for both individual and public passenger transport. Pedestrian and bicycle traffic is accommodated within the designated roadway width.

Collector streets link the primary and secondary road networks of an urban area and distribute traffic at the level of urban planning units. They are intended for both individual and public motor vehicle traffic, as well as for pedestrian and bicycle movement directly alongside the roadway.

The secondary road network consists of roads primarily intended for access to specific facilities and locations. This network level is characterized by a reduced emphasis on conventional traffic parameters such as flow and speed, as high speeds and intensive traffic flows are fundamentally undesirable and unacceptable [7]. Elements of this segment of the road network include:

- Access streets
- Parking areas

Access streets belong to the most numerous category of urban roads and serve the function of directly providing access to adjacent facilities, such as commercial and residential buildings. Bicycle traffic on access streets can be accommodated either at the roadway level or on a designated section of the pedestrian path.

Parking areas are transportation infrastructure facilities designed to serve specific locations, intended for vehicle stopping and parking. In the context of widespread individual motorization, parking areas have become a highly scarce yet essential necessity in urban areas.

2.2. Basic concepts and characteristics of cycling infrastructure

Cycling infrastructure refers to the entire traffic area designated for bicycle traffic, as well as facilities for parking and storing bicycles. This paper will focus on areas designated for cycling traffic in urban environments, which include:

- Cycling paths
- Cycling lanes
- Cyclists on the roadway

A cycling path is a part of the traffic surface designated for the movement of bicycles and motorized bicycles, which is physically separated from the roadway or placed at a different level. In populated areas, this path can be separated from the roadway by a curb, while outside populated areas, it is secured with a steel protective fence.

A cycling lane is a designated longitudinal section of the roadway intended for the movement of bicycles and motorized bicycles. It is not elevated in relation to the roadway, and to enhance safety, its surface is often painted red.

The concept of cyclists on the roadway means that bicycle traffic takes place alongside motor vehicles, with appropriate traffic signaling. This model is applied in urban areas where there is insufficient space to build separate cycling infrastructure. It is also more suitable for roads with lower motor traffic intensity.A cycling path is a part of the traffic surface designated for the movement of bicycles and motorized bicycles, which is physically separated from the roadway or placed at a different level. In populated areas, this path can be separated from the roadway by a curb, while outside populated areas, it is secured with a steel protective fence.

A cycling lane is a designated longitudinal section of the roadway intended for the movement of bicycles and motorized bicycles. It is not elevated in relation to the roadway, and to enhance safety, its surface is often painted red.

The concept of cyclists on the roadway means that bicycle traffic takes place alongside motor vehicles, with appropriate traffic signaling. This model is applied in urban areas where there is insufficient space to build separate cycling infrastructure. It is also more suitable for roads with lower motor traffic intensity.

The dimensions of the cross-sectional profile of the roadway are defined by the following profiles:

- Traffic profile represents the space in which a moving vehicle can be found. This profile consists of the transverse section of the reference vehicle, the space required for vehicle movement, and the central protective width between vehicles [8].
- Clearance profile includes the traffic profile, edge protective width, and protective height. No permanent obstacles are allowed within the clearance profile. The dimensions of the clearance profile are defined by regulations [8] and must be adhered to when designing the roadway.

Figure 1 shows the traffic and clearance profiles of one-way and two-way cycling surfaces.

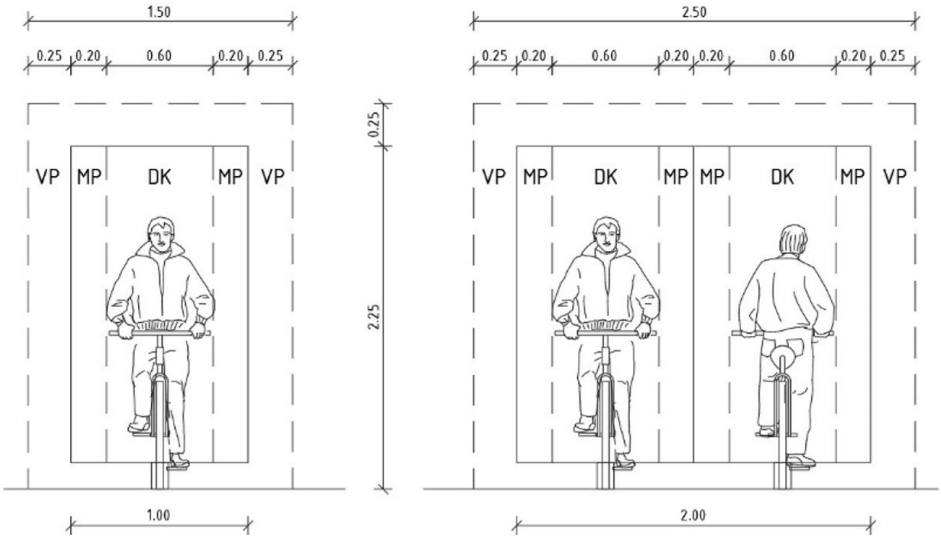


Figure 1. Traffic and free profile of the cycling surface

The labels for width in Figure 1 represent:

- DK – bicycle dimension
- MP – maneuvering space
- VP – safety space

3. DESCRIPTION AND DEVELOPMENT OF THE ALGORITHM

The algorithm presented in this paper serves the function of determining the position of the cycling surface within the existing cross-section of the urban roadway. Additionally, it analyzes the geometric elements of the site plan and the longitudinal profile of the street in question. According to its organizational structure, the algorithm can be divided into five main steps (Figure 2).

1. Input data
2. Defining the street category
3. Analysis of the cross-sectional profile
4. Analysis of the geometry of vertical and horizontal street characteristics
5. Proposed solutio

In the first step, all necessary data for its operation are entered. These data primarily refer to the geometric elements of the roadway, as well as traffic data. The following data are entered:

- Street category
- Radius of horizontal and vertical curves
- Longitudinal and transverse road slopes
- Orientation of the transverse slope
- Traffic flow of motor vehicles
- Presence of parking lanes
- Presence of public transport lanes

- Number of lanes for motor vehicles and traffic lanes
- Traffic flow regime
- Maximum allowed speed of motor vehicles
- Geometric characteristics of the cross-sectional profile

In the second step, the further course of the analysis is determined. Specifically, in this step, based on the street category, the algorithm defines how the analysis will proceed through the next step. Figure 2 schematically shows the algorithm.

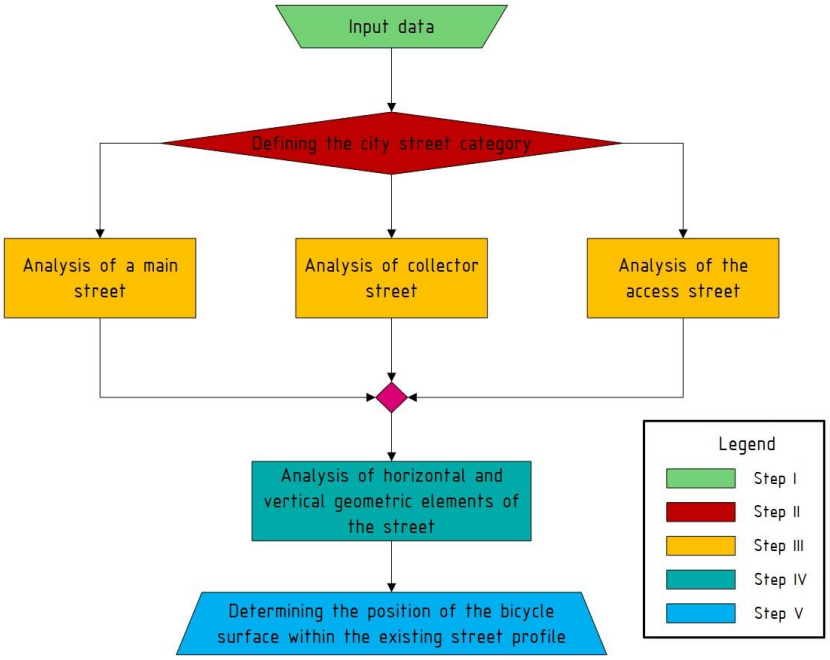


Figure 2. Schematic representation of the algorithm

The third step of the algorithm deals with the analysis of the geometric elements of the cross-sectional profile of the street in question. This step varies depending on the category of the roadway and can, therefore, be divided into three parts. Each part is dedicated to analyzing a specific category of roadway – arterial, collector, or access.

When analyzing an arterial road, the algorithm examines all key factors that directly or indirectly affect bicycle traffic and infrastructure. Since arterial roads typically have high traffic flow and high motor vehicle speeds, there is a tendency to isolate bicycle traffic from the roadway. This analysis considers the width of pedestrian paths, the presence of tree lines, and street furniture for pedestrians (e.g., benches). After reviewing these factors, in this step, the algorithm proposes a preliminary location for the cycling surface within the arterial road profile. Then, depending on whether the proposed solution is a cycling path or a lane, further analysis follows. If the solution involves a cycling lane, the algorithm considers the presence of a public transport lane and proposes solutions to increase bicycle traffic safety. Conversely, if a cycling path is proposed, the algorithm analyzes the proximity of public facilities that people naturally gravitate toward, to consider the option of positioning the path closer to these facilities. This would make the proposed solution more attractive to cyclists.

In the analysis of the collector road, the algorithm checks the traffic flow method. Depending on how the traffic is organized, it verifies the widths of pedestrian paths.

Additionally, the algorithm examines whether the width of the pedestrian paths is constant or variable. These parameters are crucial due to the desire to physically separate bicycle traffic from motor vehicle traffic, if possible. In the case of one-way streets, the algorithm also considers the number of traffic lanes and the presence of parking lanes. At the end of this step, the algorithm proposes a preliminary location for the cycling surface within the collector road profile.

In the part that deals with the analysis of access streets, the first step is to determine whether the street is one-way or two-way. For two-way streets, the algorithm checks the motor vehicle traffic flow and the width of pedestrian paths. One-way access streets undergo a more extensive analysis. This includes checking the number of traffic lanes, the presence of parking lanes, the traffic flow, and the width of pedestrian paths. Upon completion of this step, a preliminary solution for the location of the cycling surface is proposed.

The fourth step of the algorithm involves analyzing the horizontal and vertical geometric elements of the urban roadway (Figure 2). The necessary input parameters for this phase are:

- Number of vertical and horizontal curves
- Number of grade changes
- Design speed

Due to the potentially larger number of data points passing through the same analysis, this step is organized by applying "for" and "while" loops. The first loop in this step checks if the radius of horizontal curves in the roadway are greater than the minimum required value for cycling surfaces. The condition of this loop includes a counter that tracks how many times the loop has repeated. This solution is applied to avoid the occurrence of an infinite loop, which would prevent the algorithm from completing its work.

Next, the analysis of vertical curvature and longitudinal slopes follows. In this part, an array of elements is formed, where each element represents an individual value of the longitudinal slope of the roadway. The values in the array are entered in the same order in which they appear, observed in the direction of increasing stationing.

After the array is formed, a "for" loop is applied to iterate through the array and analyze the values of two consecutive elements, i.e., the values of two consecutive longitudinal slopes. Depending on the values of the longitudinal slopes, the algorithm checks whether additional vertical curvature is needed or not, with the restriction that the radius value cannot be smaller than the minimum allowed.

The final part of this step analyzes the length of the section with a longitudinal slope greater than 10%. This analysis is conducted using a new "for" loop, which iterates through the previously formed array and checks whether the given condition is met.

After this step, the algorithm verifies if all the parameters are in accordance with the proposed preliminary solution. If they are, the preliminary solution is accepted as final, which marks the fifth step and the end of the analysis.

The developed algorithm provides a clear and systematic approach to planning cycling infrastructure within existing urban road networks. It enables the adoption of optimal solutions that are safe, functional, and adapted to the urban environment.

Its implementation can significantly contribute to the development of a safer and more connected cycling network, making cycling more comfortable and accessible to all citizens.

4. CONCLUSION

Cycling infrastructure plays a key role in creating sustainable and functional cities, and this paper presents an algorithm that helps in its efficient planning. Through the analysis of different categories of urban streets and their geometric characteristics, the algorithm allows for optimal positioning of bike lanes and tracks, considering safety, space, and traffic flows.

The results of the research show that arterial roads are the most challenging for integrating cycling traffic, while collector and access streets offer more opportunities for adaptation and further flexibility for designers to optimize the proposed solution. It is crucial for cycling facilities to be well-connected and safe in order to promote cycling as a sustainable alternative to car transportation

By applying this algorithm, cities can improve their cycling networks, which not only enhances the mobility and safety of cyclists but also reduces traffic congestion and the negative impact on the environment.

Furthermore, testing the algorithm in real urban conditions would allow for its calibration and adaptation to the specific needs of cities of different sizes and structures.

REFERENCES

[1] Alessandro Lonardi, Michael Szell, Caterina De Bacco: **Cohesive urban bicycle infrastructure design through optimal transport routing in multilayer networks**. *Journal of the Royal Society Interface*, 22, 20240532. https://doi.org/10.1098/rsif.2024.0532.

[2] Kuan Yeh Chou, Mads Paulsen, Otto Anker Nielsen, Anders Fjendbo Jensen: **Analysis of cycling accessibility using detour ratios – A large-scale study based on crowdsourced GPS data**. *Sustainable Cities and Society*, 93, 104500. https://doi.org/10.1016/j.scs.2023.10450.

[3] Mogens Fosgerau, Mirosława Łukawska, Mads Paulsen, Thomas Kjær Rasmussen: **Bikeability and the Induced Demand for Cycling**. *Proceedings of the National Academy of Sciences (PNAS)*, 120(16), e2220515120. https://doi.org/10.1073/pnas.2220515120.

[4] Michael Szell, Sayat Mimard, Tyler Perlman, Gourab Ghoshal, Roberta Sinatra: **Growing Urban Bicycle Networks**. *arXiv preprint*, 2022. https://arxiv.org/abs/2107.02185.

[5] Nicolas Palominos, Duncan A. Smith, Sam Griffiths: **Identifying and Characterising Active Travel Corridors for London in Response to Covid-19 Using Shortest Path and Streetspace Analysis**. *Proceedings of the 2021 Transport Research Arena (TRA)*. https://doi.org/10.5281/zenodo.3783807.

[6] Geneviève Boisjoly, Ugo Lachapelle, Ahmed El-Geneidy: **Bicycle Network Performance: Assessing the Directness of Bicycle Facilities Through Connectivity Measures, a Montreal, Canada Case Study**. *International Journal of Sustainable Transportation*, 14(8), 620-634. https://doi.org/10.1080/15568318.2019.1600303.

[7] Mihailo Maletin, Vojo Anđus, Jovan Katanić: **Tehnička uputstva za planiranje i projektovanje gradske putne mreže (PGS-M/06)**. *Građevinski fakultet Univerziteta u Beogradu*, Institut za saobraćajnice i geotehniku, Beograd, 2006.

[8] **Smjernice za projektovanje, građenje, održavanje i nadzor na putevima**. Sarajevo/Banja Luka, 2005.

doi.org/10.62683/SINARG2025.022

Research paper

THE ROLE OF URBAN PLANNING IN THE PRACTICE OF ADDING LATERAL AND VERTICAL EXTENSIONS TO EXISTING RESIDENTIAL BUILDINGS

Kefajet Edip[1]

Abstract

In the city of Skopje there are many existing residential buildings which have been subjected to lateral and vertical extensions. This research paper questions the role of urban planning in the practice of adding surface area and additional floors to existing residential buildings, while considering the concept of sustainable urban development.

The lateral and vertical extensions applied to existing residential buildings were analyzed through a case study, an urban block in Municipality of Karposh in Skopje. The urban block and its buildings were compared in different periods to define the amount of changes in terms of enlargements applied compared to the initial state of the buildings. To conduct the study, the geodetic survey map, Detailed Urban Plan, an on-site survey study by IZIIS, Google Maps and the cadaster GIS database served as information sources.

In the case of existing buildings, the Detailed Urban Plans do not clearly specify if the changes to urban parameters, such as surface area, number of floors, building percentage and coefficient of use, mean replacing the existing buildings with new ones or applying lateral and vertical extensions to the existing buildings. Viewed from the aspect of sustainable development, the practice of extensions over the long-term has negative impacts, such as reduced amount of natural light indoors due to enlargements, interference with the initial architectural value of the building (aesthetics), insufficient number of car parking spaces and increased seismic risk.

The main aim of this study is to increase awareness about the importance of applying the concept of sustainability in urban planning when dealing with the existing urban areas. The urban planners, decision-making authorities responsible for regulating the physical spaces and the citizens should be informed about sustainable urban development to achieve higher quality living environments.

Key words: *Extensions to Existing Buildings, Urban Planning, Sustainable Urban Development*

[1] PhD, Asst. Professor, International Balkan University, Faculty of Engineering, Department of Architecture, Republic of North Macedonia, k.edip@ibu.edu.mk, ORCID 0009-0003-4241-9897

1. INTRODUCTION

Urban planning of the existing urban areas is challenging to meet the requirements of the newer times. A significant problem is the need for more living space in the existing residential buildings. As a practical solution, on individual initiatives of the occupants, they decide to increase their living space by enclosing the balconies and converting them into rooms and in some cases adding horizontal extensions to the longitudinal facades of the buildings. The extensions are made also by adding floors to the flat roofs of the existing buildings [1;2].

Initially, the practice of adding extensions to the existing buildings was considered as against the regulations of the building law in Republic of North Macedonia. However, by mid-2000s the extensions to existing buildings became subjected to regular procedure of obtaining building permit. Also, the citizens were provided with the option to legalize the extensions built prior to the adoption of the new regulations [1]. According to the building law, the lateral and vertical extensions to the existing building should be made in line with the urbanistic parameters overseen within the urban plan [3].

Examples of lateral and vertical extensions to the existing buildings can be seen in almost every municipality within the City of Skopje. This research paper is based on the doctoral dissertation of the author [4] and it studies the role of urban planning in the practice of adding extensions, lateral and vertical, to the existing residential buildings through a case study urban block in municipality of Karposh. The case study urban block is analyzed at three different states, the initial state, the actual state and planned state. The initial and actual states of the urban block are based on a study report provided by Institute of Earthquake Engineering and Engineering Seismology (IZIIS) [2], while the planned state is based on the Detailed Urban Plan (DUP) prepared for region Z 08 in municipality of Karposh [5]. The urban planning system of North Macedonia consists of urban plans at different levels depending on the size of the area which is subjected to planning. The Detailed Urban Plans (DUPs) are prepared at municipality level for neighborhoods or districts [4, 6].

2. THE CASE STUDY URBAN BLOCK

The case study is mainly a residential urban block, and it is located in the municipality of Karposh in Skopje [4]. The area of the case study urban block is defined with the streets Nikola Tesla, Orce Nikolov, Ivan Agovski and Ruger Boshkovic. There are in total eight residential buildings distributed in the form of open urban block (Figure 1). The space between the buildings serves as green park areas and car parking lots. In the 1990s the trend of increasing the living space of the existing buildings started [1, 2, 4]. Six out of eight buildings in the case study were subjected to modifications such as lateral and vertical extensions. The building with identity number 1_1 remained as it was initially planned without application of any changes. Based on the geodetic layout of the DUP [5], at the initial state of the urban block building 1_6 was the same as building 1_5, however, a new building was built in 2007 and there are no changes applied to building 1_6 in the meanwhile. Also, in the DUP [5] the buildings 1_1 and 1_6 do not have any changes. Only the buildings that were subjected to changes in terms of lateral and vertical extensions were analyzed.

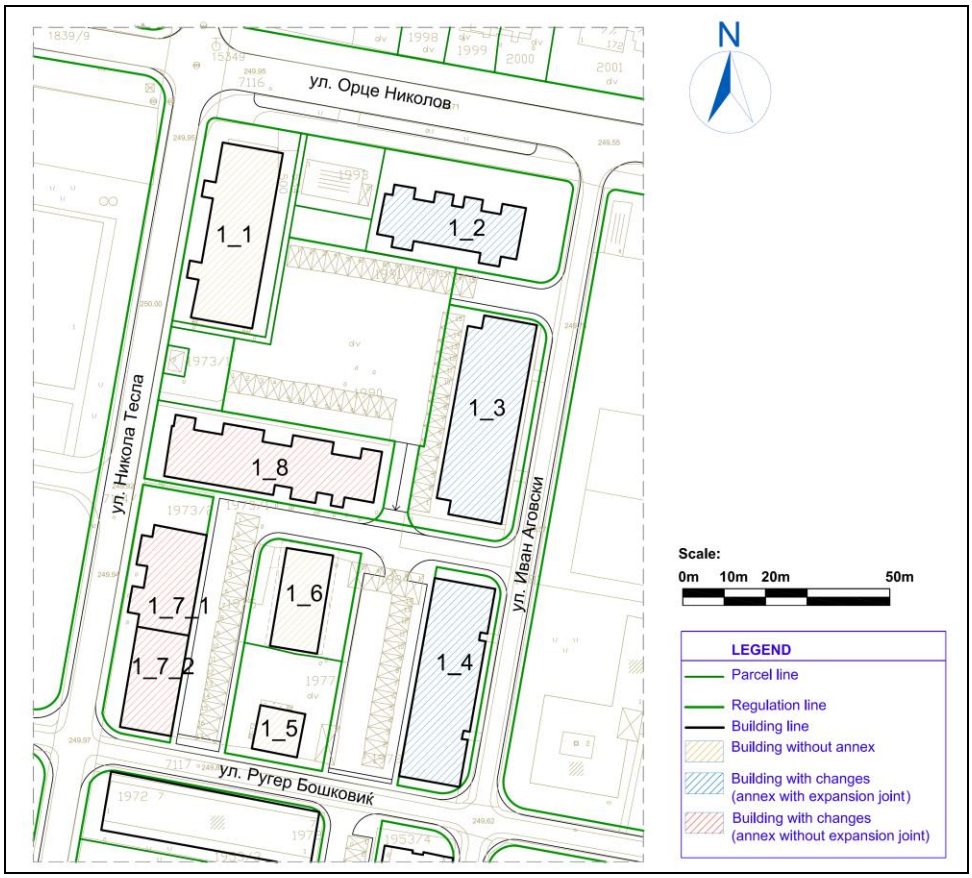


Figure 1. Case study urban block. Source: graphical presentation in AutoCAD [4] based on geodetic data of DUP [5]

3. METHODOLOGY

The selected case study is a small-scale representative example of the practice of adding lateral and vertical extensions to the existing buildings to increase the dwelling area [4]. To understand the role of urban planning in this practice of applying changes to existing buildings the case study was analyzed according to three states of the buildings:

- Initial state which represents the original state of the buildings
- Actual state, buildings are presented in their current state with extensions applied
- Planned state, representing the buildings according to DUP

Two main sources of input information were used for constructing the layouts of the buildings in different states, an on-site survey study conducted by IZIIS in 2013 [2] and the Detailed Urban Plan (DUP) [5]. The DUP was prepared in 2015 for zone Z08 [5] where the case study urban block is located. However, this plan later in 2015 was abolished by the municipality of Karposh [7]. The study conducted by IZIIS [2] was a rapid visual screening method for evaluating the seismic stability of the buildings. In the report of this study for each of the buildings there is information about the year of construction, number of floors, approximate total-built area, changes applied to the original building and information about the structural system and its material [2]. As additional resources were used the Google Maps

[8], the cadaster GIS database [9] as well as field visits were made to have more thorough information about the buildings.

First, the case study buildings were analyzed at their different states from the aspect of urban planning parameters, such as height, ground floor area and total built area.

Second, the structural system and material of each building was categorized into a taxonomy definition. The difference in the structural system and material between the existing buildings and their extensions was analyzed.

3.1. Analysis of the Urban Parameters at Different States of the Buildings

The buildings in the case study urban block to which extensions were applied were analyzed at three different time periods from aspect of the following urban planning parameters:

- Height
- Ground floor area (m²)
- Total built area (m²)

The buildings with their identity numbers and urban planning parameters at the three different states, initial, actual and planned, are presented in Table 1.

Table 1. Comparison of urban planning parameters at different states of the buildings.

ID	State / Urban parameter	Initial state	Actual state	Planned state (DUP)
1-2	Height	5 (G + 4)	7 (G + 4 + 2 RF)	6 (G + 4 + 1 RF)
	Ground floor area (m²)	408	408	510
	Total built area (m²)	2040	2830	3060
1-3	Height	5 (G + 4)	7 (G + 4 + 2 RF)	6 (G + 4 + 1 RF)
	Ground floor area (m²)	626	770	850
	Total built area (m²)	3130	5390	5100
1-4	Height	5 (G + 4)	8 (G + 6 + 1 RF)	8 (G + 6 + 1 RF)
	Ground floor area (m²)	620	724	724
	Total built area (m²)	3100	5792	5792
1-5	Height	2 (G + 1)	2 (G + 1)	6 (G + 4 + 1 RF)
	Ground floor area (m²)	117	117	296
	Total built area (m²)	234	234	1776
1-7	Height	5 (G + 4)	6 (G + 4 + 1 RF)	6 (G + 4 + 1 RF)
	Ground floor area (m²)	658	745	745
	Total built area (m²)	3290	4470	4470
1-8	Height	5 (G + 4)	6 (G + 4 + 1 RF)	6 (G + 4 + 1 RF)
	Ground floor area (m²)	495	750	750
	Total built area (m²)	2475	4500	4500

In the table the letter “G” stands for ground floor and letters “RF" stand for roof floor. The initial state represents the buildings how they were originally planned and constructed. The

geodetic information within the DUP [5] served for understanding what the original version of the buildings in terms of length and width was. The height of the buildings at initial state was obtained from the IZIIS report [2].

The actual state is based mainly on the IZIIS report [2], while Google Maps [8] and cadaster GIS database [9] information was used as additional resources. The square meter areas of the buildings, both at initial and actual states, were defined according to the geodetic information of the DUP [5]. Although there is a gap of 12 years between the time of conducting the study by IZIIS [2] and today, the buildings have not been changed in the meantime.

The planned state of the buildings is solely based on the information present in the DUP [5]. The DUP was prepared in 2015 [5], however it was abolished the same year by the Municipality of Karposh [7].

Analyzed from the aspect of height of the buildings, initially most of the buildings were designed and built as five floors high buildings consisting of a ground floor and four floors. All the buildings presented in Table 1 were added on one or two roof floors in the period following after 1981. Building with id 1_4 was added two regular floors plus a roof floor. The ground floor area at most of the buildings was increased because of the lateral extensions. As consequence of the changes applied, enlarged dimensions of the buildings and increased heights, the total built area was increased. The DUP includes almost all the changes applied to the urban parameters and allows greater increase of the ground floor and total built area. Exception are the buildings 1_2 and 1_3 where the height given by DUP is smaller than the actual state of the buildings.

Figure 2 presents these changes to urban planning parameters at the different states of the buildings with figure-ground relationship as well as sections through the urban block. The buildings grow in width and height. This causes the open spaces to be reduced and the distances between the buildings become smaller.

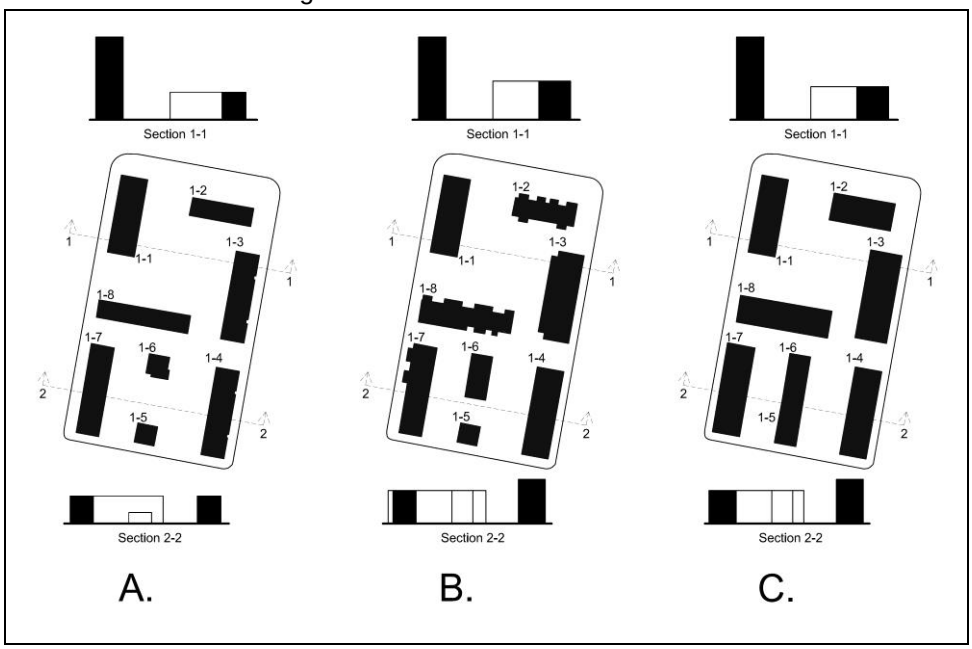


Figure 2. Figure-ground relationship of the case study at different states (A: initial state, B: actual state, C: planned state). Source: graphical presentation in AutoCAD based on geodetic data and urban parameters of DUP [5]

3.2. Analysis of the Taxonomies at Different States of the Buildings

A comparison was made between the structural system and material characteristics of the buildings and their extensions (Figure 3). For this analysis the actual state of the buildings was considered. Each of the buildings was categorized according to a certain taxonomy which serves to define the structural characteristics important for seismic stability. For defining the taxonomy of the buildings, the Global Earthquake Model [10] taxonomy definition was used.



Figure 3: Building 1_8 with lateral and vertical extensions. Source: photos by K. Edip.

The taxonomy information is important to relate the structures to selected fragility and vulnerability functions. The fragility function shows how much damage a structure can endure, while the vulnerability function relates to how much losses, in terms of economic and human losses, a structure may cause depending on the structure's response to earthquakes [11]. The taxonomy definition was based on the data of European Seismic Risk Model 2020 (ESRM20) [11] where wide range of fragility and vulnerability functions were developed for the taxonomies of buildings characteristic of the European countries. The taxonomies of the case study buildings consist of information regarding the material of the structural system, the type of the lateral load resisting structural system, the level of ductility or alignment with the seismic design codes and number of floors [4].

In Table 2 the buildings are shown as taxonomy of building representing the initial state of the building and taxonomy of extension part which defines the characteristics of the structure added to the building.

Table 2. Taxonomy of buildings and their annexes

ID	Taxonomy of the buildings	Taxonomy of the extension part
1-2	MCF_LWAL-DUL_H5	CR_LDUAL-DUM_H7
1-3	MCF_LWAL-DUL_H5	CR_LFM-CDM-10_H6
1-4	MCF_LWAL-DUM_H5	CR_LFM-CDM-10_H6
1-5	MUR-CL99_LWAL-DNO_H2	No annex
1-7	MCF_LWAL-DUL_H5	CR_LFM-CDM-10_H6
1-8	MCF_LWAL-DUL_H5	CR_LFM-CDM-10_H6

The explanation of the taxonomies used in Table 2 is as follows:

- MCF_LWAL-DUL_H5: confined brick masonry, load bearing wall, low ductility, five floors high.
- MCF_LWAL-DUM_H5: confined brick masonry, load bearing wall, moderate ductility, five floors high.
- MUR-CL99_LWAL-DNO_H2: unreinforced brick masonry, load bearing wall, no ductility, two floors high.
- CR_LDUAL-DUM_H7: reinforced concrete, dual frame-wall system, moderate ductility, seven floors high
- CR_LFM-CDM-10_H6: reinforced concrete, frame, medium seismic design code, coefficient of lateral force, six floors high

The urban block is an old area and most of the buildings were constructed in the 1950s. It is important to note that before the 1963 Skopje earthquake the seismic forces were not included in the design of the structures [12]. The “Provisional Technical Regulations for Construction in Seismic Regions” [13] was the first seismic design code in the country [12, 14, 15] while the updated modern version of the seismic design code, the “Regulations with Technical Norms for Construction of Buildings in Seismic Regions” [16] was adopted in 1981 [14,15]. Starting from 2020 the Eurocode 8 was adopted in N. Macedonia [17].

Most of the buildings built in the period before 1963 were made of masonry load bearing structures, while the use of reinforced concrete increased after 1981 [4]. Based on the definition of the seismic design code levels and ductility levels in ESRM20 [11], in the case study there are buildings considered as low code designed according to seismic code of 1964 and buildings with moderate code designed according to seismic code of 1981 [4]. The ductility level of structures is also related to their year of construction with regard to the seismic design codes [4]. The method of implementing the extensions is also important for the seismic stability of the buildings. Extensions can be applied with the use of expansion joints or directly to the existing structure, without the use of expansion joints [4].

4. DISCUSSION OF THE RESULTS

While the occupants of the older residential buildings require enlargement of their dwelling space by adding extensions, the quality of life drops which is contradicting to the concept of sustainable development. The needs of today's generation should be fulfilled while having considerations also for the needs of the future generations [18]. The current generations make changes to their built living environment which will have an impact on the future generations.

The DUPs prepared for existing urban areas when referring to existing buildings contain a dilemma, if the new urban planning parameters mean adding extensions to the building or should be interpreted as rebuilding a new building by demolishing the existing one [4]. Beside the urban plans the building law also supports the practice of adding extensions to existing buildings [3].

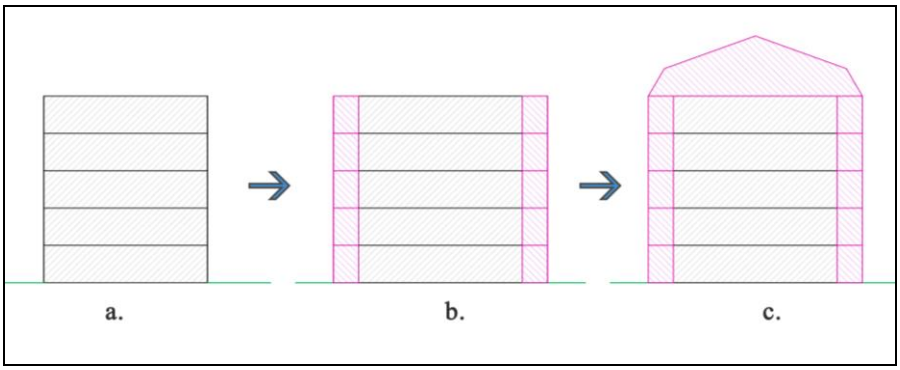


Figure 4. Schematic presentation of the extensions applied to existing buildings presented in section views (a: original building, b: horizontal extension, c: vertical extension). Source: drafted by K. Edip.

From architectural point of view, by increasing the surface area of the buildings the depth of the rooms increases. This causes a reduced amount of sunlight in the rooms. Initially buildings were designed according to standards and norms to meet the requirements for quality housing. Changes to buildings, such as lateral and vertical extensions (Figure 4) cannot be foreseen in the initial architectural project. Viewed from the aesthetical aspect, the initial form of the building is changed and the material difference between the existing and later added part is obvious. There is no harmonization of the materials when adding extensions, the only purpose is obtaining a greater amount of square meter space.

The number of occupants per dwelling can increase thanks to the enlarged space, however, this brings with it also problems related to car parking spaces. Especially in the case of Skopje where the only means of public transport are the buses, most of the residents rely on private car ownership.

Another, important problem which should not be neglected is the seismic stability of such buildings with extensions. Skopje is situated in a seismically active region where earthquakes with magnitudes ranging between 4 and 6 degrees can happen any time [19]. The scientific researchers from the field of earthquake engineering agree that such interventions to the existing buildings require detailed analysis and should be very carefully implemented since they might affect the seismic stability and safety of the existing buildings [20].

5. CONCLUSION

Although extending the existing buildings might be more economical and faster way for obtaining greater living space than building a new building, in the long term it has much more negative influences on the overall quality of the living environment. In the first place the urban planners and decision makers should be informed about the long-term consequences of the lateral and vertical extensions to the existing buildings. At the same time, awareness about the importance of applying the concept of sustainability in urban planning should be increased at urban planners, decision makers and the general public. This study suggests that in the existing urban regions, the Detailed Urban Plans should not allow changes to the urban planning parameters of the existing buildings. However, this idea should be supported also by the building law in order to be implemented.

ACKNOWLEDGMENTS

I would like to acknowledge that this research is based on my doctoral dissertation [4]. I am grateful to the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at Ss. Cyril and Methodius University in Skopje, N. Macedonia for providing me the report of the visual screening study [2] for the case study location.

REFERENCES

[1] Mariotti Jasna, Baldwin Hess Daniel: **Enlargement of Apartments in Socialist Housing Estates in Skopje Under Transition: The Tension Between Individual Preferences and Collective Action**. *Journal of Housing and the Built Environment*. Vol. 38, 39-59, 2023, https://doi.org/10.1007/s10901-021-09875-4.

[2] Nechevska - Cvetanovska Golubka, Apostolska Roberta, Garevski Mihail, Bojadzieva Julijana, Vitanova Marija, Stojanoski Blagojce, Bogdanovik Aleksandra, Gorgievska Elene, Jekik Goran, Kitanovski Toni, Runevski Kristijan, Trajcevski Jovan, Dimitrovski Mirko, Tomik Daniel, Jovanov Gjorgi. (2013). **Upgrade of the Database of Municipality of Karpos with New Attributes for Defining and Tracking the Seismic Stability and Safety of the Existing Buildings in the Territory of Municipality of Karpos GIS Environment. Book 1: Visual Inspection and Conclusion for the Current State of the Buildings at the Location of Municipality of Karpos With Using Defined Form**. **IZIIS Rport 2013-47**. *Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at „Ss. Cyril and Methodius University“* in Skopje, North Macedonia, 2013.

[3] Official Gazette of Republic of North Macedonia, nr. 59/2011: **Building Law - Refined Text,** Skopje, North Macedonia, 2011.

[4] Edip Kefajet: **Seismic Risk Assessment as a Basis for Sustainable Urban Development**. Doctoral dissertation, *Institute of Earthquake Engineering and Engineering Seismology – IZIIS at „Ss. Cyril and Methodius University“* in Skopje, North Macedonia, 2023.

[5] Tajfa Plan. **Detailed Urban Plan for urban region Z 08,** Skopje – Municipality of Karposh, 2015.

[6] Official Gazette of Republic of North Macedonia, nr. 32/2020: **Law for Urban Planning,** Skopje, North Macedonia, 2020.

[7] https://karpos.gov.mk/ (accessed on 25.04.2025)

[8] https://www.google.com/maps/@42.0045183,21.4120056,251m/data=!3m1!1e3?entry=ttu&g_ep=EgoyMDI1MDcwOS4wIKXMDSoASAFQAw%3D%3D (accessed on 24.04.2025)

[9] https://e-uslugi.katastar.gov.mk/imotenList (accessed on 26.04.2025)

[10] Brzev Svetlana, Scawthorn Charles, Charleson Andrew William, Allen Luke, Greene Marjorie, Jaiswal Kishor, Silva Vitor: **GEM Building Taxonomy Version 2.0,GEM Technical Report 2013-02,** V1.0.0, 188 pp., *GEM Foundation*,Pavia, Italy, 2013, doi: 10.13117/GEM.EXP-MOD.TR2013.02.

[11] Crowley Helen, Dabbeek Jamal, Despotaki Venetia, Rodrigues Daniela, Martins Luis, Silva Vitor, Romao Xavier, Pereira Nuno, Weatherill Graeme, Danciu Laurentiu: **European Seismic Risk Model (ESRM20), EFEHR Technical Report 002, V1.01, 84 pp, https://doi.org/10.7414/EUC-EFEHR-TR002-ESRM20**. Pavia, Italy: *EUCENTRE Foundatio*n, 2021.

[12] Petrovski Jakim: **Damaging Effects of July 26, 1963 Skopje Earthquake**.Skopje earthquake: 40 years of European Earthquake Engineering: SE-40EE. Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University "Ss. Cyril and Methodius" Skopje, R. N. Macedonia, 2003.

[13] Official Gazette of Socialist Federal Republic of Yugoslavia (SFRY) nr. 39/64: **Provisional Technical Regulations for Construction in Seismic Regions**, *Yugoslav Institute for Standardization,* Belgrade, Yugoslavia, 1964.

[14] Milutinovic Zoran, Salic Radmila, Tomic Daniel: **An Overview on Earthquake Hazard and Seismic Risk Management Policies of Macedonia.** *16th World Conference on Earthquake Engineering*, 16WCEE 2017, Santiago, Chile, 2017

[15] Blagojevic Nikola, Brzev Svetlana, Petrovic Milica, Borozan Jovana, Bulajic Borko, Marinkovic Marko, Hazdima-Nyarko Marijana, Kokovic Veljko, Stojadinovic Bozidar: **Residential Building Stock in Serbia: Classification and Vulnerability for Seismic Risk Studies.** *Bulletin of Earthquake Engineering*, Vol. 21, 4315-4383, 2023, https://doi.org/10.1007/s10518-023-01676-0.

[16] Official Gazette of Socialist Federal Republic of Yugoslavia (SFRY), nr. 31/81: **Regulation with Technical Norms for Construction of Buildings in Seismic Regions**, *Yugoslav Institute for Standardization*, Belgrade, Yugoslavia, 1981.

[17] Official Gazette of Republic of North Macedonia, nr. 211/2020: **Regulation for updating the Regulation for Standards and Norms for Design,** Skopje, North Macedonia, 2020.

[18] United Nations: Report of the World Commission on Environment and Development –Our Common Future, *United Nations*, New York, USA, 1987.

[19] Salic Radmila: **Advanced Approach to Seismic Hazard Assessment for the Republic of Macedonia**. Doctoral dissertation, *Institute of Earthquake Engineering and Engineering Seismology – IZIIS at „Ss. Cyril and Methodius University"* in Skopje, North Macedonia, 2015.

[20] Apostolska Roberta, Necevska-Cvetanovska Golubka, Shendova Veronika, Bojadzieva Julijana: **Seismic Performance Assessment of „Hybrid" Structures Using Two-Level Multi Group GIS Oriented Approach: Case Studies.** *Bulletin of Earthquake Engineering,* Vol. 16, 4797-4824, 2018, https://doi.org/10.1007/s10518-018-0366-0.

doi.org/10.62683/SINARG2025.023

Research paper

THE ANALYSIS OF OPEN SPACES IN NEWLY BUILT APARTMENTS IN SERBIA – CASE STUDY: THE CITY OF NIŠ

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

Abstract

The paper deals with the analysis of open spaces in newly built apartments in Serbia. The research was conducted as a case study of selected examples of newly built or under-construction apartments in the city of Niš. Considering the trends in residential construction from the post-socialist period to the present day, as well as the investor-driven focus on profit, which is a characteristic feature of so-called "investor architecture", highly prevalent in Serbia, the assumption is that open spaces within apartments are not given much importance. On the other hand, open spaces are crucial for a healthy life and comfort, so their functionality is of great significance. In this regard, the paper investigates the current state of open spaces within apartments in new constructions and possibilities for their improvement. The aim of this paper is to examine the size, shape, functionality, and positioning of open spaces through the analysis of selected newly built apartments, in order to assess their contribution to the overall quality of housing. The main scientific methods applied in the research are analysis, synthesis and comparison. The findings highlight the inadequate functionality of open spaces and underscore the necessity for regulatory and design interventions aimed at enhancing their quality and their role within residential environments.

Key words: *open spaces, newly built apartments, functionality, residential comfort*

[1] PhD., Assistant Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, hristina.krstic@gaf.ni.ac.rs, https://orcid.org/0000-0001-6812-8826
[2] PhD., Associate Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, branislava.stoiljkovic@gaf.ni.ac.rs, https://orcid.org/0000-0002-1315-1970
[3] PhD., Assistant Professor, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, natasa.petkovic@gaf.ni.ac.rs, https://orcid.org/0000-0003-0245-4842

1. INTRODUCTION

Global urbanization is continuously increasing, leading to the rapid densification of cities [1], which in turn drives intensive construction activities and significantly impacts housing quality as well as shifts in residential typologies [2].

The process of urbanization is also evident in the Republic of Serbia, with a particularly notable increase in residential construction in its larger cities. According to data from the Statistical Office of the Republic of Serbia [3], the number of newly constructed apartments across the country has been steadily rising (Figure 1). The high demand for housing in urban areas has driven the accelerated development of multi-family residential buildings. In order to gain a clear understanding of what is currently being offered on the housing market and whether the quality of newly built apartments aligns with user needs, it is essential that construction be accompanied by research. Such research should examine the issue from multiple perspectives and guide future development, so as to avoid causing long-term harm to both the built environment and the urban ecosystem.

With the broader aim of examining the quality of newly built apartments in Serbia — and recognizing that the presence and quality of open spaces within residential units significantly influence overall housing quality — this study focuses specifically on assessing the quality of open spaces in new-built apartments. While the quality of open spaces alone does not provide a complete picture of overall apartment quality, it represents one of its key components, and was therefore selected as the central subject of this research. The study was conducted as a case study within the city of Niš, analyzing open spaces in a total of 45 apartments, categorized by size into groups of small, medium, and large apartments, defined for the purposes of the research. This is an indicative sample that may serve as a basis for broader conclusions in similar urban contexts across Serbia. The primary focus was placed on medium-sized apartments (50–60 m² — approximately the national average), while small (<50 m²) and large (>60 m²) apartments were included for comparative analysis.

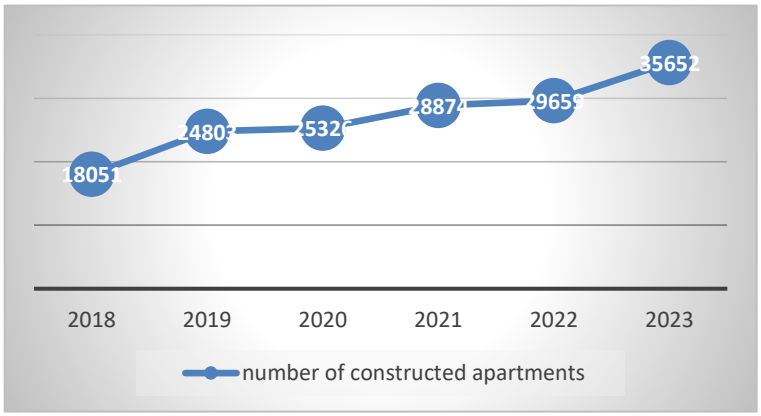


Figure 1 – Number of constructed residential units in the Republic of Serbia from 2018 to 2023, according to data from the Statistical Office of the Republic of Serbia [3]

The specific aim of this study is to examine the functionality of open spaces within apartments in multi-family residential buildings. In medium-sized apartments in Serbia, it is common to find undersized interior spaces, often as a result of efforts to incorporate the maximum possible number of bedrooms [4]. Furthermore, the current Regulation on Conditions and Standards for the Design of Residential Buildings and Apartments [5] does

not mandate the inclusion of open spaces as a required component within apartment units. Based on this context, this study is grounded in the hypothesis that open spaces in newly constructed apartments are considered secondary elements—insufficient in number, reduced in size, and often inadequately integrated into the overall functional organization and architectural design of residential units.

The methods applied in the research include analysis, comparison, synthesis, description, and observation. Initially, 45 newly built apartments from the city of Niš were selected and individually analyzed. The comparison of the obtained results (summarized in tabular form) allowed for the synthesis of the final findings, which are presented in the paper. The primary criteria for selecting apartments for analysis were apartment size and the diversity of functional layouts. The analyzed examples were taken from catalogs of apartments available on the official websites of the developers. Some of the apartments were completed, while others were still under construction but advertised for sale. Based on the available drawings, the selected apartments were uniformly sketched to facilitate better examination and analysis.

2. THE IMPORTANCE OF OPEN SPACES IN MULTI-FAMILY RESIDENTIAL BUILDINGS

Open spaces in an apartment are areas through which the apartment connects with nature and its surroundings. In multi-family residential buildings, the following types of open spaces can be identified within apartments (Figure 2): terrace (an open area of ground-floor apartments, a private garden at ground level, a kind of original type of private outdoor space [6]), balcony (an external space in the form of an elevated platform that extends as a cantilever beyond the building's main facade plane), loggia (an external space recessed within the building's main volume; one side is open, while the other three are enclosed), semi-loggia (a transitional form between a loggia and a balcony, which may be partially recessed and open on multiple sides), and roof terrace (flat roof terrace belonging to the apartment; rarely appears in small apartments). An additional type is the so-called french balcony (a glazed opening on the facade, the size of a full balcony door, but without a standing platform), although its function is somewhat different. Each type of open space within the apartment has its own advantages and disadvantages: a terrace is characterized by direct contact with the ground, greater spatial comfort, but often reduced privacy; a balcony offers greater openness to the surroundings, but also less privacy; a loggia has a high degree of privacy, is less exposed to weather conditions, but is less well-lit and affects the apartment's lighting; a semi-loggia has a higher degree of privacy than a balcony and better natural lighting than a loggia; a rooftop terrace has a high degree of privacy, good views, but is exposed to weather conditions.

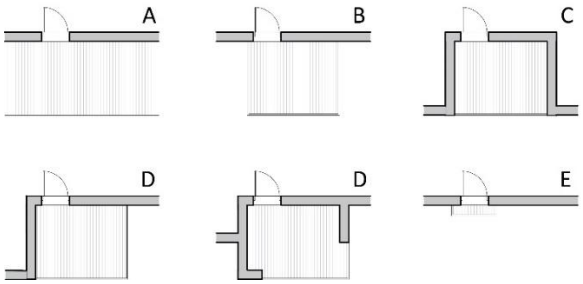


Figure 2 – A) Terrace, B) Balcony, C) Loggia, D) Semi-loggia, E) French balcony

As open spaces in apartments within multi-family residential buildings function as substitutes for the private gardens typical of single-family homes, their careful consideration and thoughtful integration are essential components of the architectural design process - open spaces within the apartments play a crucial role in multi-family residential buildings by providing private outdoor spaces for residents, improving their quality of life and enhancing the connection between indoor and outdoor environments. Such open spaces are places for rest and relaxation inside the apartment, social interaction and many other everyday activities. They are especially important in dense urban environments where access to green or open areas may be limited.

In discussing open spaces, Stamm-Teske W., Fischer K., and Haag T. [6] emphasize that the function of open spaces — although technically secondary — has become one of the central concerns in residential architecture. Due to their significant impact on the plastic articulation of the building as a whole, private outdoor spaces have evolved into key design drivers [6]. Consequently, a residential building designed without consideration for external spaces may be regarded as functionally obsolete. The renowned architect Neufert E. notes that the value of a dwelling increases when balconies or other types of open spaces are incorporated into the design [7]. According to Nestorović, every contemporary apartment should include at least one open-air space — this is a requirement of residential hygiene and a contributor to living comfort [8].

The COVID-19 pandemic further highlighted the value of open spaces within the apartment, as they became essential extensions of the living space. According to Carlos C. Duarte et al. [9] the importance of home balconies increased during the pandemic, demanding an update of its design features to accommodate the newly rediscovered activities with direct implications on its users' health and life quality. Evaluating the main design characteristics and associated uses that modern home balconies should incorporate, in light of how COVID-19 lockdowns have reshaped people's understanding and experience of home, they indicate that the perceived value of balconies has changed during the pandemic, suggesting that balconies are now expected to support a variety of activities — such as eating, reading, writing, using media, socializing, or simply relaxing, which were previously carried out in other spaces, highlighting that the shift in usage, has underscored the need for rethinking balcony dimensions and functions [9]. The experience of the pandemic could be seen as a call to reevaluate existing standards for apartment design.

3. CASE STUDY

Since the 2000s, and before, open spaces within apartments in Serbia have often been reduced to minimal areas under the influence of investor-driven architecture[4], i.e., market pressures and rationalization. The primary objective of this research is to analyze apartments currently available on the market and assess the quality of open spaces within apartments of average size in Serbia. According to the most recent data available on the official website of the Republic Statistical Office from 2023 [3], the average floor area of newly sold apartments in the Republic of Serbia was 55 m², in Belgrade, the average was 59 m², in Novi Sad it was 55 m², and in the two municipal areas of Niš, Mediana and Pantelej, the average area of newly sold apartments was 57 m² and 53 m², respectively [3]. Niš follows the national trend of increasing numbers of apartments on the market. Given that the situation in the housing sector in Niš is similar to that at the national level, the city of Niš was selected as the territorial scope for this study, with the reasonable assumption that the results obtained in this research could be largely applied to a broader geographic context. Therefore, focusing on the average size of apartments sold, this case study provides a more detailed analysis of newly built apartments in Niš within a size range close to the city and national averages — between 50 m² and 60 m². The study also includes apartments of smaller and larger sizes than the defined main category, with the aim of comparing specific parameters.

For the purposes of the case study, based on the primary criteria of size and diversity of functional layouts, 45 apartments were selected for analysis. Although the sample is not statistically representative, its selection enables an informed understanding of the prevailing spatial characteristics of newly constructed apartments at both local and national levels. The main analysis was conducted on 15 apartments ranging in size from 50 to 60 m² (Table 1).

[4] Investor-driven architecture refers to the practice of configuring residential spaces primarily according to market profitability, often at the expense of functionality, comfort, and sustainability.

Table 1. Analysis of open spaces in selected newly built apartments ranging from 50 to 60 m².

Apartment number	Location	Total floor area of the apartment (m2)	Number of open spaces	Size of open spaces (m2)	Type of open spaces	Open-to-total area ratio (%)	Shape of open spaces – approximate geometry	Dimensions of open spaces (m)	Dimensions ratio
01	*Vojvode Mišića*	53	1	4.03	loggia	7.60	rectangular	1.30*3.10	1:2.38
02	*Gornjomateje vačka*	53.5	1	4.60	semi-loggia	8.60	polygonal	1.80*2.50	1:1.39
03	*Vojvode Tankosića*	50	1	1.70	loggia	3.40	rectangular	1.05*1.74	1:1.66
04	*Vojvode Tankosića*	50	1	2.56	loggia	5.12	rectangular	1.53*1.80	1:1.18
05	*Vojvođanska*	60	2	2.83+ 2.32	semi-loggia / loggia	8.58	rectangular	1.68*1.71 1.18*1.89	1:1.02 1:1.60
06	*Bulevar Sv. Pantelejmona*	54	1	2.97	loggia	5.50	trapezoidal	1.17*2.20	1:1.88
07	*Lamartinova / Nobelova*	56	1	2.61	loggia	4.66	rectangular	1.47*1.70	1:1.16
08	*Zdravke Vučković*	57	1	4.47	loggia	7.84	rectangular	1.18*3.79	1:3.21
09	*Dubrovačka*	54.5	1	2.40	loggia	4.40	rectangular	1.20*2.02	1:1.68
10	*Matejevački put*	55.5	1	3.36	loggia	6.05	rectangular	1.40*2.40	1:71
11	*Gornjomateje vačka*	55	1	3.55	loggia	6.45	rectangular	1.20*2.94	1:2.45
12	*Blagoja Parovića*	55	1	5.48	balcony	9.96	rectangular	1.66*3.30	1:1.99
13	*Knjaževačka / Vase Pelagića*	54.5	1	6.00	loggia	11.01	rectangular	1.38*4.10	1:2.97
14	*Radoja Domanovića*	50	1	3.41	loggia	6.82	rectangular	1.38*2.48	1:1.80
15	*Borivoja Stevanovića*	60	1	4.56	loggia	7.60	rectangular	1.50*3.12	1:2.08

The analysis focuses on this group as it represents the most prevalent type of apartments on the market in Niš, as well as at the national level in the Republic of Serbia. According to their structure, the apartments in this analyzed group are two-bedroom and two-and-a-half-bedroom units[5] — either with a single master bedroom or with one master bedroom and one smaller single children's bedroom. The analysis identified the following parameters: the number of open spaces within the apartment, the size of the open spaces, the type of open spaces, the percentage of open spaces in relation to the total apartment area, the shape of the open spaces, the dimensions of the open spaces, and their interrelationship. Tables 2 and 3 present examples from a broader analysis (smaller and larger apartments compared

[5] Classification according to the current Regulation on the Conditions and Standards for the Design of Residential Buildings and Apartments in the Republic of Serbia

to the main analyzed category), which were used for comparison with the apartments that constitute the primary subject of the research.

Table 2. Analysis of open spaces in selected newly built apartments, smaller than 50 m².

Apartment number	Location	Total floor area of the apartment (m2)	Number of open spaces in the apartment	Size of open spaces (m2)	Type of open spaces	Open-to-total area ratio (%)	Shape of open spaces – approximate geometry
01	*Knjaževačka / Vase Pelagića*	42.8	1	3.16	loggia	7.38	rectangular
02	*Milentijeva*	42.48	1	5.46	loggia	12.85	rectangular
03	*Dubrovačka*	41.66	1	2.04	semi-loggia	4.90	rectangular
04	*Cvijiceva*	36.41	1	2.85	semi-loggia	7.83	rectangular
05	*Vase Pelagića*	44.37	1	4.12	loggia	9.28	rectangular
06	*Pane Đukića / Hadži Prodanova*	47.52	1	6.02	semi-loggia	12.67	polygonal
07	*Lamartinova / Nobelova*	39.54	1	2.36	loggia	5.97	rectangular
08	*Zdravke Vučković*	41.9	1	3.2	loggia	7.64	rectangular
09	*Cara Dušana*	42.8	1	3.08	loggia	7.20	rectangular
10	*Matejevački put*	45.39	1	5.05	loggia	11.13	rectangular
11	*Bulevar Nemanjića*	44.13	1	2.85	loggia	6.46	rectangular
12	*Vardarska / Novopazarska*	31.67	1	2.54	loggia	8.02	rectangular
13	*Mačvanska*	45	1	3.14	loggia	6.98	rectangular
14	*Dejana Dinića*	44.47	1	3.35	loggia	7.53	rectangular
15	*Gornjomatejevačka*	42.46	1	4.54	loggia	10.69	rectangular

Table 3. Analysis of open spaces in selected newly built apartments, larger than 60 m².

Apartment number	Location	Total floor area of the apartment (m2)	Number of open spaces in the apartment	Size of open spaces (m2)	Type of open spaces	Open-to-total area ratio (%)	Shape of open spaces – approximate geometry
01	*Knjaževačka / Vase Pelagića*	83.25	1	6	loggia	7.21	rectangular
02	*Milentijeva*	89.33	1	7.85	semi-loggia	8.79	polygonal
03	*Dubrovačka*	75.93	1	3.63	loggia	4.78	square
04	*Cvijiceva*	78.5	1	6.8	loggia	8.66	trapezoidal
05	*Vase Pelagića*	87.29	2	6.36 + 3.62	loggia / loggia	11.43	polygonal
06	*Pane Đukića / Hadži Prodanova*	68.95	1	11.94	semi-loggia	17.32	polygonal
07	*Lamartinova / Nobelova*	67.51	1	2.87	loggia	4.25	rectangular
08	*Zdravke Vučković*	96.6	1	7.9	semi-loggia	8.18	rectangular
09	*Cara Dušana*	70.37	1	7.26	loggia	10.32	rectangular
10	*Matejevački put*	75.51	1	4.35	loggia	5.76	rectangular
11	*Bulevar Nemanjića*	80.3	1	8.44	loggia	10.51	rectangular
12	*Vardarska / Novopazarska*	75.87	1	8.89	loggia	11.72	rectangular
13	*Mačvanska*	80	1	5.9	loggia	7.37	rectangular
14	*Dejana Dinića*	71.77	1	3.67	loggia	5.11	rectangular
15	*Zelengorska*	86.2	1	3.3	loggia	3.83	rectangular

4. DISCUSSION

Based on the conducted case study, the following conclusions have been drawn:

1) Medium-sized apartments (50-60 m²) predominantly have only one open space. This space is primarily connected to the living area and is usually accessible from the living room. In some cases, for apartments with single-sided orientation, it is possible to find an additional exit from the bedroom to the open space, allowing the open area to serve both the day and night zones simultaneously. Although it is desirable for both the day and night zones to have access to open spaces, combining them through a shared open area could compromise the privacy of the night zone. Ideally, an apartment should have at least two open spaces, separated by zones. Of the 15 analyzed examples from the medium-sized apartment group, only one apartment has two open spaces — one in the living area and one in the night area. In the group of smaller apartments (<50 m²), all units have only one open space, while in the group

of larger apartments (>60 m²), only one apartment also features two open spaces. The positioning and connection to other rooms in these groups of apartments are very similar to those in medium-sized apartments. Based on this, we can conclude that the number and position of open spaces in apartments in Niš do not necessarily depend on the size of the apartment. Researching the adaptability of balconies in multifamily housing design, Peters T. and Masoudinejad S. [10] emphasize the importance of the location and placement of the balconies in relation to the floorplan (indicating as an example the inability of the balconies that are accessible only from the bedroom to provide extensions of the living space).

2) Looking at the relationship between the sizes of open spaces in the apartments from the analysis (graph in Figure 3), it can be concluded that the sizes of open spaces in smaller apartments (below 50 m²) and medium-sized apartments (50-60 m²) are quite consistent. This may be the result of typical design solutions rather than the architect's original intent. The greatest variation in the size of open spaces is observed in larger apartments (over 60 m²). The average sizes of open spaces in small, medium, and large apartments from the case study are: 3.58 m², 3.79 m², and 6.58 m², respectively. The average sizes of open spaces in small and medium apartments are roughly the same, with a slight difference in favor of medium-sized apartments, while the size of open spaces is noticeably larger in larger apartments.

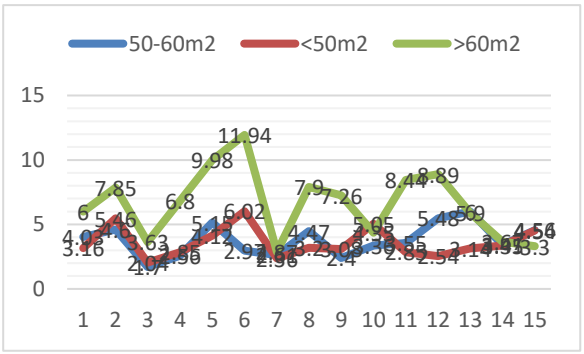


Figure 3 – Variations in the Area of Open Spaces in Apartments

3) The average percentage share of open spaces in relation to the total apartment area (Figure 4) for medium-sized apartments is around 6.9% for the analyzed apartments, while for smaller and larger apartments, this share is higher, with the examples from the extended analysis showing approximately 8.4% for smaller apartments and around 8.3% for larger apartments.

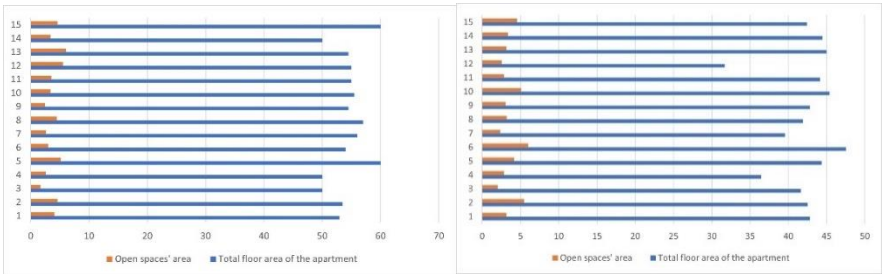


Figure 4 – Open spaces' area in relation to the total apartment area in: a) small apartments (50-60 m²), b) medium-sized apartments (<50 m²)

4) The area of a space is crucial for its proper functional organization – for a particular space to accommodate all necessary functions, it must primarily provide sufficient room for positioning the required furniture and equipment, their usage, and adequate circulation. However, the area of a space alone is not a sufficient parameter for determining its functionality. The dimensions of the open space also play a significant role in evaluating its functionality. An open space with the same area will not be equally functional if its dimensions (width and length) are disproportionate. Therefore, attention must be paid to the relationship between the width and length, as well as the geometry. According to Nestorović B. [8], the most favorable shape for open spaces is an elongated rectangle with the longer side facing the building. This shape allows for more favorable furniture arrangement, more efficient circulation, and less compromised room lighting. The width of the open space should not be less than 150 cm, as this would hinder movement around a table, which should be provided for [8]. In the analyzed apartments, with an area of 50-60 m², from the case study, the shape of the open space is rectangular or approximately rectangular in the majority of cases (13/15). However, only 1/3 of the analyzed apartments (5/15) meet the criterion of a minimum width of 150 cm, indicating a problem in space organization and functionality (Figure 5). If we consider Nojfert's recommendation to include space for flower beds (plantings) in the functional depth [7], we can conclude that none of the analyzed examples meet the criterion for adequate depth. In the analyzed examples of apartments with an area of 50-60 m², it is evident that little consideration was given to greenery in the design of the open spaces, and, if included, it might only be placed peripherally, along the longer side.
5) When discussing the sizing of common (shared) rooms in an apartment, the main factor considered is the number of users. The number of seating places in the living room and dining area is most commonly sized according to the pattern: number of users + 2 [11, 12], where the number of residents is increased by 2, to account for occasional visitors. Considering that the open space in an apartment is a space whose function includes socializing among residents (family) as well as interacting with visitors (friends), similar to a living room outdoors, it is logical that the dimensions of this space should follow the mentioned formula. Furthermore, which is particularly relevant after the pandemic, these spaces serve not only as areas for rest but also for work activities (e.g., working from home in a garden setting). The type of furniture most commonly planned for open spaces is a table with chairs or more comfortable furniture such as garden sets and lounge chairs. In this regard, when sizing the open space, it should be ensured that at least one garden set or table with chairs for household members and visitors is provided. Since the current regulation [5] does not specify a minimum area for open spaces in an apartment, the decision is left to the designer, often (or almost always) influenced by the requirements of the investor. In the analyzed examples, only 40% of the medium-sized apartments (6/15) have open spaces where seating for the number of users corresponding to the mentioned pattern n+2 can be arranged (in apartments 1, 2, 8, 12, 13, and 15 – see the Figure 6). However, it should be emphasized that, in all cases, movement around the table when users are seated is difficult because there is not enough width for circulation (Figure 6).

6) According to the case study, it can be concluded that, regardless of apartment size, the most common type of open space in newly built apartments in Niš is the loggia. Although the loggia has advantages in terms of protection from weather conditions, increased privacy, and better thermal insulation, caution should be exercised when applying this type, as it can lead to issues with sunlight penetration in the rooms adjacent to it. In current practice, it is common to find apartments where the living room, dining room, and kitchen are combined in a linear arrangement along the depth of the space, resulting in very deep areas that require adequate lighting. If an open space in the form of a loggia is attached to them, there is a risk of disrupting the lighting comfort of the apartment's day zone.

Research on the use of apartment balconies [13], revealed that developers and designers often associate balconies primarily with residents' leisure activities, which leads to their design being limited to minimal dimensions without considering the impact on usability and comfort, while, in reality, balconies serve many other functions related to everyday household tasks. Considering that the dimensions of open spaces in newly built apartments have been reduced to a minimum, often below the necessary minimum, it is concluded that these open spaces barely meet the most basic needs for outdoor living, while there is no space for other auxiliary activities and amenities that are significant for the user. In this regard, one of the conclusions of the paper is that the current regulation in the field of residential building design, which does not require open spaces in apartments as mandatory, should be improved. The proposal is to amend the regulation to require the mandatory design of at least one open space within the apartment and to define its minimum dimensions and area to ensure the minimum necessary functionality (proposal: minimum area of 3.5 m² and minimum width of 1.5 m). It is further recommended that the regulations incorporate typological guidelines, given their differing functions and limitations.

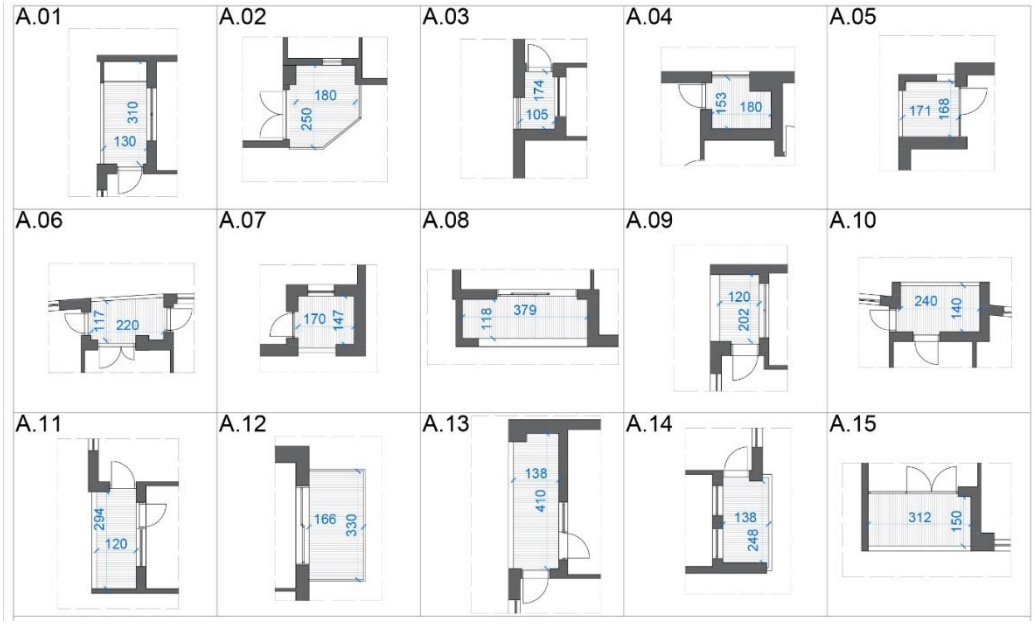


Figure 5 – Dimensions of open spaces from the case study (medium-sized apartments)

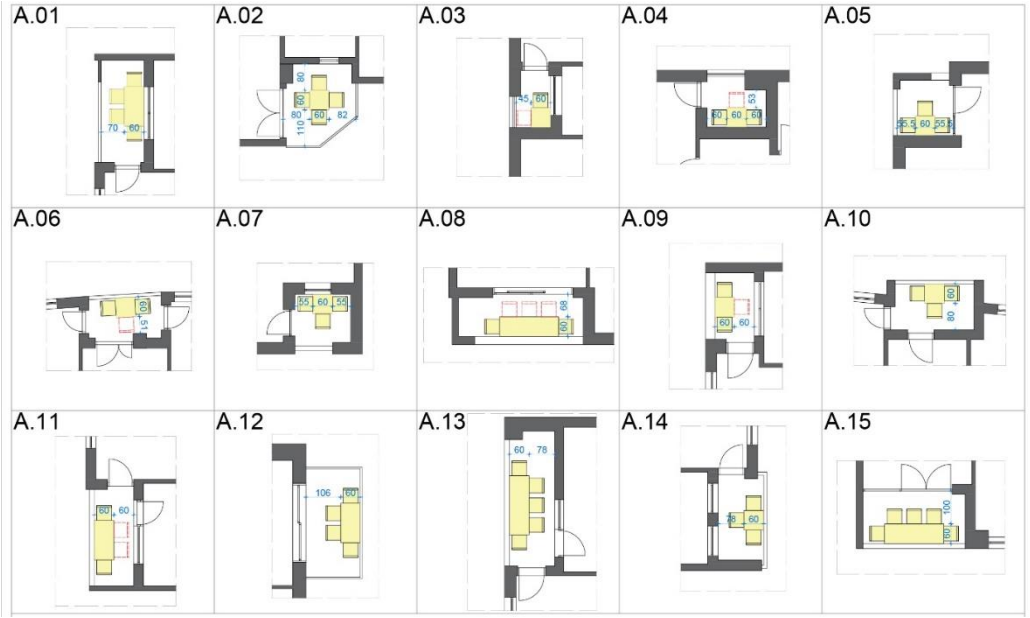


Figure 6 – Testing the possibility of seating users in open spaces from the case study (medium-sized apartments)

The second conclusion drawn from the research is that open spaces in an apartment should also be considered as green spaces, and sufficient space should be provided for the placement of greenery (in pots, planters), so that these areas can compensate for the lack of a yard and contribute to the creation of a more favorable microclimate and a more pleasant living environment. Considering that "investor architecture" is still prevalent in Niš, where the residential building project is primarily geared towards maximizing the investor's profit from the outset, without giving excessive consideration to the satisfaction of the end user, it is common for open spaces within the apartment to be marginalized. When determining the price of an apartment, open spaces are calculated in the same way as other spaces in the apartment — the total saleable area of the apartment includes the open space at 100% of its area. Due to the low purchasing power of residents, future buyers often opt for apartments where the open space area is reduced in favor of increasing the area of other rooms — such as the living room or bedrooms, leading to another factor that influences the existence and quality of open spaces in the apartment. This vicious circle, driven on one hand by the investor's desire for high profit and on the other by the users who, due to financial difficulties, are forced to lower their criteria when choosing their living spaces, is one of the key aspects defining the direction of housing construction in Niš and Serbia. This issue could be alleviated by introducing certain measures that would prioritize the users' needs. For example, the saleable area of open spaces within an apartment in Germany is calculated as ¼ to ½ of its area [14]. To satisfy both the investors' interests and encourage them to meet these requirements, certain incentives for investors could also be introduced, such as tax reductions for greening open spaces, etc.

5. CONCLUSION

The constant reduction of apartment size and the drive to maximize the number of units within a residential building have led to a decline in housing quality. Open spaces within an apartment are a crucial functional element that enhances the quality of living and impacts human health. This is especially important in densely built environments, where there is limited access to public green spaces near residential buildings. The recent experience stemming from the Covid pandemic further underscores the importance of open spaces within the apartment.

The research presented in this paper aimed to identify the quality of designed open spaces within newly built apartments in Serbia, with the goal of improving them and adapting them to the contemporary needs of users. The results of the study confirm the initial hypothesis that open spaces in newly constructed apartments in Niš are marginalized both functionally and spatially. They are present in minimal dimensions, often with inadequate proportions, limited functionality, and without a standardized architectural approach.

The findings indicate that open spaces are not given adequate attention during the design process, they are often non-functional or barely functional, fail to meet all the essential needs of users, and therefore require deeper analysis and a more thoughtful design approach, given their importance.

The key recommendations, aimed at enhancing the quality of open spaces within the apartments, emerging from the research include: introducing a requirement for the design of at least one open space per apartment; defining minimum standards for the area and width of open spaces; and redefining the method of calculating the saleable floor area in order to encourage the construction of such spaces.

Although the research is based on an indicative sample of apartments in the city of Niš, the results point to broader trends in residential construction practices across Serbia. Future studies should encompass a larger number of cities, including comparative analyses within a regional context, as well as qualitative methods (e.g., user satisfaction surveys), in order to gain a deeper understanding of residents' perceptions, usage patterns, and expectations regarding open spaces.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under the Agreement on the Implementation and Financing of Scientific Research Work of the NIO in 2025 - Registration number: 451-03-136/2025-03/ 200095 dated 04/02/2025.

REFERENCES

[1] Lehmann Steffen: **Sustainable urbanism: towards a framework for quality and optimal density?**, *Future Cities and Environment*, Volume 2:8, 2016. https://doi.org/10.1186/s40984-016-0021-3

[2] Meriläinen Sanna, Tervo Anne: **The changing typology of urban apartment buildings in Aurinkolahti**, *Buildings and Cities*, 6 (1), 2025., pp. 50–69. https://doi.org/10.5334/bc.484

[3] https://www.stat.gov.rs/sr-cyrl/, accessed 18th March 2025.

[4] Krstic Hristina, Stoiljković Branislava, Petković Nataša, Petrović Vladana: **Functional organization of medium-sized apartments in new construction in Serbia**, *International Conference Synergy of Architecture & Civil Engineering SINARG 2023*, Niš, pp. 388-401, 2023.
[5] **Pravilnika o uslovima i normativima za projektovanje stambenih zgrada i stanova**, Sl. Glasnik RS, br. 58/2012, 74/2015 i 82/2015.
[6] Stamm-Teske Walter, Fischer Katja, Haag Tobias: **Raumpilot Wohnen**, Kraemerverlag, Wüstenrot Stiftung, Ludwigsburg, 2012.
[7] Nojfert Ernst, **Arhitektonsko projektovanje**, Građevinska knjiga, Novi Sad, 2003.
[8] Nestorović Bogdan: **Stambene zgrade: Osnovi projektovanja**, Univerzitet u Beogradu, Naučna knjiga, 1962.
[9] Duarte Carlos C., Cortiços Nuno D., Stefańska Anna, Stefańska Aneta: **Home Balconies during the COVID-19 Pandemic: Future Architect's Preferences in Lisbon and Warsaw**. *Applied Sciences*, Vol. 13, No. 1, 298, 2023. https://doi.org/10.3390/app13010298
[10] Peters Terri, Masoudinejad Sepideh: **Balconies as adaptable spaces in apartment housing**. *Buildings and Cities*, 3(1), pp. 265–278, 2022. https://doi.org/10.5334/bc.191
[11] Jovanović Goran: **Uvod u arhitektonsko projektovanje**, Građevinsko-arhitektonski fakultet Univerziteta u Nišu, AGM Knjiga, 2015.
[12] Ilić Dušan: **Projektovanje stambenih zgrada 1, Organizacija stana**, Univerzitet u Nišu, 1991.
[13] Smektała Marta, Baborska-Narozny Magdalena: **The use of apartment balconies: context, design and social norms**. *Buildings and Cities*, 3(1), pp. 134–152, 2022. https://doi.org/10.5334/bc.193
[14] **Verordnung zur Berechnung der Wohnfläche (Wohnflächenverordnung - WoFlV),** https://www.gesetze-im-internet.de/woflv/BJNR234610003.html, accessed 30th April 2025.

doi.org/10.62683/SINARG2025.024

Research paper

A METHODOLOGICAL FRAMEWORK FOR INTEGRATED LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST OF PASSIVE ENERGY RENOVATION OF RESIDENTIAL BUILDINGS IN SERBIA

Bojana Lević[1], Ljiljana Đukanović[2]

Abstract

This paper develops a methodological framework for the integrated assessment of life cycle assessment (LCA) and life cycle costs (LCC) in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia. The proposed framework enables a systematic selection of building materials and components for energy renovation, taking into account both the environmental footprint and the total costs over the life cycle of the building after renovation. The methodological framework consists of seven steps. The first step involves calculating the operational energy of the existing building, analyzing the total energy consumption required for the building's functionality, including heating, cooling, ventilation, lighting, and electrical appliances. Next, passive energy renovation scenarios are defined, and various material and assembly proposals for improving energy efficiency are formulated. The next step involves calculating the embodied energy for each renovation scenario, considering the energy required for material extraction, production, transportation, installation, maintenance, and recycling. This is followed by a simulation-based calculation of operational energy for each renovation scenario and the determination of potential energy savings. Subsequently, the environmental impact of materials is evaluated through a life cycle assessment of selected materials and assemblies. In parallel with the life cycle assessment, a life cycle cost analysis is conducted to assess the long-term economic aspects of energy renovation from the moment of renovation until the end of the building's life cycle. Finally, the results are integrated to support optimal decision-making by analyzing all previous steps to determine the best material choices for achieving both environmentally and economically sustainable energy renovation. The aim of this research is to provide an applicable framework for assessing the environmental impacts and life cycle costs of a building from the renovation phase to the end of its life cycle, facilitating the advancement of sustainable energy renovation strategies for multi-family residential buildings.

Key words: *Energy renovation, methodological framework, life cycle assessment (LCA), life cycle cost (LCC), operational energy, embodied energy*

[1] MSc, Teaching Assistant, University of Belgrade – Faculty of Architecture, Department of Architectural Technologies, bojana.levic@arh.bg.ac.rs, ORCID 0000-0002-6431-4979
[2] PhD, Associate Professor, University of Belgrade – Faculty of Architecture, Department of Architectural Technologies, djuli@arh.bg.ac.rs, ORCID 0000-0002-5431-7308

1. INTRODUCTION

The construction sector is the largest energy consumer in Europe, being responsible for 40% of total energy consumption and 36% of greenhouse gas emissions, while 75% of existing buildings are energy inefficient, and it is estimated that 85–90% of these buildings will still exist in 2050 [1]. The renovation of the existing housing stock is a key factor in meeting the targets set by the European Commission for the period up to 2050 through the European Green Deal strategy [2]. This ambitious strategy, adopted in 2019, relies on the Energy Efficiency Directive (DIRECTIVE (EU) 2018/844) and the Energy Performance of Buildings Directive (EPBD (EU) 2024/1275) as legislative frameworks for reducing energy consumption and greenhouse gas emissions, with an emphasis on achieving climate neutrality across the entire economy by no later than 2050 [3].

With the implementation of the "Fit for 55" legislative package developed to support these strategies, which requires a reduction of net greenhouse gas emissions by at least 55% compared to 1990 levels by 2030, and the decarbonization of the building stock by 2050 [4], the targets are no longer limited to reducing emissions caused by the operational energy of buildings—i.e., the energy required for their functioning—but are instead oriented toward the entire life cycle of buildings, encompassing both embodied and operational energy throughout the building's life span. In addition, the revised Energy Performance of Buildings Directive promotes the assessment of life cycle performance during building renovation [3]. The Directive emphasizes that life cycle performance assessment should be an integral part of both new construction and the renovation of existing buildings, requiring the inclusion of policies to reduce emissions throughout the entire life cycle in national building renovation plans of EU Member States.

Moreover, the Directive expects EU Member States to define minimum requirements for the energy performance of buildings and building elements, taking into account the achievement of an optimal balance between investment and energy savings over the life cycle of the building [3].

Although Serbia is not an EU member state, it has committed to the Green Agenda for the Western Balkans, which extends the EU Renovation Wave to the Western Balkans [5]. Based on Serbia's membership in the Energy Community, a Long-Term Strategy for Promoting Investment in the Renovation of the National Building Stock of the Republic of Serbia until 2050 has been adopted, aiming to define measures for building renovation [6]. The strategy promotes the energy renovation of residential and commercial buildings, with a focus on major renovation, to reduce primary and final energy consumption. According to the current Rulebook on Energy Efficiency of Buildings in Serbia, major renovation is defined as adaptation or rehabilitation works whose value amounts to at least 25% of the value of the building with land, or if at least 25% of the building envelope is subject to energy refurbishment [7].

According to research conducted during 2011 and 2012 as part of the project for the classification of multi-family residential buildings in Serbia, which was aligned with the methodology of the international TABULA project, it was determined that the multi-family residential stock in Serbia has poor energy performance. The research results indicate a pronounced need for the implementation of energy refurbishment measures to reduce operational energy consumption in this significant segment of the building stock, as well as to improve overall energy efficiency in the residential sector [8].

2. METHODOLOGY

The methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia comprises seven steps (Fig. 1).

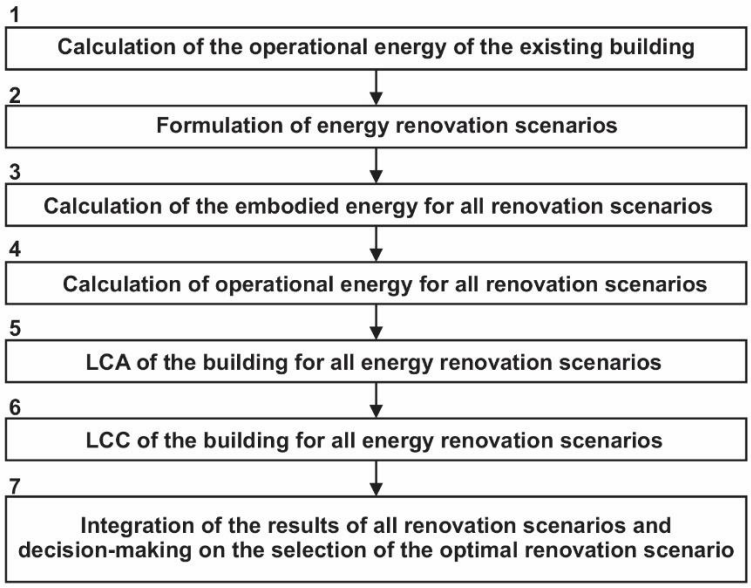


Figure 1. Diagram of the methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the decision-making process for passive energy renovation of buildings

2.1. LCA assessment in the context of building energy renovation

Life cycle assessment (LCA) is a structured, comprehensive, and internationally standardized method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle [9]. In the context of building energy renovation, LCA enables the identification and quantification of environmental burdens associated with the production of construction materials, transportation, installation, use and maintenance of systems, as well as the demolition and disposal phases. By applying this method, it is possible to objectively assess the contribution of various energy efficiency strategies to the reduction of greenhouse gas emissions, primary energy consumption, resource depletion, and other relevant environmental indicators.

The international standards ISO 14040 and ISO 14044 define the fundamental methodology for conducting life cycle assessment. The LCA process includes four main phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of results [9, 10].

In the context of building energy renovation, the goal of the assessment is to evaluate the life cycle of a building after renovation. This analysis involves assessing the life cycle of all materials applied during the renovation, which constitute the inventory (LCI). The environmental impact is then assessed using specific impact categories. For building impact assessment in Europe, the CML impact assessment methodology is applied, as prescribed by European standards EN 15978 and EN 15804.

When defining the subject of the LCA, it is necessary to consider the function of the product—which, in this case, is a multi-family residential building—the functional unit, the structure of the product system, and the system boundaries. The functional unit is the basic measure of performance that the product should achieve. In the case of building energy renovation, the most commonly used functional unit is one square meter of heated floor area.

For building life cycle assessment, the system boundaries of the building life cycle are defined by standard EN 15804 and include the life cycle stages illustrated in Figure 2 [11].

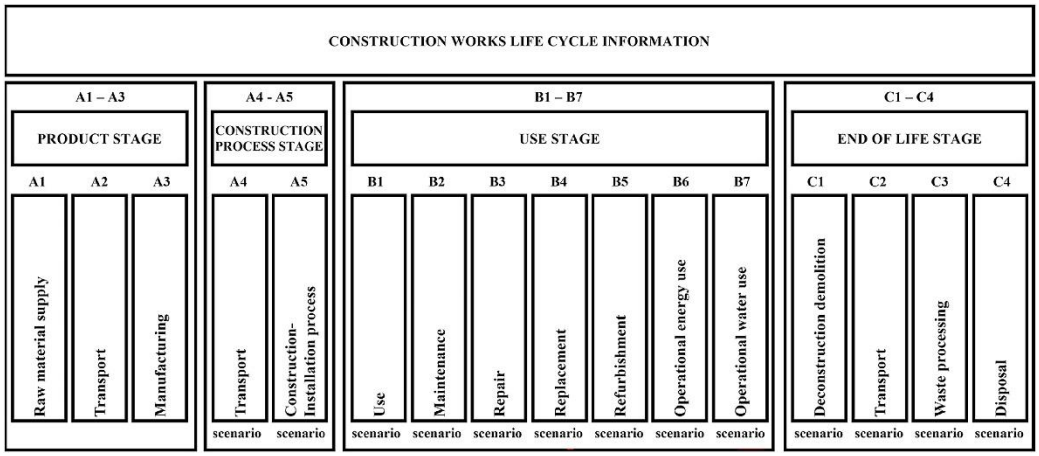


Figure 2. Life cycle stages and modules according to EN 15804 [11]

Modules A1–A3 are referred to as the **Product Stage**, also known as "cradle to gate." This stage includes all impacts associated with raw material extraction (A1), transportation of raw materials to the factory (A2), and the manufacturing of construction products (A3).

Modules A4–A5 represent the **Construction Process Stage** and cover all impacts related to the transportation of materials to the construction site (A4) and on-site activities associated with installation, including waste generation and its disposal (A5).

Modules B1–B7 comprise the **Use Stage**, which includes all impacts associated with the use of the building throughout its life cycle (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7).

Modules C1–C4 represent the **End-of-Life Stage**, which includes the deconstruction and demolition of the building (C1), impacts from transportation to waste processing facilities (C2), waste processing for reuse and recycling (C3), and final disposal (C4) [11].

2.2. LCC assessment in the context of building energy renovation

Life Cycle Cost Analysis (LCC) is a method for assessing the total costs of a building, taking into account all expenses—from raw material extraction, transportation of raw materials to manufacturing facilities, production of building materials, transportation of materials, construction of the building, usage, to its demolition. LCCA is particularly useful when comparing design alternatives that meet the same performance criteria but differ in initial and operational costs, in order to select the option that maximizes net savings. LCCA should be conducted early in the design process, while changes can still be made to reduce life cycle costs [12].

Over the years, numerous economic evaluation methods associated with LCC have emerged. Commonly used methods include: Simple Payback Period (SPP), Discounted

Payback Period (DPP), Equivalent Annual Cost (EAC), Internal Rate of Return (IRR), Net Savings (NS), and Net Present Value (NPV) [13]. Among these, ISO 15686-5, the standard for life cycle costing of buildings, recommends the use of the Net Present Value (NPV) method. NPV represents the difference between the present value (PV) of future cash flows generated by an investment and the initial investment cost. It is calculated based on a fixed standard discount rate over the assessment period, typically 5%. The PV reflects the value of cash flows generated at one or more points in time, expressed in today's terms. In other words, it is the value of future funds discounted to the present using a defined interest rate. If the cash flow occurs in the future, the calculation accounts for the time value of money by discounting it. Calculating PV enables comparative analysis of cash flows occurring at different times.The NPV method is widely used to evaluate the profitability or level of return of an investment project and is a commonly applied tool for project valuation. The viability of an investment idea is determined by calculating the NPV of the project. If the result is positive, the project is financially viable. If negative, the project is not financially viable. When multiple options exist within an investment project, the NPV should be calculated for each alternative with the same initial investment, and their results compared. Generally, the investor should select the option with the highest NPV, as it represents the most valuable investment from a financial standpoint [12, 13].

There are many different costs associated with the construction, use, maintenance, and demolition of a building. These costs are usually categorized as follows: initial costs (construction costs), operating costs, maintenance and repair costs, replacement costs, and demolition costs. Only those costs within each category that are relevant to the decision and significant in amount are necessary for making a valid investment decision. Costs are relevant if they differ between alternatives, and significant if they are large enough to impact the project's total LCC. All costs are entered in today's prices; the LCCA method accounts for their escalation to the year of occurrence and then discounts them back to the base year to obtain their present value [12].

3. RESULTS

The following text presents the methodological framework for integrated Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) evaluation in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia. The framework comprises seven steps, with each step explained in more detail according to the established methodology.

1. Calculation of the operational energy of the existing building

The first step corresponds to module B1 and involves calculating the total operational energy consumption of the existing building. Operational energy refers to the energy required for the functionality of a residential building, including heating, cooling, ventilation, domestic hot water preparation, lighting, and the operation of electrical appliances. According to current energy efficiency regulations for buildings in Serbia, only heating energy consumption is considered when determining a building's energy class [7]. This limitation arises from the lack of developed tools for calculating total operational energy. Although heating energy accounts for the largest share of operational consumption, other types of energy use must not be neglected. For more reliable and comprehensive assessments, it is recommended to

calculate the total operational energy using building energy simulation software, such as EnergyPlus.

2. Formulation of energy renovation scenarios

The formulation of energy renovation scenarios represents the second step in the integrated assessment process. In this step, variants for improving the building's thermal envelope are created in accordance with the characteristics of its individual components, as presented in Table 1.

Table 1. Criteria for determining the significance and potential for improving the thermal envelope positions

No.	Criterion	Impact Description
1	Surface area of the envelope position	Larger surfaces have a greater impact on total energy losses.
2	Degree of transmission heat loss	High U-values indicate significant thermal losses.
3	Position of the element (external/internal)	External elements are in direct contact with outdoor conditions.
4	Condition and deterioration level	Deteriorated components require urgent and more extensive renovation.
5	Impact on indoor comfort and living quality	Direct influence on thermal comfort, acoustic insulation, indoor air quality, and occupant satisfaction.
6	Potential for integration of additional energy systems (e.g., photovoltaics panels, ventilated facades)	Increases overall sustainability of the building, especially when combined with passive and active systems.
7	Type of element (transparent/opaque)	Transparent elements have specific characteristics and contribute to solar gains.
8	Spatial availability for additional insulation	Limited space may constrain the choice of material or insulation thickness.
9	Possibility for phased implementation	Enables more flexible and cost-efficient renovation strategies.
10	Orientation of the envelope position	North-facing elements have higher losses; south-facing can contribute to passive solar gains.
11	Cultural protection status	Limits the scope of interventions and requires specific conservation-compliant solutions.
12	Accessibility for renovation works	Hard-to-reach areas increase the complexity and cost of construction works.

Based on the identification of elements of the thermal envelope with the greatest potential for improvement, the formulation of energy renovation scenarios is approached. In this phase, renovation variants are defined, and the selection of appropriate materials and technologies for renovation is carried out. The key issue becomes the selection of materials

and the criteria according to which the selection is made. The choice of materials for energy renovation must include multiple criteria listed in Table 2.

Table 2. Criteria for the selection of materials and products for energy renovations

No.	Criterion	Impact Description
1	Thermal conductivity (λ-value)	Lower values indicate better insulation and reduced heat loss.
2	Thermal mass / heat storage capacity	Higher capacity contributes to thermal stability of indoor environments.
3	Vapor permeability	Important for preventing condensation and maintaining hygrothermal comfort.
4	Resistance to moisture, mold, and biological agents	Improves durability and reduces health risks.
5	Fire resistance	Material must meet fire safety standards.
6	Material lifespan	Longer lifespan reduces the need for replacement and overall impacts.
7	Origin of material (natural / synthetic)	Natural materials often have lower environmental impact but differing performance.
8	Local availability	Reduces transport emissions and costs.
9	Material cost	Directly affects the financial feasibility of renovation scenarios.
10	Ease of installation and disassembly	Enables fast installation, lower labor costs, and potential reuse.
11	Recyclability and reusability	Determines end-of-life impacts and waste generation.
12	Impact on indoor environmental quality (e.g., VOC emissions)	Important for occupant health and indoor air quality.
13	Compatibility with cultural heritage protection	Material must be aligned with conservation requirements.
14	Compliance with standards and regulations	Necessary for legal application and potential subsidies.

It is recommended to form several clearly differentiated variants of renovation scenarios in order to precisely identify which option offers the optimal balance between ecological sustainability and economic feasibility through the subsequent phases of analysis, including life cycle assessment (LCA) and life cycle cost (LCC) evaluation.

3. Calculation of the embodied energy for all renovation scenarios

This step analyzes the energy footprint associated with the production and implementation of materials before the building begins functioning. The embodied energy analysis is carried out through a systematic series of steps that quantify the energy expended

during the entire production and installation process of materials proposed for the energy renovation scenarios. The first step in this analysis is the identification and quantification of all construction materials and products used in each renovation scenario, achieved by preparing a detailed bill of quantities. For each building component, the material type, thickness, density, unit measure, and total quantity are precisely defined. Next, for each material, the specific embodied energy data (measured in MJ/kg, MJ/m², or MJ/m³) is taken from relevant databases (e.g., Ecoinvent[3]), which includes the energy expended for raw material extraction (module A1), transport and processing (A2), production (A3), transportation to the construction site (A4), and installation (A5). The total embodied energy for a given material is calculated by multiplying its specific value by the quantity of material intended for each scenario.

If specific materials have a shorter lifespan than the overall time horizon of the analysis, their replacement is planned under module B4, and the additional energy consumption is included in the overall balance for that scenario. All data is then summed by scenario and compared to identify those scenarios with the lowest total embodied energy.

4. Calculation of operational energy for all renovation scenarios

This step of the methodological framework concerns the calculation of operational energy for all renovation scenarios, estimating the amount of energy needed for the building's operation over its useful life after renovation. This analysis includes energy consumption for heating, cooling, ventilation, domestic hot water preparation, lighting, and electrical devices. In contrast to the initial estimate of operational energy for the existing state (step 1), energy simulations are carried out for each defined improvement scenario, allowing for a precise prediction of the effects of proposed solutions on the building's future energy efficiency. Simulations are performed using validated software tools for modeling building energy performance, such as DesignBuilder, EnergyPlus, or other BIM-based tools integrated with energy modules. The building model is updated according to each individual scenario—in terms of thermal properties of the envelope, types and thicknesses of insulation materials, window and door quality, and any additional passive measures. Furthermore, the data input includes local climate conditions, building usage profiles, heating and cooling regimes, and technical system characteristics.

In this phase, the predicted consumption of primary and final energy for each energy use is quantified and expressed in kWh/m² per year. The results allow for the comparison of scenarios in terms of operational energy consumption reduction and overall contribution to the building's energy efficiency.

5. LCA of the building for all energy renovation scenarios

This step involves the life cycle assessment of the building after the simulated renovation, in accordance with the defined renovation scenarios. This analysis corresponds to the full scope of the LCA methodology "from cradle to grave," as it includes the assessment of the entire life cycle of the materials used in the renovation, as well as the building itself, from the point of renovation to the end of its life cycle.

This step includes a life cycle inventory (LCI) analysis, which quantifies all materials and products proposed in the renovation scenarios. An environmental impact assessment (LCIA) is then performed for the phases of material production, transportation, and installation (modules A1–A5). Special attention is given to evaluating the durability of the selected

[3] Ecoinvent v3 is an LCI database with global spatial coverage regionalized by country or continent.

materials. If the lifespan of a proposed material is shorter than the projected lifespan of the renovated building, its replacement during the usage phase (module B4) within the analyzed time horizon should be considered. This ensures a realistic and representative depiction of potential impacts throughout the entire exploitation period.

Additionally, the end of life for the applied materials and the entire building (modules C1–C4) is analyzed. This phase is particularly complex because it encompasses all materials and components installed in the building, representing the most comprehensive segment of the LCA analysis.

The environmental impact assessment is carried out according to the CML impact assessment methodology, which includes thirteen environmental impact categories, such as global warming, ozone depletion, and resource depletion [14].

The LCA analysis is performed using a bill of quantities with material quantities, so all applied materials are standardized to a common unit—kilogram.

6. LCC of the building for all energy renovation scenarios

The life cycle cost (LCC) evaluation of the building is the fourth step of the methodological framework and directly follows the previous LCA analysis. The net present value (NPV) method is used in this phase, which involves discounting all future costs to the current time to /material prices, on the final results.

The LCC analysis includes all costs arising during the building's life cycle. Investment costs encompass the procurement and installation of building materials and systems specified for each energy renovation scenario, as well as transportation, construction works, site organization, and all associated design, supervision, and logistics costs. Furthermore, the analysis takes into account usage and maintenance costs, including periodic repairs and potential replacement of components with a shorter lifespan than the overall analyzed period. In this regard, it is crucial to account for material replacements if their durability does not cover the entire designed lifespan of the building, which is calculated as an additional future cost in the LCC analysis under module B4.

The analysis also includes operational costs, primarily energy costs, which are estimated based on the energy consumption simulation results for each renovation scenario. This quantifies the long-term savings each scenario offers, directly affecting the return on investment. If data is available, end-of-life costs—such as deconstruction, transportation, recycling, or disposal of materials—can also be included, providing a more complete economic picture.

The analysis is performed for a period of ten years, which is a common horizon for assessing the profitability of energy renovations, particularly from an investment decision-making perspective. Within this period, the payback period of initial investments is determined, comparing scenarios and identifying the one that offers the fastest or most favorable financial effect relative to its ecological contribution.

7. Integration of the results of all renovation scenarios and decision-making on the selection of the optimal renovation scenario

This step consolidates the data obtained through the life cycle assessment (LCA), life cycle cost (LCC) analysis, and embodied and operational energy calculations. The results are compared to identify the variant that offers the best balance between ecological sustainability, economic feasibility, and technical justification. The decision on the optimal scenario is made based on an integrated approach that involves evaluating and weighting various indicators according to predefined decision-making criteria.

4. DISCUSSION

The development of a methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the context of passive energy renovation of multi-family residential buildings in Serbia raises important questions about the complexity of the decision-making process, which must simultaneously consider the ecological, economic, and technical aspects of renovation. In Serbia, practice still largely relies on simple energy efficiency indicators, limited mainly to heating energy consumption. Therefore, the significance of this work is crucial as it highlights the need to expand the analytical framework to include other forms of energy consumption, as well as the impacts of materials and processes across all life cycle stages. Unlike many EU countries, where building sustainability assessments are increasingly based on frameworks like Level(s) [15] and the Renovation Wave initiative [16], Serbia still lacks fully developed tools to assess environmental and economic performance throughout a building's life cycle. In addition to these well-known frameworks, many European research and innovation projects have played an important role in improving methods and adding both LCA and LCC into building assessments. Projects like ENSLIC – Building (a pilot project under Intelligent Energy Europe), SuPerBuildings, and OPEN HOUSE have made significant contributions by creating metrics, indicators, and comprehensive models that consider the entire life cycle [17]. The results of these projects have helped develop new standardized tools and methods that are now widely used in many EU countries. While EU countries are moving towards flexible assessment methods that include circularity metrics, Serbia still mainly focuses on traditional energy performance improvements. This difference highlights the need to adapt international methods to the local context while aligning more with the EU's broader sustainability goals.

The implementation of the proposed methodological framework faces challenges such as the availability and reliability of data for both LCA and LCC analyses. At the national level, there is still no developed system of databases for construction materials with local environmental indicators, which forces the analysis to rely on international databases (such as Ecoinvent) that do not fully reflect the local context. Additionally, accurate cost prediction in LCC analysis requires stable and regularly updated data on market prices of materials, energy, and labor, which, under conditions of economic instability, presents an additional obstacle. Despite these challenges, the methodological framework developed in this paper has the potential to become the foundation for more rational planning and implementation of energy renovations, enabling decision-making based on quantitative assessments that lead to sustainable and long-term cost-effective solutions. Furthermore, future research is needed to further validate the framework through concrete case studies. It is important to emphasize that the methodological framework presented in this paper should not be seen as a static model, but as a dynamic tool that can be developed and improved in accordance with advances in technology, standards, and societal demands.

5. CONCLUSIONS

This paper develops a methodological framework for the integrated assessment of life cycle analysis (LCA) and life cycle cost (LCC) as a support tool for the decision-making process in the field of passive energy renovation of multi-family residential buildings in Serbia.

The proposed framework provides a systematic approach to evaluating the environmental and economic performance of different renovation scenarios, considering both operational and embodied energy, as well as all life cycle stages—from the production and installation of materials to their maintenance, replacement, and disposal.

Through seven steps, the framework enables the precise identification of the optimal renovation scenario that achieves the best balance between reducing environmental impact, lowering operational costs, ensuring technical feasibility, and ensuring long-term sustainability. The application of this methodological framework can contribute to improving energy efficiency strategies at the building level and can also serve as a tool for enhancing public policies related to energy renovation, investment planning, and the promotion of sustainable construction. Additionally, such an approach enables more rational decision-making, thereby increasing the likelihood of implementing energy renovations that are both environmentally justified and economically sustainable. In this way, it contributes to the development of a more resilient, energy-efficient, and climate-responsible existing housing stock in Serbia.

REFERENCES

[1] European Union: **Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.** *Official Journal of the European Union*, L 156, 75–91, 2018, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L0844

[2] European Commission: **The European Green Deal**. 2024, https://ec.europa.eu/commission/presscorner/api/files/attachment/879954/3%20European%20Green%20Deal.pdf

[3] European Union: **Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast).** *Official Journal of the European Union,* L 202, 1–64, 2024*,* https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

[4] European Commission: **Commission welcomes completion of key 'Fit for 55' legislation, putting EU on track to exceed 2030 targets**, 2022, https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_4754/IP_23_4754_EN.pdf

[5] Regional Cooperation Council: **Sofia Declaration on the Green Agenda for the Western Balkans**, 2020, https://www.rcc.int/files/user/docs/196c92cf0534f629d43c460079809b20.pdf

[6] Ministry of Construction, Transport and Infrastructure of the Republic of Serbia: **Long-Term Strategy to Promote Investment in the Renovation of the National Building Stock of the Republic of Serbia until 2050***, Official Gazette of the RS*, No.27/2022-5, 2022. https://pravno-informacioni-sistem.rs/eli/rep/sgrs/vlada/strategija/2022/27/1/reg

[7] Ministry of Construction, Transport and Infrastructure of the Republic of Serbia: **Rulebook on the Energy Efficiency of Buildings,** *Official Gazette of the RS*, No.61/2011, 2011. https://www.paragraf.rs/propisi/pravilnik_o_energetskoj_efikasnosti_zgrada.html

[8] Jovanović Popović Milica, Ignjatović Dušan, Radivojević Ana, Rajčić Aleksandar, Đukanović Ljiljana, Ćuković Ignjatović Nataša, Nedić Miloš: **Atlas of Multi-Family Buildings in Serbia.** *Faculty of Architecture, University of Belgrade*,

Belgrade, 2013. http://eeplatforma.arh.bg.ac.rs/publikacije/atlas-vi%C5%A1eporodi%C4%8Dnih-zgrada-srbije

[9] International standard **ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework.** Edition 2, 2006. https://www.iso.org/standard/37456.html

[10] International standard **ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines.** Edition 1, 2006. https://www.iso.org/standard/38498.html

[11] **BS EN 15804:2012+A2:2019** Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products.

[12] https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca (25.4.2025.)

[13] Hao Xie, Qiao Cui, Yang Li: **Net Present Value Method: A Method Recommended by ISO 15686-5 for Economic Evaluation of Building Life Cycle Costs**. *World Journal of Engineering and Technology*, Vol.10 No.2, 2022. DOI: 10.4236/wjet.2022.102013

[14] European Commission: **ILCD Handbook: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessmen**. First edition, European Commission Joint Research Centre Institute for Environment and Sustainability, 2010. https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf

[15] https://green-forum.ec.europa.eu/levels_en *(13.5.2025.)*

[16] European Commission: **Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives.** COM/2020/662 final. 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0662

[17] Gervasio, H. and Dimova, S.: **Model for Life Cycle Assessment (LCA) of buildings**. *Publications Office of the European Union*, 2018, https://data.europa.eu/doi/10.2760/10016

doi.org/10.62683/SINARG2025.025

Research paper

OPTIMIZING BUILDING SUSTAINABILITY: A LIFE-CYCLE CO_2 EMISSIONS ASSESSMENT OF NOVEL AND CONVENTIONAL INSULATION WALL MATERIALS

Hamed Afsoosbiria[1,2], Hesam Afsoosbiria[3], Agnieszka Machowska[4]

Abstract

The growing concern over climate change has intensified the need to control greenhouse gas emissions, particularly in the building sector. A significant portion of a building's environmental impact arises during its operational phase, primarily due to energy consumption for heating and cooling. Insulation wall materials play a crucial role in enhancing energy efficiency by reducing heat transfer, thereby lowering energy demand and long-term carbon emissions. However, the selection of insulation materials is often driven by technical performance, with limited consideration of their full life-cycle impact.

This study adopts a Life Cycle Assessment (LCA) approach to evaluate the environmental performance of various insulation materials, comparing their embodied carbon, thermal properties, and overall contribution to sustainability. By analyzing both conventional and emerging solutions, the research aims to provide quantitative insights that assist in selecting materials that balance energy efficiency, durability, and environmental impact. The findings will contribute to informed decision-making in sustainable construction, supporting efforts to minimize the carbon footprint of buildings while maintaining optimal thermal performance.

Key words: *Sustainable Construction, Environmental Impact, Life Cycle Assessment (LCA), Low-Carbon Buildings, Thermal Envelope.*

[1] MSc. Eng. Hamed Afsoosbiria, Doctoral study, VSB-TU Ostrava, Faculty of Civil Engineering, e-mail: hamed.afsoosbiria@vsb.cz, Czech Republic, ORCID: 0000-0002-7210-6379.
[2] Faculty of Civil Engineering, Warsaw University of Technology, 00-637 Warsaw, Poland; hamed.afsoosbiria.stud@pw.edu.pl, Poland, ORCID: 0000-0002-7210-6379.
[3] MSc. Eng. Hesam Afsoosbiria, Doctoral study, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: hesam.afsoosbiria.dokt@pw.edu.pl, Poland, ORCID: 0000-0002-9408-6073.
[4] DSc, PhD. Eng. Agnieszka Machowska, university professor, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: agnieszka.machowska@pw.edu.pl, Poland, ORCID: 0000-0002-3573-6822.

1. INTRODUCTION

The building sector is regarded as one of the largest energy consumers worldwide. Consequently, insulation plays a crucial role in reducing the energy consumption of this sector [1]. The energy consumption of a building strongly depends on the characteristics of its envelope [2]. The envelope is recognized as a key component in enhancing thermal efficiency, as it accounts for between 50% and 60% of the total heat transfer [3]. The thermal performance of external walls illustrates a key factor in increasing the energy efficiency of the building sector and reducing greenhouse gas emissions. Thermal insulation is definitely one of the most effective methods to reduce energy consumption due to both winter heating and summer cooling [2]. The choice of suitable insulation materials is one of the fundamental methods for reducing a building's energy consumption. The thermal performance of insulating materials can directly influence the shape of the building's energy consumption and effectively minimize heat transfer from building envelopes, both internally and externally, helping in the provision of more desired indoor thermal comfort for residents [4]. Materials for building insulation, with proposed solutions, can be categorized as either traditional or state-of-the-art. The most widely used, conventionally available low-thermal-conductive building insulation materials are cellulose, cork, EPS, polyurethane, and XPS [5]. Insulation materials in the construction industry are essential to enhancing the thermal performance of buildings, reducing energy demands, and carbon emissions. In transitioning to a low-carbon economy, building renovations can significantly enhance energy Europe, deep renovation of the EU's existing stock (110 million buildings) and new construction could result in 80% of cumulative energy savings by 2050. The EU's need for insulation materials has increased to reduce energy consumption, and this trend is expected to continue [6]. As new constructions are characterized by reduced operational energy use, more attention should be paid to the Global Warming Potential (GWP) of building materials and systems.

Life Cycle Assessment (LCA) is one of the most effective strategies for monitoring environmental consequences throughout the life cycle and calculating carbon footprints. It is a tool that is increasingly being used in various areas of the construction sector to evaluate impacts on ecosystems, natural resources, and human health by using a standardized approach to model, assess, and quantify the impacts of a product or process over a complete time horizon extended to the useful life of products [7]. By analyzing both novel and conventional options, this study intends to provide quantitative insights that will help in the choice of materials that balance energy efficiency, durability, and environmental impact. The findings will assist in influencing decision-making in sustainable design, supporting attempts to reduce buildings' carbon footprint while maintaining optimal thermal performance.

2. INSULATION BUILDING MATERIALS AND THEIR CONTRIBUTION TO SUSTAINABILITY

Thermal insulation systems and materials are designed to lessen heat flow transmission. The thermal insulation performance of individual or combined homogeneous materials is generally determined by thermal conductivity and thermal transmittance [8]. The insulation of the external envelopes constructs the main stage in ensuring the energy efficiency of a building. There are many alternatives available for insulation materials [9]. The performance of thermal insulation of the building's vertical walls can be considered as an investment for

economic objectives. This investment, however, has a notable impact on the environment. On the one hand, there must be some costs incurred, associated with production, transport, and location of thermal insulation. On the other hand, during the use of the building phase, there is a depletion in energy demand for heating [10,11]. The most important parameters that state the thermal performance of an insulation material are the thermal conductivity λ (W/mK) for the steady state and the thermal diffusivity D for the unsteady state [2]. A material is mainly considered a thermal insulator if its conductivity is lower than 0.07 W/mK [8]. Thermal conduction, also known as U-Value, and the development of requirements for the U-Value [W/(m^2·K)] of walls from 1962 to 2024 is shown in Figure 1 [12]. The choice of insulation materials is important both for the construction of new buildings and retrofitting, i.e., throughout the operational phase of the building. There exists a variety of insulation materials exhibiting different properties [13].

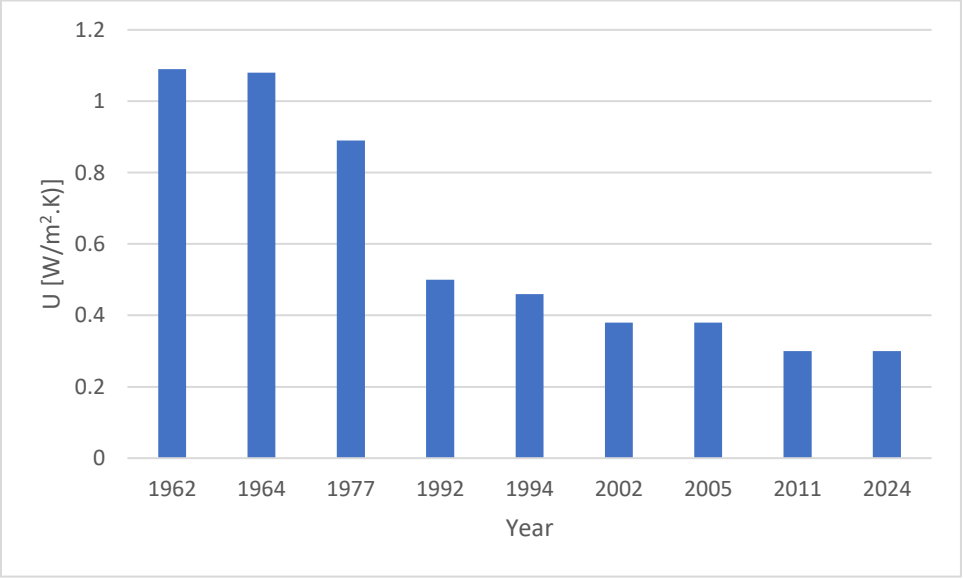


Figure 1. Development of requirements for the heat transfer coefficient of walls (bar chart elaborated based on [12]).

In recent decades, the sustainable development of the planet has been negatively influenced by several factors, including the building industry. Further, demands for energy savings have increased [14]. Accordingly, the European Union's significant objectives for 2030 and 2050 imply that energy measures, climate neutrality, CO_2 decline, and emphasis on the Green Deal [15] strongly emphasize the construction industry [14]. As there is a growing awareness of the environmental impact of building materials. This has given rise to the development of more sustainable building products that attempt to decrease embodied carbon emissions, lessen reliance on non-renewable resources, and improve indoor environmental quality [16]. The building sector is considered one of the key consumers of energy, where the major usage accounts for the heating and cooling of the building. Energy consumption could be reduced using novel insulation strategies, and the building would be energy-efficient in this scenario as it would need less heating in winter and less cooling in summer to maintain the desired internal temperature [1,17]. A well-insulated home will assist

in reducing energy use and, in turn, the consumption of fossil fuels and the production of carbon emissions. Enhancing a home's energy efficiency, through better insulation, for example, can lessen its carbon footprint.

2.1. Classification of Wall Insulation Building Materials

Insulation has a critical function in improving environmental sustainability. It is an essential element in reducing the consumption of energy, limiting carbon dioxide release, and supporting the overall goal of creating a more sustainable future for our planet. These materials can be categorized based on their function, specifically directed at insulation materials for walls in the EU. This categorization eases a comparative analysis of novel (innovative) and common (traditional) materials, allowing a more effective evaluation of their performance and properties. Table 1 presents different Thermal Insulation groups for residential buildings and their features. Here, the insulation material is divided into 4 types, namely Bio-Based (Organic), Mineral-Based (Inorganic), Petrochemical (Organic Chemistry), and Advanced materials. In addition, 18 kinds of wall insulation materials are assessed.

Table 1. Characteristics of different types of insulation materials

Thermal Insulation Category	Type	Thermal Conductivity (W/m. K)	Density kg/m^3	EC ($kgCO_2e/kg$)
Bio-Based (Organic)	WW	0.070	180	0.98
	WF	0.038	160	0.124
	HF	0.038– 0.060	20– 90	0.14
	C	0.04– 0.050	80– 115	1.156
Mineral-Based (Inorganic)	GW	0.031– 0.037	13– 100	1.533
	RW	0.029– 0.042	40– 200	1.050 *
	F	0.030– 0.050	10– 100	1.350 *
	P	0.040– 0.055	139– 166	0.520
	V	0.04– 0.064	64– 130	0.520
	FG	0.038– 0.045	100–120	1.565
Petrochemical (Organic Chemistry)	EPS	0.031– 0.038	15– 35	4.205– 7.3
	XPS	0.032– 0.037	32– 40	5.84–7.55
	PUR	0.022– 0.046	30– 100	4.260
	PIR	0.018– 0.028	30– 45	3.089 *
	PF	0.018– 0.024	40– 160	4.15–7.21
Advanced materials	VIP	0.0035– 0.008	160– 230	8.551
	A	0.015– 0.028	150– 220	4.200
	CR	0.044	60	0.367

Sources: created based on [2, 4, 5, 18- 35].

WW: Wood Wool, **WF**: Wood Fiberboard, **HF**: Hemp Fiber, **C**: Cork, **GW**: Glass Wool, **RW**: Rock Wool, **F**: Fiberglass, **P**: Perlite, **V**: Vermiculite, **FG**: Foam Glass, **EPS**: Expanded Polystyrene, **XPS**: Extruded Polystyrene, **PUR**: Polyurethane foam, **PIR**: Polyisocyanurate, **PF**: Phenolic Foam, **VIP**: Vacuum Insulation Panels, **A**: Aerogel. **CR**: Cellulose-recycled. **EC**: Embodied Carbon, ***:** only Carbon.

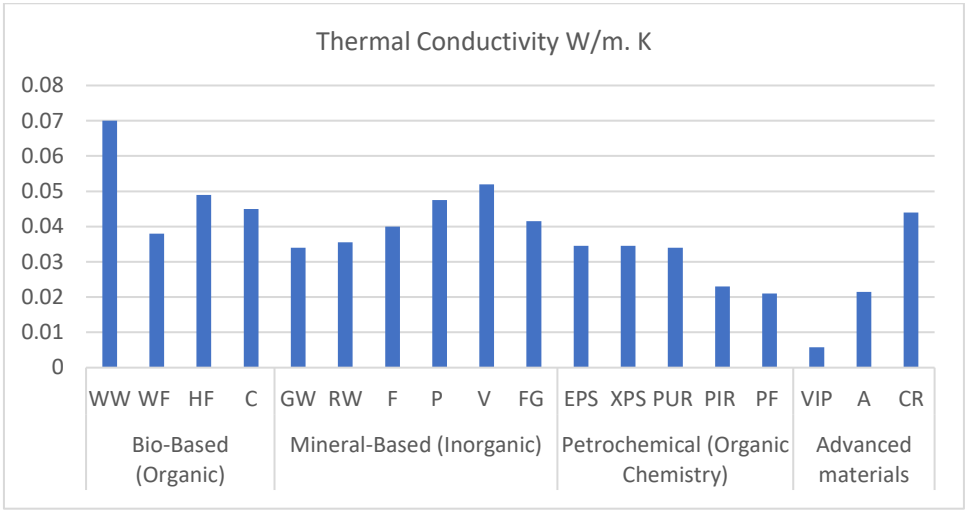


Figure 2. Comparative thermal conductivity overview of various thermal insulation materials

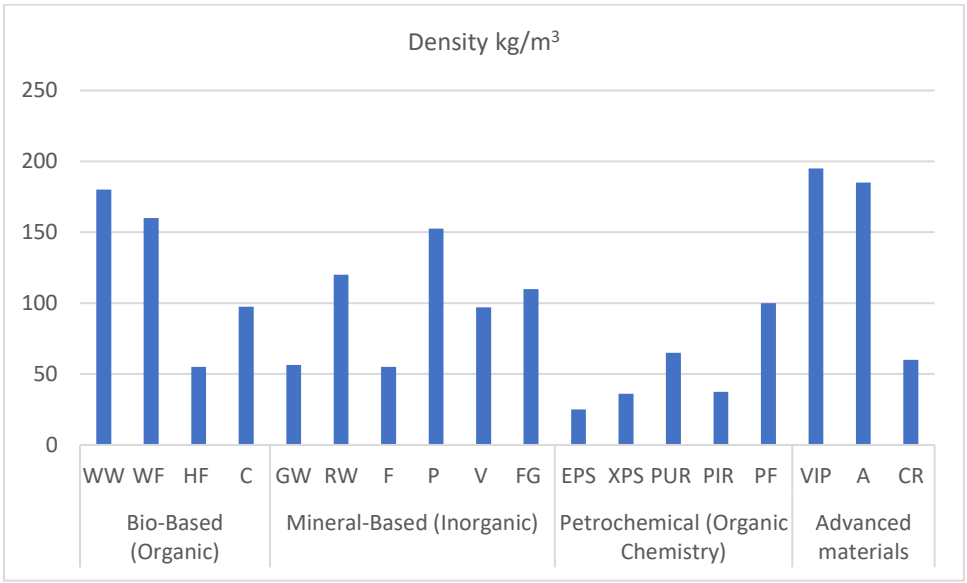


Figure 3. Comparative density overview of various thermal insulation materials

Bar charts in Figures 2 and 3 provide a comparative investigation of numerous thermal insulation materials classified into Bio-Based (Organic), Mineral-Based (Inorganic), Petrochemical (Organic Chemistry), and Advanced Materials. Each material is specified by its thermal conductivity (W/m·K) and density (kg/m³), which are key properties for evaluating insulation performance. Furthermore, many sources and databases [2, 4, 5, 18- 35] have been used to prepare Table 1, and given that numerous ranges are provided for different materials and these ranges seem logical, the average values of each material have been used to prepare the bar charts.

Lower values of thermal conductivity (λ) indicate less heat transfer. In this regard, Vacuum Insulation Panels (VIP), as an advanced material with λ = 0.0035–0.008 W/m·K, are the best performers, followed by Aerogel (A), Phenolic Foam (PF), and Polyisocyanurate (PIR), with λ = 0.015–0.028 W/m·K. Advanced and petrochemical insulation materials offer highly effective solutions with the potential to greatly enhance the thermal insulation performance of building walls.

In terms of density, the petrochemical categories indicate a lower average density. For instance, EPS has a density of 25 kg/m³, XPS has 36 kg/m³, and PIR has 37.5 kg/m³. Additionally, some bio-based and mineral-based categories, like GW and F, have an average density of 55 kg/m³. However, it is important to note that mineral-based (inorganic) insulation materials exhibit higher heat conductivity compared to petrochemical (organic) options. Generally, petrochemical insulation materials have lower mean heat conductivity and density compared to bio-based and mineral-based materials. However, the average heat conductivity of advanced insulation materials may be lower than that of petrochemical insulation, although they tend to have higher density than petrochemical materials. In addition, further investigation into the required thickness of materials is needed to meet building energy efficiency requirements for specific project conditions and regional contexts. For instance, reference [

12] suggests different walls using aerogel and EPS that based on wall design, walls using aerogel had lower thickness compared to walls designed using EPS, and also both walls had approximately the same weight, so it is important to consider all aspects for designing energy-efficient walls.

3. LIFE-CYCLE CO_2 EMISSIONS ASSESSMENT

Life cycle assessment (LCA) is a tool used to estimate the potential environmental impacts and resources consumed throughout a product's life cycle (cradle to grave or cradle to gate), i.e., from raw material acquisition, through production, use phases, and waste management, to the recycling phase [36]. The method to do this assessment is defined in the ISO standards 14040 [37] and 14044 [38]. The life cycle center is required to assist decision-making when choosing the finest technology to hand and reduce the environmental impact of the buildings throughout their design or refurbishment [18]. Life cycle assessment should cover the definition of goal and scope, inventory analysis, impact evaluation, and explanation of results, as painted in Figure 4 [37].

This research applies a Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) methodology to assess the embodied carbon (EC) impact of several insulation materials, following ISO 14040 and ISO 14044 standards. Python is used to efficiently examine, rank, and visualize the results.

A comparative bar chart in Figure 5 shows the Environmental Impact of thermal insulation materials based on type and embodied carbon (kg CO_2e/kg) for each category. In addition, the Python output for the Cradle-to-Gate (A1–A3) LCA approach to analyzing insulation materials' environmental impact is shown in Figure 6.

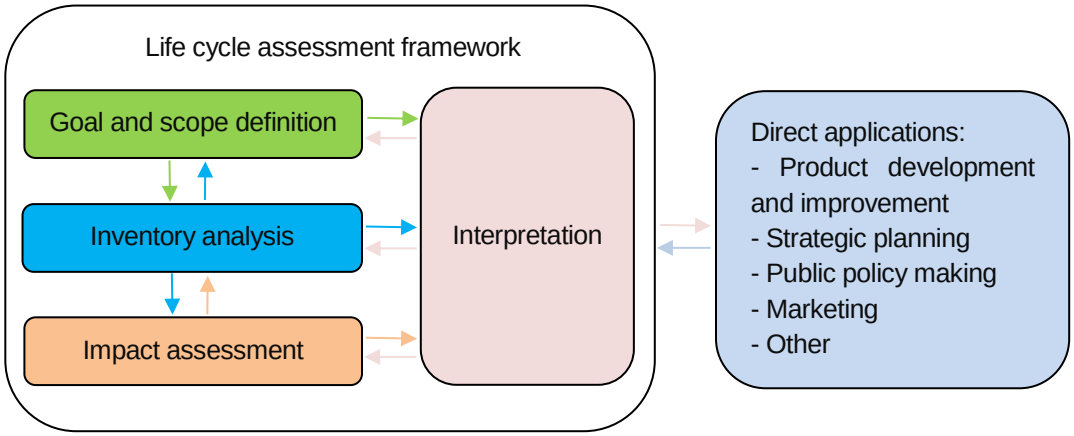


Figure 4. Phases of a Life Cycle Assessment (figure elaborated based on [37]).

Thermal insulation plays a vital function in decreasing a building's operational energy demand, but the embodied carbon (EC) related to insulation materials is increasingly urgent for evaluating their full life-cycle environmental consequence. Figure 5 shows the average EC (kg CO_2e/kg) values for commonly used insulation wall materials and highlights their role in sustainable construction.

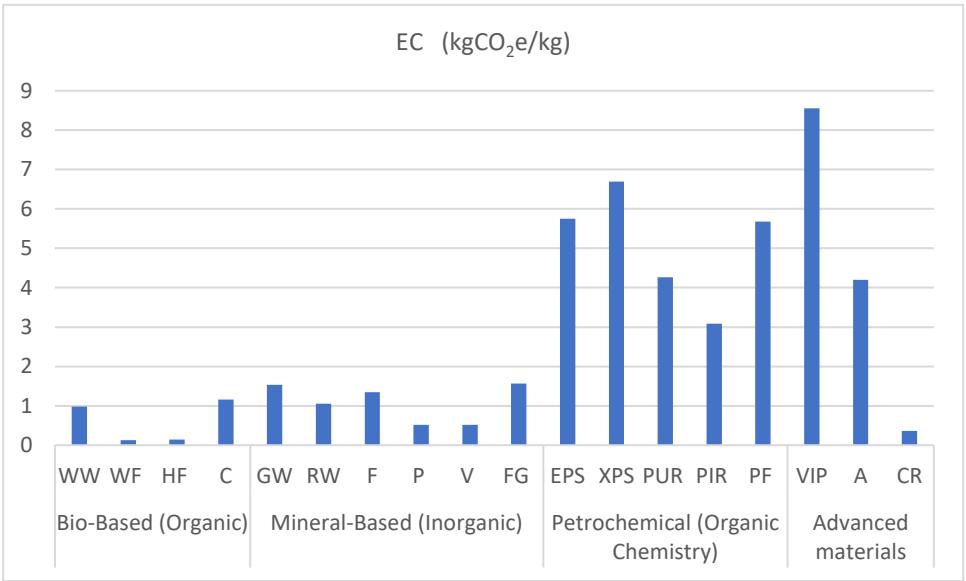


Figure 5. Embodied Carbon (kg CO_2e/kg) of various thermal insulation materials based on different categories.

In a time where the buildings in Europe are in charge of 40% of total energy consumption and 36% of greenhouse gas (GHG) emissions [39], improving insulation and optimizing wall and roof thickness not only reduce energy consumption by up to 40% [12], but also selecting suitable insulation with low embodied carbon is an effective step toward climate-resilient, regenerative buildings. Although most advanced and petrochemical insulation materials offer

lower thermal conductivity than the other groups, except CR (Cellulose-recycled), which has low Embodied Carbon, the rest of the advanced and petrochemical categories leave a larger carbon footprint.

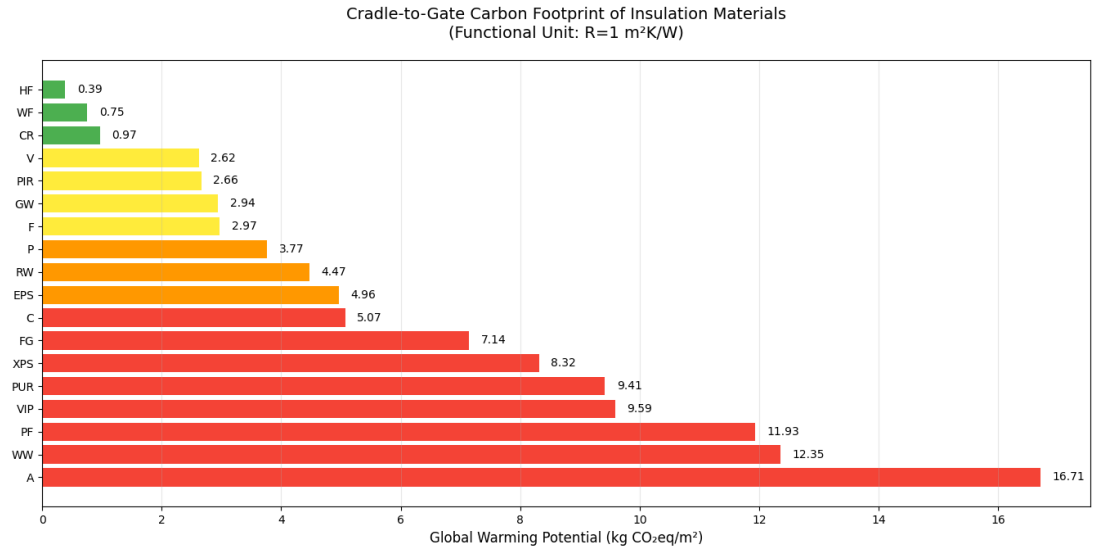


Figure 6. Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various insulation materials using Python.

To ensure a fair comparison, the thickness of each insulation material was calculated based on achieving a thermal resistance of R = 1 m²K/W using $d = R \times \lambda$. This thickness was then used to calculate the material mass per square meter and, subsequently, the GWP (kg CO_2e/m²), based on the embodied carbon per unit mass of each material [2]. Figure 6 shows the comparative analysis of Global Warming Potential (kg CO_2eq/m²) for various insulation materials in the building envelope per unit area (m²) to achieve the requirements of thermal resistance (R=1 m²K/W). The graph visualizes GWP (kg CO_2eq/m²) values, clearly indicating that HF (Hemp Fiber), WF (Wood Fiberboard) from bio-based categories have lower carbon with GWP of 0.39 and 0.75 (kg CO_2eq/m²) respectively, and CR (Cellulose-recycled) from advanced groups has GWP of 0.97 (kg CO_2eq/m²), which means these materials offer GWP less than 1 kg CO_2eq/m² and are shown with green colors which have low carbon on environment. Furthermore, in this study, the medium carbon footprint is categorized between 2-3 kg CO_2eq/m², denoted by a yellow color, where V, PIR, GW, and F are placed in this group. Moreover, insulation materials like P, RW, and EPS are specified with orange colors, indicating a high carbon footprint of 3-5 kg CO_2eq/m². Finally, the insulation materials with the worst environmental impact, characterized by a very high carbon footprint (more than 5 kg CO_2eq/m²), are highlighted in red. 8 types of insulation material are placed in this group which 5 out of 8 are from advanced or petrochemical classification, and it shows that using high-tech for manufacturing these materials offers extreme thermal performance, but their manufacturing processes are energy-intensive, involving high GHG emissions.

4. CONCLUSIONS

European building stock was largely constructed in the 20th century and is characterized by high energy demands. The selection of appropriate insulation materials is one of the essential ways for reducing a building's energy consumption. In this study, by investigating different insulation options for the wall provide quantitative insights that will assist in the choice of materials that balance energy efficiency and environmental impact. The findings will assist in influencing decision-making in sustainable design, supporting attempts to reduce buildings' carbon footprint while maintaining optimal thermal performance.

The results show that the Vacuum Insulation Panels, as an advanced material with λ = 0.0035–0.008 W/m·K, are the best performers, followed by Aerogel, Phenolic Foam, and Polyisocyanurate, with λ = 0.015–0.028 W/m·K. Advanced and petrochemical insulation materials suggest highly effective solutions with the potential to greatly enhance the thermal insulation performance of building walls.

In terms of density, the petrochemical (Organic Chemistry) classification indicates a lower average density. However, the average heat conductivity of advanced insulation materials may be lower than that of petrochemical insulation, although they tend to have higher density than petrochemical materials.

Comparative analysis of the environmental impacts of various insulation materials shows that Hemp Fiber, Wood Fiberboard from bio-based categories have lower carbon with GWP of 0.39 and 0.75 (kg CO_2eq/m²) respectively, and Cellulose-recycled from advanced groups has GWP of 0.97 (kgCO_2eq/m²). The insulation materials, such as Cork, Foam Glass, Extruded Polystyrene, Polyurethane foam, Vacuum Insulation, Phenolic Foam, Wood Wool, and Aerogel, have a GWP of more than 5 (kg CO_2eq/m²).

REFERENCES

[1] Ali, A., Issa, A., & Elshaer, A.: **A Comprehensive Review and Recent Trends in Thermal Insulation Materials for Energy Conservation in Buildings**. *Sustainability*, 16(20), 8782, 2024, https://doi.org/10.3390/su16208782.

[2] Schiavoni, S., D'Alessandro, F., Bianchi, F. & Asdrubali, F.: **Insulation materials for the building sector: A review and comparative analysis**. *Renewable and Sustainable Energy Reviews*, 62, pp. 988–1011, 2016, Available at: https://doi.org/10.1016/j.rser.2016.05.045.

[3] Marín-Calvo N, González-Serrud S, and James-Rivas A.: **Thermal insulation material produced from recycled materials for building applications: cellulose and rice husk-based material**. *Front. Built Environ*. 9:1271317, 2023, doi: 10.3389/fbuil.2023.1271317.

[4] Dong, Y., Kong, J., Mousavi, S., Rismanchi, B., & Yap, P.-S.: **Wall Insulation Materials in Different Climate Zones: A Review on Challenges and Opportunities of Available Alternatives**. *Thermo*, *3*(1), 38-65, 2023, https://doi.org/10.3390/thermo3010003.

[5] Okokpujie, I.P., Essien, V., Ikumapayi, O.M., Nnochiri, E.S., Okokpujie, K. and Akinlabi, E.T.: **An overview of thermal insulation material for sustainable engineering building application**. *International Journal of Design & Nature and Ecodynamics*, 17(6), pp. 831–841, 2022, Available at: http://iieta.org/journals/ijdne.

[6] Lu, Z., Hauschild, M., Ottosen, L.M., Ambaye, T.G., Zerbino, P., Aloini, D., and Lima, A.T.: **Climate mitigation potential of biobased insulation materials: A comprehensive review and categorization**. *Journal of Cleaner Production*, 470, p. 143356, 2024, Available at: https://doi.org/10.1016/j.jclepro.2024.143356.

[7] Violano, A., & Cannaviello, M.: **The Carbon Footprint of Thermal Insulation: The Added Value of Circular Models Using Recycled Textile Waste**. *Energies*, 16(19), 6768, 2023, https://doi.org/10.3390/en16196768.

[8] Asdrubali, F., D'Alessandro, F. & Schiavoni, S.: **A review of unconventional sustainable building insulation materials**. *Sustainable Materials and Technologies*, 4, pp. 1-17, 2015, Available at: https://doi.org/10.1016/j.susmat.2015.05.002.

[9] Streimikiene, D., Skulskis, V., Balezentis, T. and Agnusdei, G.P.: **Uncertain multi-criteria sustainability assessment of green building insulation materials**. Energy and Buildings, 219, 110021, 2020, Available at: https://doi.org/10.1016/j.enbuild.2020.110021.

[10] Adamczyk, J. and Dylewski, R.: **The impact of thermal insulation investments on sustainability in the construction sector**. *Renewable and Sustainable Energy Reviews*, 80, pp. 421-429, 2017, Available at: https://doi.org/10.1016/j.rser.2017.05.173.

[11] Pavel, C. and Blagoeva, D.: **Competitive landscape of the EU's insulation materials industry for energy-efficient buildings**. EUR 28816 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-96383-4, Available at: doi:10.2760/750646, JRC108692.

[12] Afsoosbiria, H., Kubečková, D., Musenda, O. K., & Mohamed, K.: **Variability of Material Solutions for the Perimeter Walls of Buildings in Post-Industrial Settlements as Part of Energy Rehabilitation and Achieving Carbon Neutrality**. Energies, 17(24), 6236, 2024, https://doi.org/10.3390/en17246236.

[13] Aditya, L., Mahlia, T.I., Rismanchi, B., Ng, H.M., Hasan, M.H., Metselaar, H.S.C., Muraza, O., and Aditiya, H.B.: **A review on insulation materials for energy conservation in buildings**. *Renewable and sustainable energy reviews*, 73, pp.1352-1365, 2017.

[14] Kubečková, D., Kubenková, K., Afsoosbiria, H., Musenda, O. K., & Mohamed, K.: **External Thermal Insulation Composite Systems—Past and Future in a Sustainable Urban Environment**. *Sustainability*, 16(19), 8500, 2024, https://doi.org/10.3390/su16198500.

[15] **Delivering the European Green Deal (Fit for 55)**. 2021. Available online: http://energy.ec.europa.eu (accessed on 28 July 2024).

[16] Platt, S.L., Walker, P., Maskell, D., Shea, A., Bacoup, F., Mahieu, A., Zmamou, H. and Gattin, R.: **Sustainable bio & waste resources for thermal insulation of buildings**. Construction and Building Materials, 366, 130030, 2023, Available at: https://doi.org/10.1016/j.conbuildmat.2022.130030.

[17] Jaouaf, S., Bensaad, B., Habib, M.: **Passive Strategies for Energy-Efficient Educational Facilities: Insights from a Mediterranean Primary School**. *Energy Rep.* 2024, 11, 3653–3683.

[18] Zabalza Bribián, I., Valero Capilla, A., and Aranda Usón, A.: **Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential**. *Building and Environment*, 46, pp. 1133-1140, 2011, Available at: https://doi.org/10.1016/j.buildenv.2010.12.002.

[19] Grazieschi, G., Asdrubali, F. and Thomass, G.: **Embodied energy and carbon of building insulating materials: A critical review**. *Cleaner Environmental Systems*, 2, p. 100032, 2021, Available at: https://doi.org/10.1016/j.cesys.2021.100032.

[20] Dickson, T. and Pavía, S.: **Energy performance, environmental impact and cost of a range of insulation materials**. *Renewable and Sustainable Energy Reviews*, 140, p. 110752, 2021, Available at: https://doi.org/10.1016/j.rser.2021.110752.

[21] Lafond, C., & Blanchet, P.: **Technical Performance Overview of Bio-Based Insulation Materials Compared to Expanded Polystyrene**. *Buildings*, *10*(5), 81, 2020, https://doi.org/10.3390/buildings10050081.

[22] Kumar, D., Alam, M., Zou, P.X.W., Sanjayan, J.G.: Memon, R.A. **Comparative Analysis of Building Insulation Material Properties and Performance.** *Renew. Sustain. Energy Rev. 2020*, *131*, 110038. Available at: https://doi.org/10.1016/j.rser.2020.110038

[23] Raja, P., Murugan, V., Ravichandran, S., Behera, L., Mensah, R.A., Mani, S., Kasi, A., Balasubramanian, K.B.N., Sas, G., Vahabi, H. and Das, O.: **A review of sustainable bio-based insulation materials for energy-efficient buildings**. *Macromolecular Materials and Engineering*, 2023, Available at: https://doi.org/10.1002/mame.202300086.

[24] **Wood Fibre Board (n.d.)** ***Wood fibre board catalogue***. Available at: https://www.woodfibreboard.com/wood-fibre-board-catalogue.html (Accessed: [3/27/2025]).

[25] Papadopoulos, A.M.: **State of the art in thermal insulation materials and aims for future developments**. *Energy and buildings*, *37*(1), pp.77-86, 2005.

[26] Sinka, M., Bajare, D., Gendelis, S. and Jakovics, A.: **In-situ measurements of hemp-lime insulation materials for energy efficiency improvement**. *Energy Procedia*, *147*, pp.242-248, 2018.

[27] Kosiński P, Brzyski P, Szewczyk A, Motacki W.: **Thermal properties of raw hemp fiber as a loose-fill insulation material. Journal of Natural Fibers**. 2018 Sep 3;15(5):717-30.

[28] Hammond, G. P., and C. I. Jones.: **Embodied energy and carbon in construction materials**. *Proc. Instn Civil. Engrs: Energy*, 2008, in press.

[29] G. Hammond, C. Jones.: **Bath Inventory of Carbon and Energy (ICE) database**, version 4.

[30] Hammond, G. and Jones, C.: **Embodied carbon: The Inventory of Carbon and Energy (ICE)**. Edited by F. Lowrie and P. Tse, 2011. BSRIA and University of Bath.

[31] Kuni, R.: **Carbon footprint of thermal insulation materials in building envelopes.** *Energy Efficiency*, 10, pp. 1511-1528, 2017. Available at: https://doi.org/10.1007/s12053-017-9536-1.

[32] Hammond, G. and Jones, C.: **Inventory of Carbon & Energy (ICE), Version 2.0: Summary Tables. Sustainable Energy Research Team (SERT)**. *Department of Mechanical Engineering*, 2011, University of Bath.

[33] Perlite Institute. **Perlite: The most sustainable insulation solution for buildings**. 2023.

[34] Luksta, I., Bohvalovs, G., Bazbauers, G., Spalvins, K., Blumberga, A., and Blumberga, D.: **Production of renewable insulation material – new business model of bioeconomy for clean energy transition**. *Environmental and Climate Technologies*, 25(1), pp. 1061–1074, 2021. Available at: https://doi.org/10.2478/rtuect-2021-0080.

[35] Violano, A., & Cannaviello, M.: **The Carbon Footprint of Thermal Insulation: The Added Value of Circular Models Using Recycled Textile Waste**. Energies, 16(19), 6768. https://doi.org/10.3390/en16196768.

[36] Liu, M., Zhu, G. and Tian, Y.: **The historical evolution and research trends of life cycle assessment, Green Carbon**. 2(4), pp. 425–437, 2024. Available at: https://doi.org/10.1016/j.greenca.204.08.003.

[37] **International Organization for Standardization, ISO 14040: 2006.** *Environmental management– Life cycle assessment– principles and framework*.

[38] **International Organization for Standardization, ISO 14044: 2006.** *Environmental management– life cycle assessment– requirements and guidelines.*

[39] Afsoosbiria, H.: **Structural Aspects of Building Conversions in Industrial Areas, Doctoral State Exam**, *Dissertation Thesis, VSB - Technical University of Ostrava*, Faculty of Civil Engineering, Department of Building Construction, 2025.

doi.org/10.62683/SINARG2025.026

Research paper

NON-DESTRUCTIVE INVESTIGATION ON HERITAGE BUILDINGS - CASE STUDY ON ST. NIKITA CHURCH

Jasna Grujoska-Kuneska[1], Veronika Shendova[2]

Abstract

Historic buildings are a significant part of the world's cultural heritage. These buildings act like a bridge that connects us to the certain time, people and culture, providing invaluable insight into our past.

The long-term exposure to different natural, biological and human factors increase the vulnerability of the heritage buildings, therefore their condition needs to be carefully considered and monitored. Knowing the condition will significantly contribute to their long-term protection; underestimating the actual condition may lead to pointless interventions and overestimating it may lead to no interventions and further damage.

This paper presents the investigation campaign carried out to one heritage building – the Byzantine church of St. Nikita near Skopje, North Macedonia. The methodology involved archival research, review of the monument's documentation and in-situ investigation using several Non-Destructive Techniques (NDTs): visual inspections, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. This integrated methodology provided information for both, historical context and current condition of the building. NDTs proved to be a useful diagnostic tool for condition assessment of the monument without affecting its authenticity, which is especially important for this type of buildings.

Key words: *Architectural Heritage, Byzantine Churches, Protection, Investigation Campaign, Non-Destructive Techniques*

[1] Dr., assistant, International Balkan University -Skopje, North Macedonia, jasna.kuneska@ibu.edu.mk, ORCID 0009-0007-7875-8136

[2] Dr., professor, Institute of Earthquake Engineering and Engineering Seismology-Skopje, North Macedonia, veronika@iziis.ukim.edu.mk, ORCID 0000-0001-7120-0315

1. INTRODUCTION

Cultural heritage is the legacy inherited from previous generations, which plays crucial role in modern societies as it connects us to the past and fosters a sense of social and collective identity [1]. The treasury of cultural heritage in North Macedonia, built over the centuries, includes numerous monuments from different historical periods, representing the rich and creative ideas of this region [2]. Among them, Byzantine churches stand out as some of the most valuable and well-preserved medieval monuments, with exceptional architectural and artistic values [3].

Heritage buildings are inevitably exposed to a range of natural, human and climatic threats, which can lead to damage or even loss of these valuable assets. Furthermore, many heritage buildings are situated in seismic-prone regions, such as in North Macedonia, which make them particularly vulnerable to the devastating effects of earthquakes [4].

Regular assessment of building's condition helps to identify any potential risks and helps to detect early signs of damage, encouraging the timely interventions and preventing further harm of the asset. In this context, the diagnostic study plays a pivotal role in the process of sustainable and long-term preservation of our tangible heritage.

In accordance with modern worldwide protocols and practices for protection of significant cultural and historical monuments, a case study was conducted, to assess the condition of a representative Byzantine monument – St. Nikita church. This integrated diagnostic study involved several phases: archival research, documentation review, assessment of existing hazards and field surveys. Particular emphasis was placed on NDTs which enabled to investigate the monument without compromising its condition or authenticity [3].

St. Nikita church is a medieval monument that reflects the features of many Byzantine churches in the county. Its selection is based on several criteria:

- Location: the church is located in Skopje region, one of the areas with the highest seismicity in the country and wider.
- Typology: the church belongs to the group domed cross-in-square plans, which is the most prevalent architectural plan found in the country.
- Authenticity: this church has maintained its high level of authenticity [3].

2. OVERVIEW OF ST. NIKITA CHURCH

2.1. Historical Background and Architectural Design

The Church of St. Nikita is a typical late Byzantine monument. From a typological perspective, it belongs to the group of domed cross-in-square churches with a five-sided apse on the eastern side (fig. 1). The external dimensions of the church are as follows: length 11.45 meters (including the apse), width 7.72 meters, and height 12.78 meters. This church is located on the western slopes of Skopska Crna Gora, in the village of Banjani, which is 15 km northwest from the city of Skopje. According to written documents (charters), it is believed that the church dates back to the early 14th century, when King Milutin (1282–1321) rebuild the church on the site of an older ruined structure from the 11th or 12th century, which was dedicated to the same saint [5].

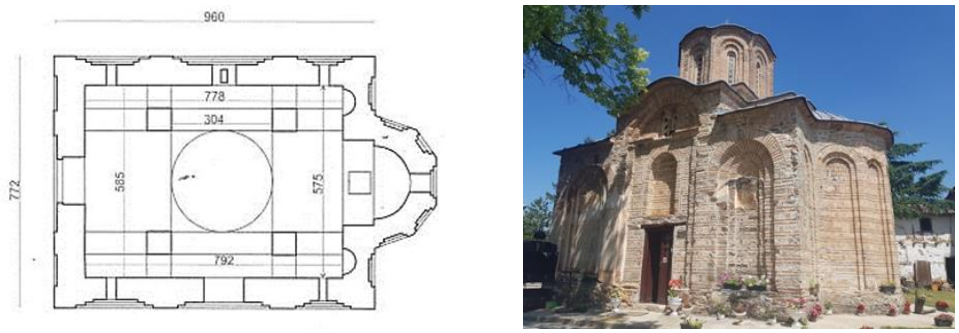


Figure 1. St. Nikita church, floor plan (left), view (right), [3][5]

The structure is built from traditional materials: local stones, bricks and lime-mortar. The structural system consists of massive peripheral walls and four interior columns that support the roof structure: central dome and vaulted elements. The additional wooden system of belts and ties contributes to the seismic performance of the building [6].

The facades of the church are playful with arches, pilasters, niches and cornices. Decorative patterns of bricks are characteristic for the apse area. Interior surfaces of the church are flat, with small perforations for windows and blind niches. These surfaces are covered with frescoes from different periods (14th, 15th and 19th centuries), which are largely preserved today.

The archival research and the review of available documentation for the church (found in NI Conservation Center - Skopje) provided information about its historical development, presented in table 1.

Table 1. Historical evolution of St. Nikita church, [5][7][8]

1307	Period of construction of the church
Ottoman period	Addition in form of small single nave structure on the south side of the church, fig. 2 (demolished in 1928)
XIX century	Reconstruction activities on the dome of the church; Addition of a closed porch along the south and west side, fig. 2, (demolished in 1928)
1963 (Skopje earthquake)	Damages in the interior of the church in form of cracks and detachments of the frescoes
1964 -	Vibrations produced by the nearby mining processes
1967	Conservation activities on the frescoes in the interior
1968	Conservation activities on the architecture
1978-80	Extensive intervention on the roof parts: reconstruction of the roof and replacement of the roof tiles with a lead sheet, fig. 3

In the 1990s, the church became the focus of research as part of the project "Seismic Strengthening, Conservation, and Repair of Byzantine Churches in Macedonia." During this time, comprehensive laboratory, field, and experimental studies were conducted on the monument using the techniques and methods available at the time [6].

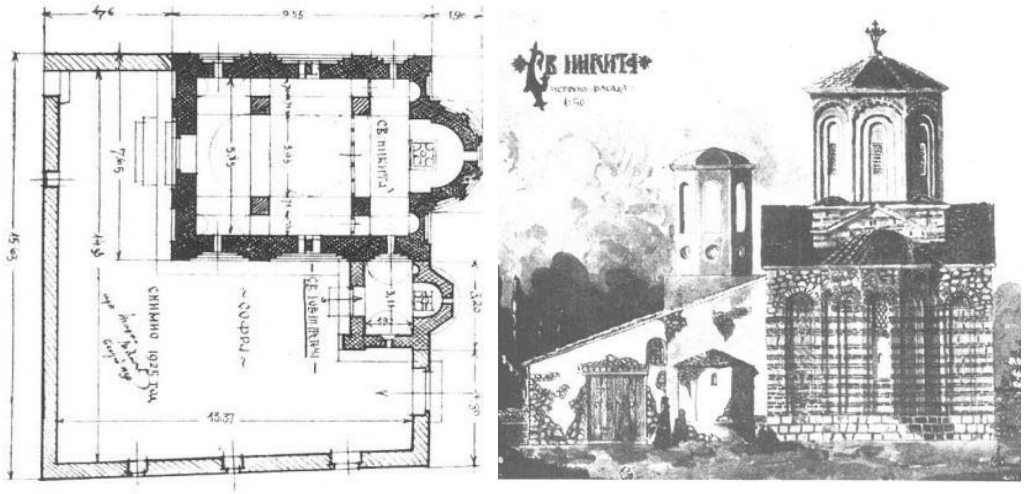


Figure 2. Later additions on St. Nikita church, floor plan (left), view (right),[5]

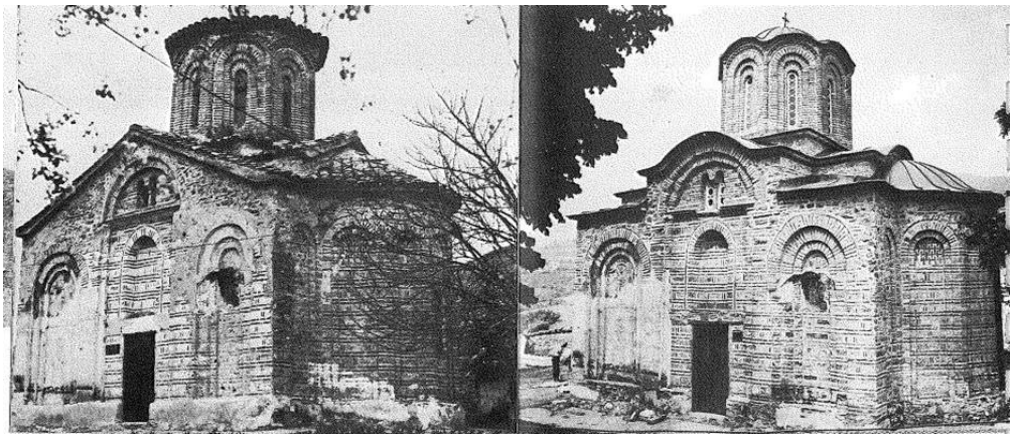


Figure 3. St. Nikita church, before (left) and after (right) the extensive intervention on the roof parts, [9]

2.2. Location: Specific Characteristics

The church is located in natural surroundings, distanced from urban infrastructure, which offers a degree of protection to the monument against pollution, urban growth, traffic –related vibrations and similar factors.

However, this area is highly susceptible to earthquakes. Since 1900, Skopje region has been affected by both nearby and distant earthquakes of varying intensity. The most destructive was the 1963 earthquake, with a magnitude of 6.1 on the Richter scale, with its epicenter located 7 km west of the city of Skopje. In the past 10 years, several earthquakes with a magnitude greater than 4 have occurred in this region, among which the 2016 earthquake was the strongest, with a magnitude of 5.1 [10].

During 1990s project [6], detailed investigations were carried out to determine the seismic characteristics of the church site: earthquake frequencies, characteristics of the macro-seismic field, spatial and temporal distribution of earthquakes, etc. It was demonstrated that the church was subjected to earthquakes with magnitudes greater than MCS 6 on numerous

occasions between 1900 and 1999. Table 2 presents the defined seismic parameters for the church of St. Nikita, specifically the maximum expected ground acceleration (a_{max}) and the expected intensities (I) for different return periods. The acceleration is presented as a combination of near earthquakes (up to 40 km) and distant earthquakes (more than 40 km).

Table 2. Maximum ground accelerations (a_{max}), corresponding return periods, and defined MCS intensities (I) for the Church of St. Nikita,[6]

St. Nikita church		Return period (years)						
		25	50	100	200	500	1000	10000
Summary effects of local and distant earthquakes	a_{max}	0.093	0.117	0.146	0.198	0.292	0.340	0.360
	I	6.73	7.06	7.36	7.82	8.38	8.60	8.68

These parameters suggests that over the course of its long history, the church of St. Nikita was most likely exposed to one or more earthquakes with the intensity of so called “design” earthquake, corresponding to a return period of 100-200 years. However, there is no indication that the church experienced a “maximum expected” earthquake with a 1000-year return period, since such an event would have caused significant damage or even structural collapse [6].

3. NON-DESTRUCTIVE INVESTIGATION OF ST. NIKITA CHURCH: METHODS AND FINDINGS

Over the past few decades, NDTs have become indispensible tool in diagnostic assessment of heritage buildings. The field survey on the church employed several NDTs: visual inspections, microscopy, infrared thermography, 3D laser scanning and ambient vibration tests. These techniques are crucial for heritage buildings since they enable to investigate the monument without causing any damage to the materials or affecting building’s authenticity [3]. The choice of techniques was primarily determined by their accessibility and applicability.

3.1. Visual Inspections Aided with Drone

The oldest and maybe the most important non-destructive technique in the field of cultural heritage is the visual inspection. This technique provides instant results regarding visible irregularities, such as cracks, signs of moisture and other critical areas of the monument. The technique is usually aided by means of optical devices and documented by photographs. However, due to its limitation to surface analysis, it is often supplemented by other techniques, [11][12].

Visual inspections were the first direct contact with the monument and served as the initial step in the in-situ diagnostic study, providing a general overview of the monument’s condition. It involved a detailed examination of the church’s facades and interior, providing immediate results regarding visible surface irregularities and damages.

During facade inspections, it was observed that the materials are generally well-preserved, showing no significant signs of degradation. However, certain irregularities were noted (fig. 4) such as: pronounced porosity of the limestone and carbonation of the lime

plaster; presence of capillary moisture in the lower zones of the northern and western walls; presence of bio-organisms (mostly lichens) in the lower and middle zones of all facades.



Figure 4. Porous limestone (left), presence of capillary moisture (center), presence of bio-organisms (right), [3]

The interior of the church is entirely plastered and painted with frescoes, which prevents any direct investigation of the condition of the underlying construction materials. Fine cracks are visible in the upper areas at several locations (fig. 5) and the most prominent is an old crack on the western wall, above the door. More substantial damage was noted on one of the wooden tie beams - the beam linking the altar area to the north-east pillar is disconnected (fig. 5).



Figure 5. Presence of damages in the upper zones of the church, fine cracks (left and middle), disruption of wooden tie (right), [3]

The use of a drone provided access to hard-to-reach areas that posed challenge during visual inspections. High-resolution aerial photographs (fig. 6) provided a detailed perspective of the church's positioning within its immediate surroundings and enabled inspection of the roof covering. It was noted that the roofing material is overall in good and well-maintained condition, except of the dome area, where some material cracking was observed (fig. 6 right), likely resulting from improper joint installation.



Figure 6. Aerial perspective of St. Nikita church, [3]

3.2. Digital Microscopy

For a more detailed analysis of the church's facade materials, a Natoli digital microscope with 40x magnification was used. This technique is cost-effective and involves a portable device, allowing for in-situ use. The microscope images (fig. 7) show presence of several types of lichens on the church's surfaces. The majority are crustose lichens, which firmly adhere to the substrate. Another type consists of lichens that group together in the form of small stones, and there are also lichens resembling moss.



Figure 7. Different types of lichens present on the facade surfaces (images from a digital microscope with 40x magnification), [3]

So far, the presence of lichens has not caused any significant damage on the facade materials (some micro cracks and color change of materials were observed). In fact, it requires long period of time for certain degradation processes to occur. Additionally, most of the lichens are tightly connected to the surface and their mechanical removal is practically impossible without damaging the underlying material.

The use of microscope also allowed observing the distinct morphological characteristics of the facade stones, with the limestone being characterized by pronounced porosity.

3.3. Infrared Thermography

Infrared thermography is an established non-destructive and non-contact technique with a wide range of applications in the field of built heritage. This technique enables to investigate large architectural surfaces, and to evaluate their condition or degree of preservation, in real time, [13]. A particularly significant advantage of the technique is the possibility to detect certain subsurface (near surface) irregularities that cannot be detected only by visual inspection of the monument. The thermal camera detect and records the infrared radiation

emitted by materials and creates a thermal image (thermograph) that shows the temperature distribution on surfaces, which can further be correlated with certain variations in material properties, morphology and microstructure of the surfaces, [12]. The limitations of this technique are related to the external conditions (sun, rain or cold) that can affect its accuracy.

For the church of St. Nikita, the infrared thermography technique enabled a real-time examination of the monument's architectural surfaces, including: evaluation of material surface condition, mapping moisture-prone areas, detecting potential subsurface anomalies, and studying the frescoes in the interior of the church. The research was conducted using an infrared camera model Testo 875-1i, with an accuracy of ± 2°C, and the data were processed using the software package IR Soft V3.4.

Figure 8 shows a segment of the masonry on the western facade of the building along with the corresponding thermal image. The thermal image displays temperature variations ranging from 16°C to 20.5°C, with the lowest temperatures observed in the stone and the highest in the bricks, due to the different thermal properties of the materials. Additionally, the surface temperatures of the stone pieces showing signs of degradation are lower compared to those with better surface conditions, which can be attributed to porosity or moisture retention. This temperature difference is approximately 1°C.

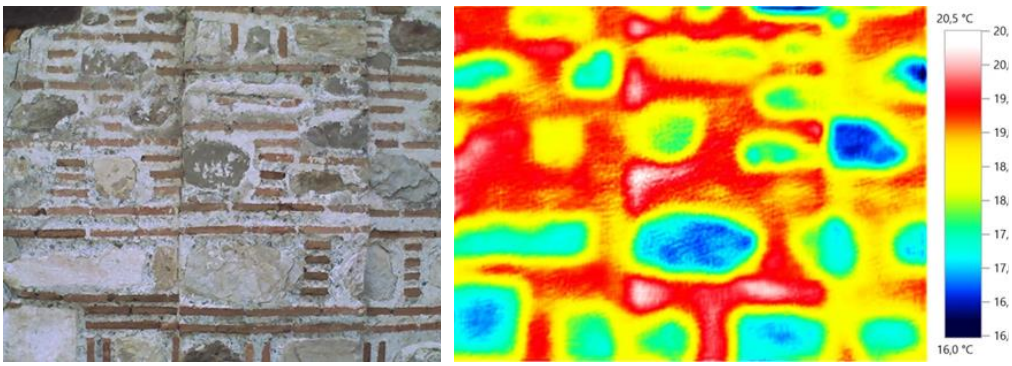


Figure 8. A segment of the masonry of St. Nikita Church (left), corresponding thermal image (right), [3]

The thermal camera enabled more accurate detection of moisture distribution within the walls. Figure 9 shows part of the northern wall (exterior side), along with the corresponding thermal image. The thermal images display irregular patterns of thermal anomalies, characteristic for moisture areas. Changes in moisture content can be correlated with surface temperature variations, and the moisture-affected areas show lower temperatures (indicated in blue color), compared to the rest of the facade's surface. It was concluded that the highest moisture levels are in the bottom of the walls, rising up to 60-80 cm.

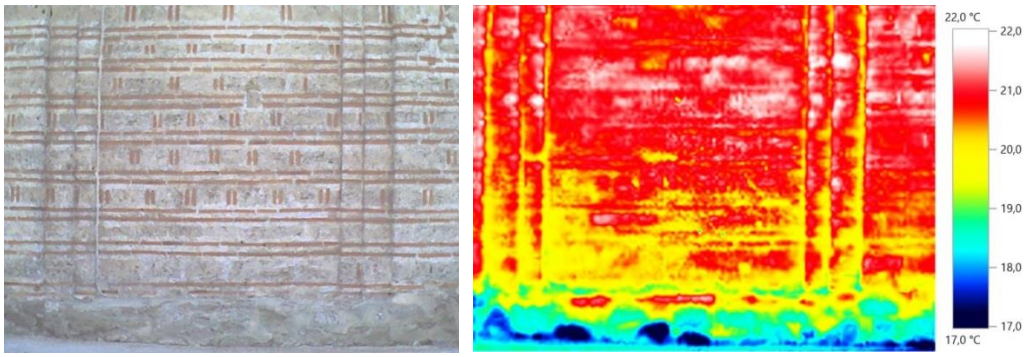


Figure 9. A segment of the northern facade of St. Nikita Church and the corresponding thermal image, [3]

The original frescoes in the interior of the church date back to the 14th century. In a later period (15th and 19th centuries), some of the damaged frescoes were partially restored, and some were repainted on a new layer of plaster, in a manner similar to the originals, making it often difficult to distinguish. The frescoes, which belong to different periods or masters, vary in composition and characteristics and have different emissive values, which can be detected on thermal camera. Figure 10 shows one composition of the southern wall, where no visible surface changes are observed. However, the thermal image of this part reveals temperature variations, precisely an area with a lower temperature (indicated by a black circle), which could suggest that part of the composition belongs to a different period.

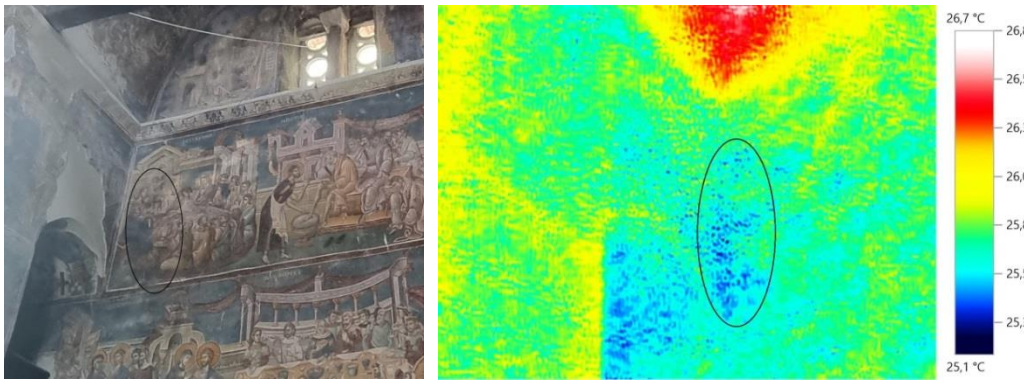


Figure 10. Fresco painting on the southern wall with corresponding thermal image, [3]

3.4. 3D Laser Scanning Technology

3D laser scanning is a non-invasive and non-destructive technology widely implemented in the field of built heritage, where it is used for surveying irregular and complex buildings [14] analysis and condition assessment, [15][16] and mainly in mapping and documenting [17][18], since it provides precise records. The limitations of this technique are related to the need for technical expertise – skills for data collection and processing.

As part of the diagnostic study of the St. Nikita church, the use of the laser scanner generated accurate digital records for the building, both in 2D and 3D, which significantly enriched the already existing documentation, which did not include this type of graphical data. The process was carried out using the Leica ScanStation P40, one of the latest scanner models, known for its exceptional accuracy and ultra-fast scanning speed of 1 million points per second. The scanner was positioned at various locations both inside and outside the

church, which combined with drone footage, provided comprehensive and highly precise definition of the building's geometry.



Figure 11. Generated 3D model of St. Nikita church [3]

The data from the 3D laser scanner generated highly accurate 3D model, i.e. digital replica of the monument, fig. 11. The accuracy of this model gives opportunity for the architects, conservators and others researchers to analyze and operate the building from different angles, at any time, regardless the real physical limitations. It also gives opportunity to measure any dimension which has significantly facilitated the creation of the mathematical model used for further structural analysis of the building. Moreover, the 3D model was imported into AutoCAD program, where two-dimensional drawings such as floor plans, sections, elevations were generated, fig. 12. With some additional processing in the program, such drawings represent important documentation for the monument.

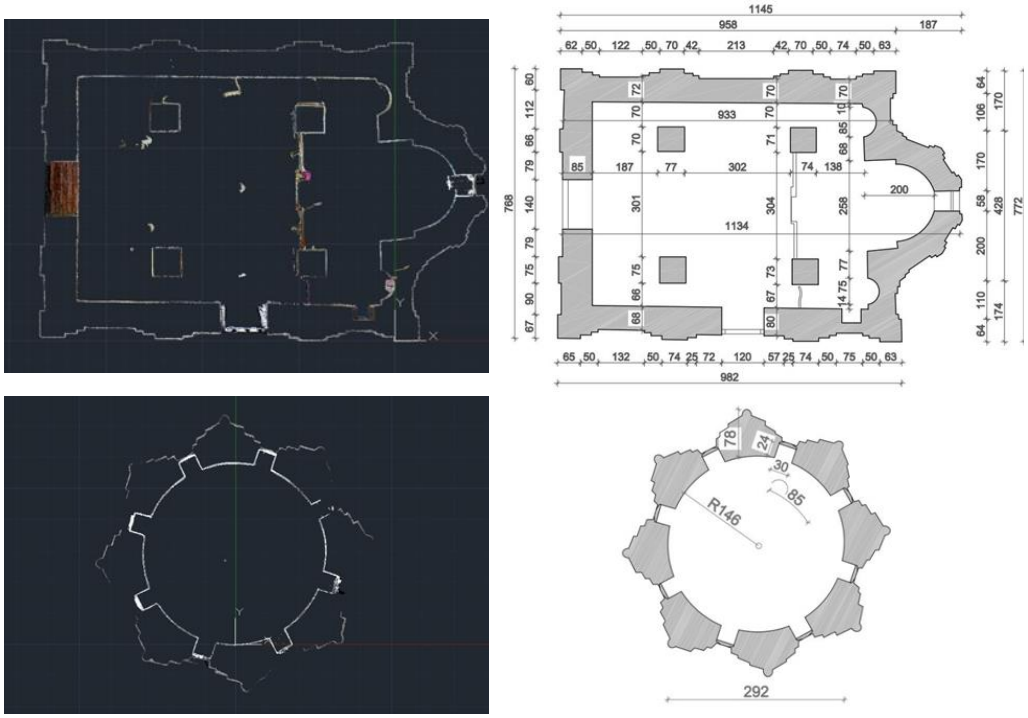
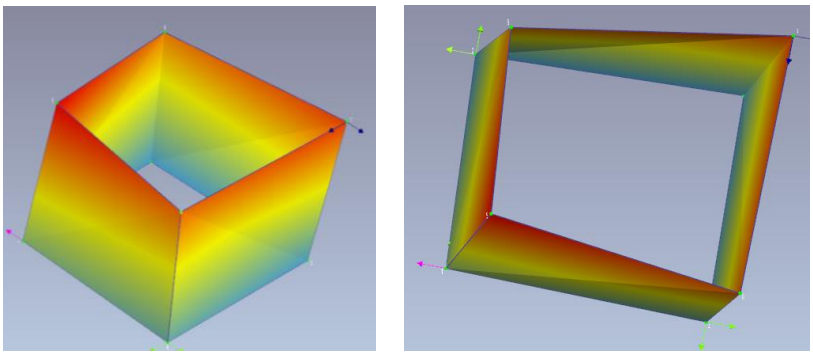


Figure 12. Floor plan of St. Nikita church - extracted from the 3D model (left) and further processed in AutoCAD (right) [3]

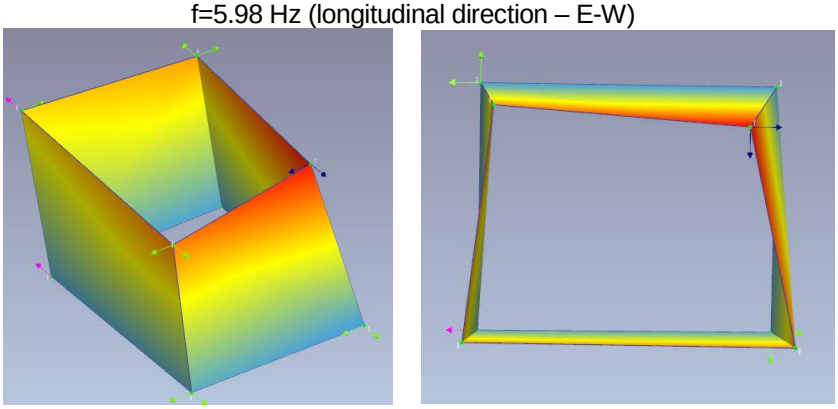
3.5. Ambient Vibration Tests

Given that dynamic parameters are related to the physical and mechanical properties of the structure (mass, stiffness, and energy dissipation), any significant structural alteration within the system will inevitably influence these parameters; therefore, the importance of their continuous monitoring, [19] .To determine the dynamic characteristics of the St. Nikita's structure (vibration periods and mode shapes) the ambient vibration method was employed. The method involves in-situ measurements of structural vibrations caused by ambient forces, such as wind, and processing of the recorded data, [20]. The advantages of this method are considerable: it offers a simple approach that does not interfere with the normal functioning of the structure, requires only a small research team, and it is both cost-effective and time-efficient. However, the sensitivity to noise can interfere with the quality of the data, which implies additional work.

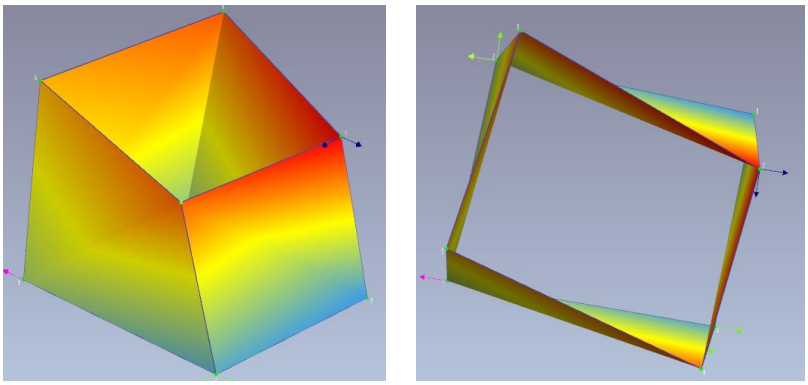
To record the vibrations, equipment comprising high-sensitivity PCB Piezotronics accelerometers, model 393B12, was utilized. These accelerometers feature a sensitivity of 10,000 mV and a measurement range of up to 4.9 m/s² (0.5g). A total of eight accelerometers were deployed, arranged across various measurement locations and orientations. A commercial software package, ARTeMIS Modal 7.0, was used for the analysis of the ambient vibration records.



f=5.98 Hz (longitudinal direction – E-W)



f=4.70 Hz (transverse direction – N-S)



f=8.05 Hz (torsion)

Figure 13. Natural frequencies and mode shapes [3]

These tests led to the identification of the natural frequencies fE-S = 5.98 Hz and fN-S = 4.70 Hz, corresponding to the natural periods TE-W = 0.167 sec and TN-S = 0.212 sec, in the two orthogonal directions, respectively. From the vibration modes, (fig. 13) it can be observed that the object, in its current state, vibrates as a single global unit. Displacements in both the longitudinal and transverse directions are generally translational, with minimal rotational movement in certain sections, more pronounced in the longitudinal direction, which is expected, given the imperfect symmetry of the plan (elongation of the altar area).

When compared with data from similar tests conducted in the 1990s ($f_{E\text{-}W}$ = 6.00 Hz and $f_{N\text{-}S}$ = 4.80 Hz) [6], which were measured using different equipment that required a longer testing time, it can be concluded that there have been no changes in the dynamic characteristics of the structure over the past 30 years.

4. CONCLUSION

Today, protection of cultural heritage goes far beyond than a simple “saving the old buildings”. It focuses on preserving their authenticity and safeguarding the material and semantic values that make each monument a unique creation of its time.

St. Nikita church is a well-preserved medieval monument, which has largely maintained its original state, despite the occasional past interventions. The church was studied in the 90s during the project "Seismic Strengthening, Conservation, and Repair of Byzantine Churches in Macedonia." The comparison between the findings from that period and current research indicated that the monument’s condition over the past three decades is practically unchanged.

The research underscores the importance of the integrated diagnostic study as a vital prerequisite and crucial factor for making well-informed decisions about sustainable and long-term monument preservation. Within its context, it highlights the importance of NDTs as essential diagnostic tool that provide valuable insight into building’s condition, without compromising its authenticity. In the study of St. Nikita Church, the application of several NDTs enabled complementary data for the monument, considering the fact that each method contributed different types of information. Visual inspections indicated on surface condition of the monument, while thermal camera pointed to some subsurface irregularities; the use of a 3D laser scanner enabled to generate precise digital documentation of the monument. The

ambient vibration method enabled to evaluate the dynamical parameters of the structure and assess its integrity.

This overall research indicates that the current condition of the monument is relatively good, with no significant damage to the architecture or structure that would pose a risk to the stability of the building. Accordingly, no immediate interventions are necessary, but regular annual monitoring of the monument is recommended.

In line with the contemporary global scientific trends, there is an increasing need to modernize existing protection protocols in North Macedonia by exploring the potential of modern technologies and integrating them into regular conservation practice.

REFERENCES

[1] Stanton-Geddes Z, Soz SA. **Promoting Disaster Resilient Cultural Heritage**. *World Bank*, Washington, 2017

[2] http://uzkn.gov.mk/mk/публикации/ (accessed April 3, 2025).

[3] Grujoska-Kuneska J. Doctoral dissertation: **Modern approach in existing state diagnosis of cultural-historical monuments - architectural perspective**. *Institute of Earthquake Engineering & Engineering Seismology*, Skopje, 2024.

[4] Feilden B. **Conservation of Historic Buildings**. *MA: Architectural Press*, 3rd Edition. Oxford; Burlington, 2003.

[5] Markovic M. S**veti Nikita kod Skopja**. *Sluzben Glasnik*, Beograd, 2015.

[6] Gavrilović P, Ginell SW, Shendova V, Šumanov L. **Conservation and Seismic Strengthening of Byzantine Churches in Macedonia**. *Getty Publications*, Los Angeles, 2004.

[7] NI Conservation Center Skopje. Written documentation St. Nikita church, 1978.

[8] NI Conservation Center - Skopje. Written documentation: Minutes of a meeting for review and acceptance of the project and the execution works on the restoration and covering of the roof of the Monastic Church of St. Nikita in the village of Gornjani, Skopje Region. Skopje: 1980.

[9] RZZSK, Kočishki I. Institute for the Protection of Cultural Monuments of the City of Skopje, 1963–1983. Institute, Skopje. 1983.

[10] https://earthquakelist.org/north-macedonia/grad-skopje/ (accessed April 9, 2024).

[11] Menéndez B. **Non-Destructive Techniques Applied to Monumental Stone Conservation**. *Non-Destructive Testing*, InTech; 2016. https://doi.org/10.5772/62408.

[12] Kilic G. **Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy**. *Journal of Cultural Heritage,* Vol. 16, Issue. 4, pp.526–35, 2015, https://doi.org/10.1016/j.culher.2014.09.010.

[13] Moropoulou A, Labropoulos KC, Delegou ET, Karoglou M, Bakolas A. **Non-destructive techniques as a tool for the protection of built cultural heritage**. *Construction and Building Materials,* Vol. 48, pp. 1222–39, 2013, https://doi.org/10.1016/j.conbuildmat.2013.03.044.

[14] Liu S, Bin Mamat MJ. **Application of 3D laser scanning technology for mapping and accuracy assessment of the point cloud model for the Great Achievement Palace heritage building**. Heritage Science, Vol. 12, Issue.1, pp. 153, 2024, https://doi.org/10.1186/s40494-024-01252-y.

[15] Costanzo A, Minasi M, Casula G, Musacchio M, Buongiorno M. **Combined Use of Terrestrial Laser Scanning and IR Thermography Applied to a Historical Building**. *Sensors,* Vol. 15, Issue. 1, pp. 194–213, 2014, https://doi.org/10.3390/s150100194.

[16] Sánchez-Aparicio LJ, Del Pozo S, Ramos LF, Arce A, Fernandes FM. **Heritage site preservation with combined radiometric and geometric analysis of TLS data.** *Automation in Construction*, Vol. 85, pp. 24–39, 2018, https://doi.org/10.1016/j.autcon.2017.09.023.

[17] Zhang Y, Ying Z, Shen Z, Nishino T, Chen X. **3D Laser Scanning Technology-based Historic Building Mapping for Historic Preservation**. *International Review for Spatial Planning and Sustainable Development*, Vol. 3, Issue. 2, pp. 53–67, 2015, https://doi.org/10.14246/irspsd.3.2_53.

[18] Lezzerini M, Antonelli F, Columbu S, Gadducci R, Marradi A, Miriello D, et al. **Cultural Heritage Documentation and Conservation: Three-Dimensional (3D) Laser Scanning and Geographical Information System (GIS) Techniques for Thematic Mapping of Facade Stonework of St. Nicholas Church (Pisa, Italy)**. *International Journal of Architectural Heritage,Vol. 10, Issue 1, pp. 9-19,* 2016, https://doi.org/10.1080/15583058.2014.924605.

[19] Masciotta M-G, Ramos LF. **Dynamic identification of historic masonry structures**. *Long-term Performance and Durability of Masonry Structures*, Elsevier; pp. 241–64, 2019,. https://doi.org/10.1016/B978-0-08-102110-1.00008-X.

[20] Birtharia A, Jain SK. **Application of ambient vibration testing: an overview.** *International Research Journal of Engineering and Technology (IRJET), Vol. 2, Issue. 5,* 2015.

doi.org/10.62683/SINARG2025.027

Research paper

THE MULTIPLE BENEFITS OF POCKET PARKS AS URBAN MICRO-INTERVENTIONS AND THEIR IMPLEMENTATION POTENTIAL IN THE CITY OF NIŠ

Natalija Stanković[1], Maša Ranđelović[2]

Abstract

In urban areas, which are increasingly facing environmental and spatial challenges such as the urban heat island effect, air pollution, and a decline in quality of life, there are often neglected and underutilized spaces with the potential to become valuable public resources. In this context, pocket parks represent one of the key micro-interventions that can contribute to improving urban living conditions by enhancing microclimate, increasing biodiversity, and creating accessible public spaces. By analyzing theoretical frameworks and examples of best practices from various cities worldwide, this paper explores the multiple benefits of pocket parks from ecological, microclimatic, social, and urban planning perspectives. Special emphasis is placed on the possibilities for implementing pocket parks in the city of Niš, Serbia through the identification of potential locations based on an analysis of the urban context and spatial-functional criteria. The research indicates that pocket parks, as part of a sustainable development strategy, can contribute to the regeneration of degraded areas and the improvement of urban structures. By examining relevant criteria and implementation challenges, the paper provides recommendations for integrating pocket parks into the urban development of Niš, highlighting the potential of micro-interventions in creating a higher-quality and more sustainable urban environment

Key words: *Pocket parks, Urban micro-interventions; Sustainable development; Ecological aspects; Niš*

[1] PhD Student, Junior Researcher, Innovation Center University of Niš, Serbia, natalija.stankovic@icun.ni.ac.rs, ORCID 0009-0009-3532-8878
[2] PhD Student, Junior Researcher, Innovation Center University of Niš, Serbia, masa.randjelovic@icun.ni.ac.rs, ORCID 0009-0004-9275-8448

1. INTRODUCTION

We are witnessing that contemporary cities, perhaps more markedly than ever before, are facing a series of global challenges, among which the risks posed by climate change, rapid urbanization, and the effects of urban heat islands stand out. These and other global processes and issues further emphasize the need for a thoughtful approach to urban space planning and design. One of the key problems arising from the above is the insufficient amount of green spaces. Cities often lack an adequate number of parks, tree-lined avenues, green squares, and other green areas relative to their population density. This presents a serious urban planning challenge, as it fails to meet the basic needs of citizens for recreation, outdoor activities, microclimate mitigation, and maintaining a connection with nature in daily life. Furthermore, even when green spaces do exist, they are not evenly distributed across urban neighborhoods. This leads to situations where certain areas, particularly those that are socially or infrastructurally neglected, lack access to green spaces within walking distance (typically defined within a 300- to 500-meter radius) [1]. Such spatial inequality raises the issue of urban justice, as privileged neighborhoods are often significantly better equipped with greenery, while less developed and poorer areas are neglected, further deepening social and environmental disparities within cities. Among the existing urban green spaces, smaller, often overlooked areas stand out — despite their limited size, they possess significant potential to become active parts of urban life through appropriate transformation. Pocket parks, as a form of small (semi-)public green spaces, offer a response to these challenges by enhancing the quality of space and life at the micro-location level, particularly in densely built urban environments.

This paper explores the concept of pocket parks as a form of urban micro-intervention, with a special focus on their multifaceted significance and potential implementation in the urban context of the city of Niš, Serbia. The aim of the paper is to identify and explain the key values that pocket parks can offer in contemporary cities, both in terms of microclimatic and ecological improvement and in promoting social inclusion and urban justice. Additionally, the goal is to, through the analysis of Niš's specific spatial context, identify potential locations suitable for the implementation of pocket parks and offer guidelines for their integration into sustainable urban development strategies. The methodological framework of the paper includes a qualitative analysis of the available literature, as well as the examination of a best practice example from New York, the Paley Pocket Park, in order to recognize applicable models for the local context. It also encompasses an analysis of the urban context of a selected municipality within Niš, including cartographic representations and data on the existing green infrastructure, an assessment of location potentials, and a synthesis of findings to formulate recommendations for future interventions.

2. THEORETICAL FRAMEWORK

Pocket parks originally emerged in Harlem, one of the poorest neighborhoods in New York City, during the mid-1960s, through a pilot project. Generally, they developed as a response to the presence of numerous underutilized urban spaces, with the aim of assigning new purposes to these areas. The core idea was to explore and activate neglected parts of the city to create spaces that facilitate social interaction among residents and contribute to enhancing the quality of everyday urban life [2]. Pocket parks have been subject to various

interpretations and approaches, and as such, the literature offers numerous definitions that vary depending on the author, context, and disciplinary perspective. While some authors identify pocket parks as a distinct, independent category of urban green spaces [3], others view them as a subtype of local parks, often defined by a size of up to 1.2 hectares according to certain criteria [4]. Spinelli confirms the initial definition of a pocket park as a public space located within a city block, primarily intended to serve and benefit the local community. Some authors emphasize that pocket parks have a broader role in enhancing urban sustainability by providing opportunities for employment, creating spaces for creativity and entrepreneurship, and improving public health and well-being [5]. To encompass the diverse views, pocket parks can be broadly defined as small urban green spaces that, as a form of urban micro-intervention, serve to improve the urban quality and resilience of the city, foster well-being, connectivity, diversity, and flexible use. Their design should reflect urban specificity, promote a sense of community, and respect the needs of the local population as the primary users of such spaces. There is no "standardized" pocket park, which is undoubtedly a positive feature, as the design of public spaces should always respond to local needs and context.

Since the late 1960s, when they were first recognized as a distinct category of urban spaces, 13 different types of pocket parks have been identified, including: small urban gardens and mini-parks, green street strips/greenways, playgrounds, adventure playgrounds, street workout parks, relax areas/parklets/sunset parklets, street charge/smart areas, smart energy-gym areas/fitness spaces, pop-up cafes and restaurants/pop-up activity parking, public art parks, urban farming/allotment gardens, street food parks, and flood protection parks/flood control parks [6]. Due to this wide variety in typology, the design process must be flexible and inclusive. In this context, the concept of co-design is particularly important — a participatory approach in which users are actively involved in all stages of planning and designing spaces, ensuring that the design aligns with different age groups, the real needs of the community, and the specific characteristics of the location [2].

3. EXAMPLE OF GOOD PRACTICE FROM NEW YORK CITY AND THE MULTIPLE SIGNIFICANCE OF POCKET PARKS

Paley Park, located in the heart of Midtown Manhattan, New York City, stands as one of the most famous and highly regarded examples of a pocket park, designed to offer an oasis of peace and quiet amid the urban hustle and bustle (*Fig. 1a*). Originally opened in 1967, the park was the result of a vision by architect Robert Zion and a philanthropic initiative led by William S. Paley, founder of CBS (Columbia Broadcasting System). Paley Park is a privately owned public space, primarily intended to provide opportunities for rest and relaxation within a densely urbanized environment. Covering an area of 390 m², the park is dominated by an impressive six-meter-high waterfall that spans the entire width of the rear wall, helping to mask city noise and creating a soothing soundscape. Additionally, twelve locust trees positioned in the central part of the park provide pleasant shade, while visitors are offered movable wire chairs and marble tables (*Fig. 1b*). The ground is paved with granite slabs, and the side walls are covered with English ivy, creating a harmonious blend of natural and urban elements. One of the key features of the park is its flexibility and ability to adapt to the needs of its visitors, including accessibility for people with disabilities. Paley Park is carefully designed to create an optimal microclimatic environment, with strategic orientation that allows

for maximum sunlight exposure during the day, while greenery and water features contribute to a pleasant atmosphere. Although small in size, the park is highly functional and efficiently used, accommodating up to around 200 visitors at a time, predominantly during daylight hours when it is most frequented. Paley Park also serves as an excellent example of sociological impact, providing a much-needed space for rest and relaxation, which is crucial in the fast-paced life of a major city like New York. It allows people to retreat from the stress of the urban environment, positively influencing mental health and overall well-being. Due to its intimate nature, the park becomes more than just a physical space; it is a setting for informal social interaction, often used for taking breaks, meetings, creative work, or simply enjoying a quiet moment. One of the reasons for the park's long-standing popularity and sustainability lies in its thoughtful design. By respecting the spatial planning regulations, using high-quality materials and natural elements, Paley Park has become a symbol of how small urban spaces can be effectively utilized to meet community needs. Its renovation in 1999, which included the replacement of the waterfall system (*Fig. 1c*), upgrades to the underground irrigation systems, revitalization of green areas, and preservation of original design elements, once again confirmed the importance of maintaining the park's integrity [7].



Figure 1a. Park location, Google Maps; Figure 1b. Park courtyard and Figure 1c. Waterfall, https://www.paleypark.org/

Pocket parks, such as Paley Park, represent more than just spatial micro-interventions; they are multi-layered urban resources offering a wide range of benefits across ecological, microclimatic, sociological, and urban planning aspects. Their significance lies not only in the aesthetic enhancement of the urban landscape but also in their ability to address key challenges of contemporary urban life. From an ecological perspective, pocket parks contribute to the reduction of the urban heat island effect, increase soil permeability, and enable natural rainwater infiltration—an especially important function in densely built environments with a high percentage of impermeable surfaces. Through the planting of trees and the introduction of green spaces, these parks improve air quality, support biodiversity conservation, and create micro-ecosystems. In terms of microclimate, the thoughtful placement of greenery and water features, such as the waterfall in Paley Park, helps create a more pleasant outdoor environment during the summer months, reduces noise levels, and enhances the comfort of open public spaces. Sociologically, the importance of pocket parks is particularly evident in their function as places for gathering and informal interaction. In urban environments where private spaces often dominate over public ones, these small parks become crucial points of social cohesion, allowing people of different ages, interests, and professions to share common space. From an urban planning perspective, pocket parks complement the existing network of public spaces, helping to create urban green corridors and revitalizing neglected parcels. They can serve as catalysts for further development in their immediate surroundings, improve the visual identity of neighborhoods, and contribute to overall urban regeneration.

4. ANALYSIS OF THE URBAN CONTEXT OF NIŠ, SERBIA AND IDENTIFICATION OF POTENTIAL POCKET PARK LOCATIONS IN THE CITY

The Municipality of Medijana, as the central and most urbanized part of Niš, faces significant challenges related to the lack of accessible and evenly distributed green spaces. Although the area includes several larger parks and green corridors, many densely built residential neighborhoods remain without adequate small-scale green spaces that are easily accessible to pedestrians. An analysis of the current state of green infrastructure, based on the typology of green spaces defined within the Green Surge project, identified several potential locations suitable for the development of pocket parks [8]. The selection criteria included lack of nearby green areas, degraded or underused spaces, good pedestrian access, and potential for integration into the urban fabric. The attached map presents the selected area of analysis within the territory of the City Municipality of Medijana and marks the identified potential locations for the development of pocket parks (*Fig. 2*). The visualization highlights their distribution within the broader urban matrix, as well as the characteristics of each micro-location, which are additionally illustrated through detailed enlarged views. At several locations, urban furniture intended for children, such as playgrounds and benches, was observed. However, it is generally in poor condition, worn out, neglected, or poorly maintained, which further emphasizes the need for intervention. Each of these sites was evaluated in the context of its spatial potential, current land use, and the needs of the local community, with the aim of formulating recommendations for their transformation into high-quality and functional micro-urban green spaces.



Figure 2. Identification of potential P.P. locations in the City of Nis, Google Earth

5. CONCLUDING CONSIDERATIONS

In the context of sustainable development, pocket parks are recognized as significant urban micro-interventions due to their flexibility and contextual adaptability, generating multiple positive effects with minimal spatial and financial investment. The challenges that arise during their implementation include unresolved property ownership issues, lack of institutional support and long-term management strategies, as well as limited community involvement, which can lead to a mismatch between design and users' actual needs. Despite

these obstacles, the multifaceted value of pocket parks is immeasurable. Complementing the existing network of public green spaces, pocket parks contribute to the formation of an urban mosaic of microspaces, thereby increasing accessibility and ensuring a more balanced distribution of greenery across the city. The example of Paley Park in New York clearly demonstrates that even spatially modest interventions, when carefully designed and aligned with users' needs, can significantly enhance the quality of urban life. The spatial context analysis of the Medijana municipality in Niš, Serbia has identified numerous neglected and underutilized spaces which, if appropriately transformed into pocket parks, could improve the equitable accessibility of green areas, particularly in infrastructurally disadvantaged zones. The goal of identifying potential locations for pocket parks in the city is not only the physical revitalization of these small spaces but also their strategic use to enhance the urban microclimate, increase opportunities for social interaction, and strengthen the overall resilience and quality of life in the city. The proposed interventions support sustainable urban development by forming a network of green microspaces that enhance the ecological, social, and aesthetic quality of life in Niš.

ACKNOWLEDGMENTS

The paper was realized with the support of the Innovation Center of the University of Niš, within the project implemented under the institutional funding model (ID number 451-03-68/2023-14/200371).

REFERENCES

[1] Liu Shu, Wang Xinhao: **Reexamine the value of urban pocket parks under the impact of the COVID-19**. *Urban Forestry & Urban Greening,* Vol. 64, 127294, 2021, doi:10.1016/j.ufug.2021.127294.

[2] Mussi Andréa Quadrado, Deon Luisa Fernanda Nercolino, Isele Priscila Castioni, Bavaresco Fernando: **Co-design in Public Spaces for Children: The Design Process of a Pocket Park**. *Journal of Civil Engineering and Architecture*, Vol. 15, No. 10, 456–463, 2021, doi:10.17265/1934-7359/2021.10.003.

[3] Labuz Rita: **Pocket Park – A New Type of Green Public Space in Kraków (Poland)**. *IOP Conference Series: Materials Science and Engineering*, Vol. 471, No. 11, 112018, 2019, doi:10.1088/1757-899X/471/11/112018.

[4] Currie Melissa Anne: **A design framework for small parks in ultra-urban, metropolitan, suburban and small town settings**. *Journal of Urban Design*, Vol. 22, No. 1, pp. 76–95, 2017, doi:10.1080/13574809.2016.1234334.

[5] Nordh Helena, Hartig Terry, Hagerhall Caroline M, Fry Gary: **Components of small urban parks that predict the possibility for restoration.** *Urban Forestry & Urban Greening*, Vol. 8, No. 4, pp. 225–235, 2009, doi:10.1016/j.ufug.2009.06.003.

[6] Babalis Dimitra: **A new typology of pocket parks: inspiring small spaces for changing cities.** *Urban Design and Planning*, Vol. 173, No. 3, 108–117, 2020, https://doi.org/10.1680/jurdp.19.00018.

[7] Tate Alan, Eaton Marcella: **Great City Parks**. *Routledge,* Abingdon, 2015.

[8] Cvejić Rozalija, Eler Klemen, Pintar Marina, Železnikar Špela, Haase Dagmar, Kabisch Nadja, Strohbach Michael: **A Typology of Urban Green Spaces, Ecosystem Provisioning Services and Demands**. *GREEN SURGE Project*, Deliverable 3.1, 2015.

doi.org/10.62683/SINARG2025.028

Research paper

REUSE OF VACANT OFFICE BUILDINGS: ANALYSIS OF QUANTITATIVE SPATIAL CHARACTERISTICS OF BUILDINGS ACCORDING TO TYPOLOGY

Damjana Nedeljković[1], Lidija Djokić[2], Tatjana Jurenić[3]

Abstract

Adaptations, as a group of different interventions, represent an increasingly common approach in the architectural and urban practice of many cities around the world. In certain cases, conversion of an existing building presents a better solution than demolishing the building and constructing a new one on the same site. Given that it often happens that the implementation of conversion projects is interrupted at some stage and the buildings remain out of use, it is important to consider the conditions for a successful conversion. An adequate selection of a new purpose is one of the most crucial steps. This paper will present an analysis of the most significant quantitative spatial characteristics of buildings according to their typology, to establish which typologies are "spatially compatible" and thus determine the appropriate potential new purposes for unused buildings, depending on the purpose for which they were originally built.

Key words: *conversion, building typology, spatial characteristics of buildings*

[1] PhD, Teaching Assistant, University of Belgrade – Faculty of Architecture,Serbia damjana@arh.bg.ac.rs, 0009-0008-0597-293X

[2] PhD, Full Professor, University of Belgrade – Faculty of Architecture, Serbia, lidija@arh.bg.ac.rs, 0000-0003-2405-0670

[3] PhD, Associate Professor, University of Belgrade – Faculty of Architecture, Serbia, tanja@arh.bg.ac.rs, 0000-0002-4340-2881

1. INTRODUCTION

Due to market instability, unused commercial buildings are a problem that more and more cities around the world are facing. In practice, several ways of solving this problem are applied: the existing building is demolished and a new one is built in its place, the existing building is renovated to be used again for business purposes, or the existing building is converted. It has been observed that, in comparison with the demolition of the existing and the construction of a new building, adaptations, which refer to various ways of building renewal, are increasingly present in architectural practice. The advantages are primarily reflected in the reuse of already used resources, the potentially shorter time required for the building to be put into use, the preservation of the appearance of the environment, and potentially lower initial financial investments.

The quantitative spatial characteristics of buildings have a great influence on the success of the conversion process as a type of building adaptation which includes repurposing. In this context, an analysis is presented based on the relevant literature and case studies from practice in Serbia [1-14], which refers to the spatial characteristics of buildings according to typologies (by purpose). This analysis is important to conclude which new uses are, to the greatest extent, spatially compatible with commercial office buildings.

2. ANALYSIS OF QUANTITATIVE SPATIAL CHARACTERISTICS OF BUILDINGS ACCORDING TO TYPOLOGY

Figures 1-10 show analyses of the basic spatial characteristics of buildings by typology: structural assembly, grid, floor height, depth of the tract, structure and arrangement of interior walls, and number and arrangement of openings. Figure 1 shows an analysis of the basic spatial characteristics of commercial office buildings**.**

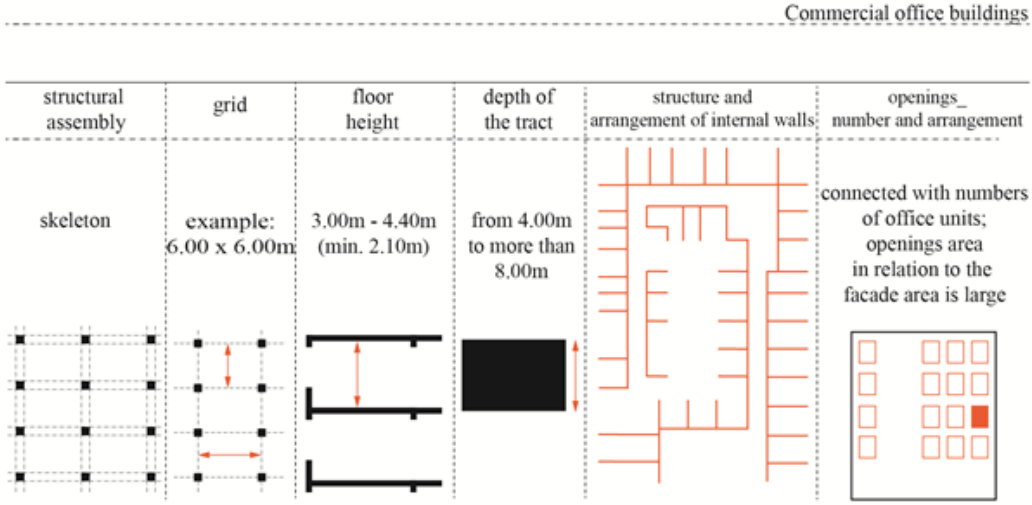


Figure 1. Analysis of the basic spatial characteristics of commercial office buildings, Authors

When it comes to the structural assembly, this type of building is dominated by a skeleton system, which, in the context of conversion, is characterized by a high degree of flexibility. The grids of commercial office buildings are different, and the 6.00x6.00m grid is highlighted

as an example. Although there are examples with a floor height between 3 and 4 meters, a large number of buildings belonging to this typology, which are out of use, have low floor heights (some examples only 2.10m). This characteristic can be a major disadvantage in terms of conversion, given that the implementation of most other purposes requires a higher floor height, and changing the floor height represents a financially demanding intervention of a large scale. The depth of the tract, similar to the grid, is different and can be 4-8 m. The structure and arrangement of the internal walls of commercial office buildings can be characterized as cellular - the space is divided into a large number of smaller units connected by corridors, which can correspond to purposes with a similar organization of the internal space. Given that the internal space is divided, the area under the openings of these buildings in relation to the facade area is large. This feature can be a great advantage several other purposes and the organization of the internal space.

Figure 2 shows an analysis of the basic spatial characteristics of business facilities – conference and congress centers. As in the case of business office facilities, the skeleton system dominates. The grids of these facilities are different, but much larger than those of business office facilities, and an 18m grid is highlighted as an example. The floor height of conference and congress centers is large – an example is given with a floor height of 6.5m. A large floor height can be a great advantage in terms of repurposing a facility, as it is possible to implement a wider range of new uses.

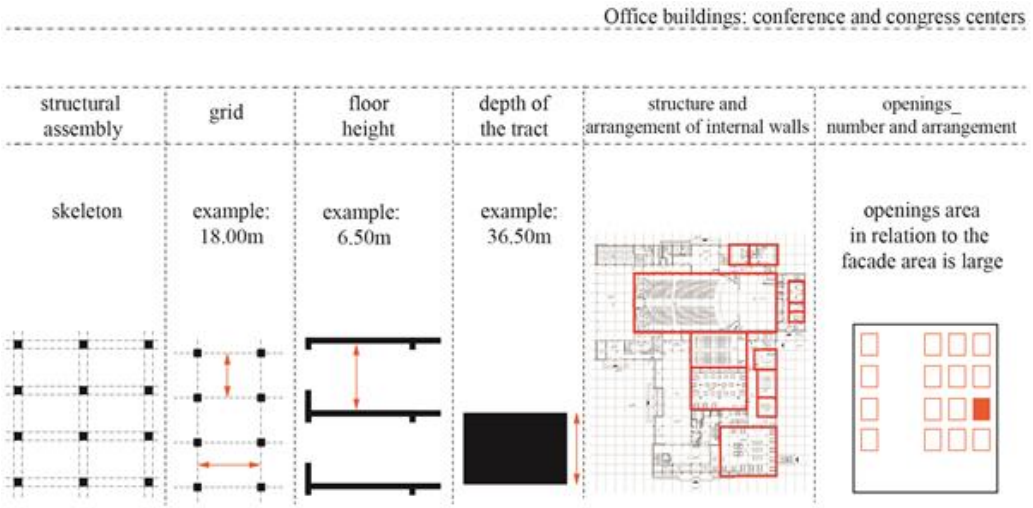


Figure 2. Analysis of the basic spatial characteristics of office buildings - conference and congress centers are significant for conversion, Authors

The depth of the tract varies, but is usually large, so the depth of 36.5m is given as an example. The interior space is divided into larger and smaller units, so the area under the openings is large in relation to the area of the entire facade, which is an advantage in terms of a greater number of options when choosing a new purpose. However, it is important to emphasize that office buildings of conference and congress centers are quite rarely out of use. Within the typology of office buildings, the degree of abandonment of commercial office buildings is much higher.

Figure 3 shows an analysis of the basic spatial characteristics of residential buildings.

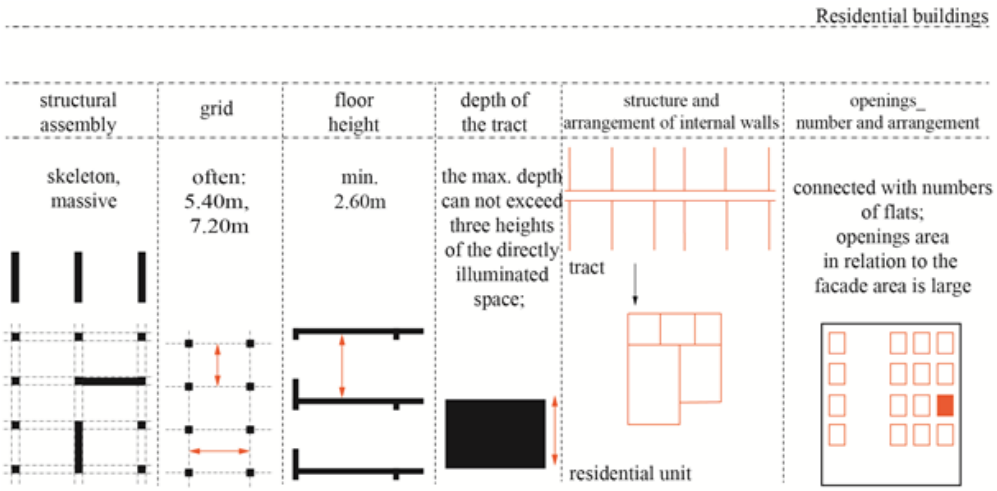


Figure 3. Analysis of the basic spatial characteristics of residential buildings is significant for conversion, Authors

Buildings of this typology are built in a skeleton or massive structural assembly, in grids of 5.40m or 7.20m, in most cases. The minimum, prescribed by the regulations, floor height is 2.60m. This prescribed condition is one of the very important factors when considering the implementation of residential use in an existing building. The maximum depth of the tract is also prescribed and cannot exceed three clear heights of the directly illuminated space. The interior space is divided by walls into units - apartments, and each of these units has its division. Given that buildings of several typologies have a similar structure of the interior space, from this aspect, residential use could be a new purpose for a large number of buildings. Buildings of this typology have a large number of openings with the facade area.

Figure 4 shows an analysis of the basic spatial characteristics of catering and tourist facilities. As representatives of this typology, hotel facilities were considered, given that their structure can contain both accommodation and catering parts (restaurants). The largest number of facilities of this typology was built in a skeleton system, in the grid that was also mentioned for residential facilities: 5.40m and 7.20m. Unlike residential facilities, the minimum floor height is not strictly defined, so there are cases among facilities with very low floor heights (2.30m). Although inadequate floor height has a negative impact on the quality of the interior space, the relative uncertainty regarding the floor height of facilities represents a certain advantage in terms of conversion, because hotel facilities provide a potential new purpose for a large number of unused facilities. Taking into account the high degree of diversity in the architectural approach to the design of these buildings, the depth of the tract varies, and 8m is highlighted as an example. The structure and arrangement of the internal walls differs in the accommodation and catering areas. The accommodation area is characterized by a cellular structure similar to office and residential buildings. The internal organization of the catering area involves separate units of different sizes, depending on the purpose of these rooms. The area under the openings is large in these buildings, in relation to the surface of the facade.

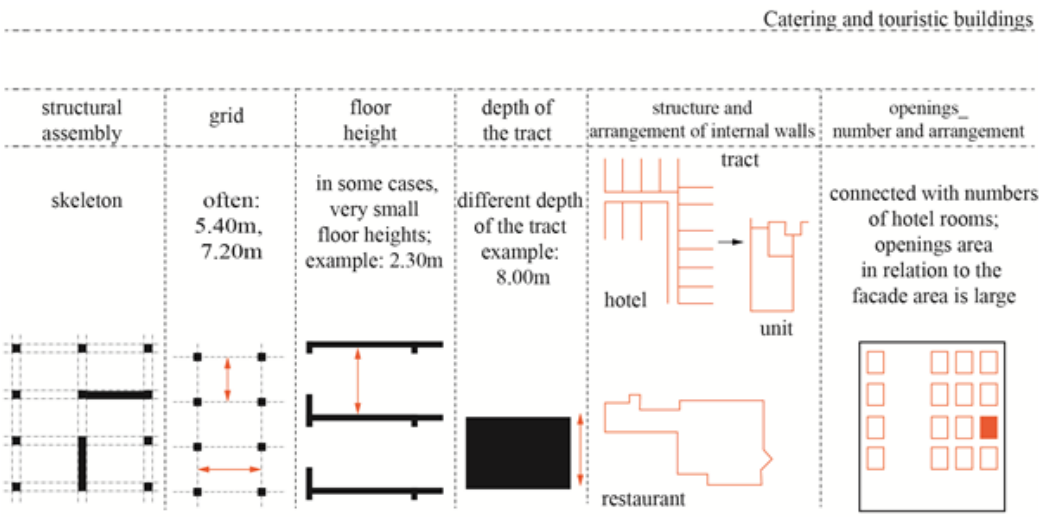


Figure 4. Analysis of the basic spatial characteristics of catering and touristic facilities significant for conversion, Authors

Figure 5 shows an analysis of the basic spatial characteristics of retail facilities – shopping malls.

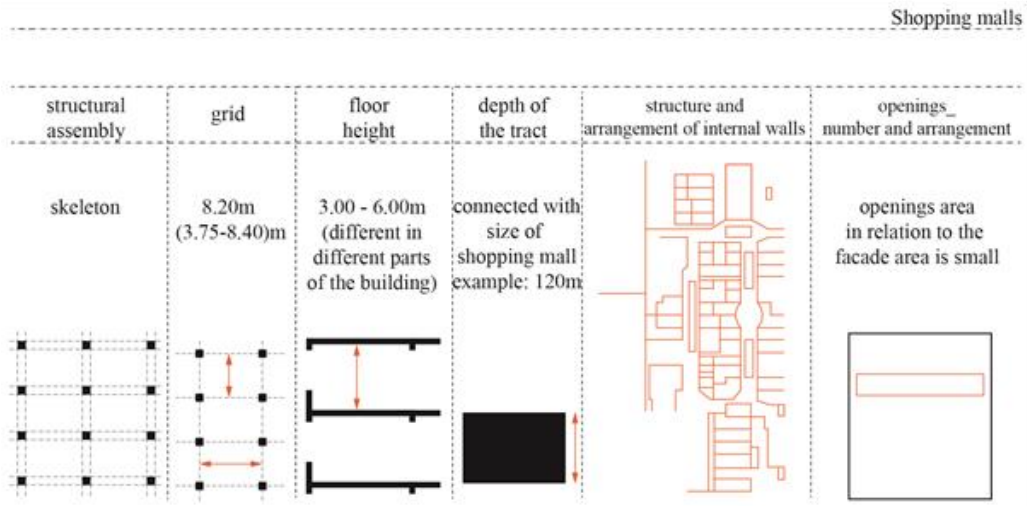


Figure 5. Analysis of the basic spatial characteristics of retail facilities - shopping malls significant for conversion, Authors

The skeleton structural system dominates, and the grids in which these buildings are most often built range from 3.75m to 8.40m. Shopping centers are characterized by a spatially very heterogeneous structure, so the floor height is different in parts of the building (3.00m - 6.00m). The depth of the tract is determined by the size of the shopping center, and an example is given whose depth of the tract is 120m. Taking into account the different activities that can take place in a shopping center, and therefore different spatial needs, the organization of the interior space of shopping centers implies an irregular division of space into units with a large difference in areas (unlike office buildings, for example). The area under the openings concerning the facade area is small, and the openings are most often arranged in a strip.

Figure 6 shows an analysis of the basic spatial characteristics of retail facilities – department stores.

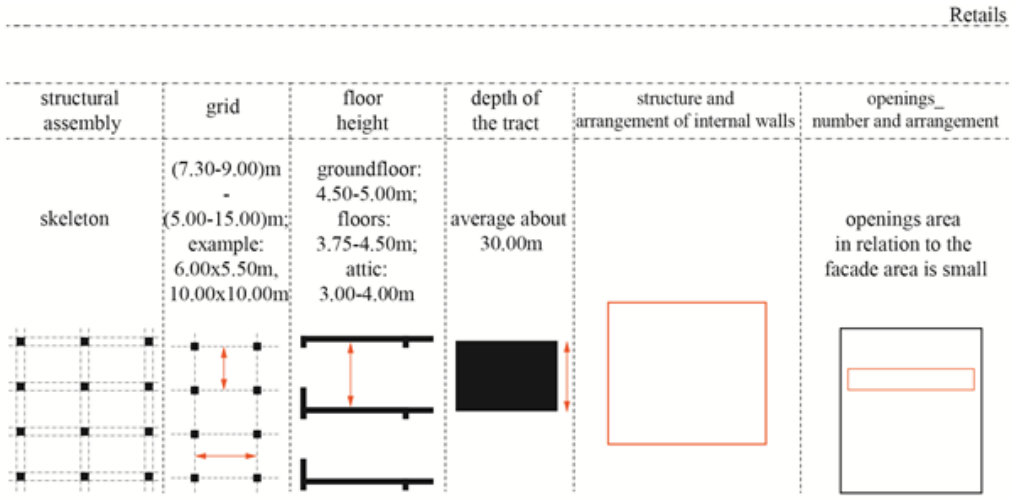


Figure 6. Analysis of the basic spatial characteristics of retail facilities – department stores are significant for conversion, Authors

The buildings of former department stores are, in large numbers, partially or completely out of use. When it comes to the structural system of department stores, the most common is the skeleton system, which was previously assessed as an advantage in the context of conversion. As an example, the grids 6.00x5.50m and 10.00x10.00m are given (the range of values for one dimension is 7.30-9.00m, and for the other 5.00-15.00m). The floor height of department store buildings varies by level: the floor height of the ground floor is most often 4.50-5.00m, the floors are 3.75-4.50m, and in the attic 3.00-4.00m. The average depth of the tract is about 30m. The interior of department stores is generally undivided, which opens up a range of possibilities for new uses without any structural interventions. The area under the openings is small in relation to the surface area of the facade.

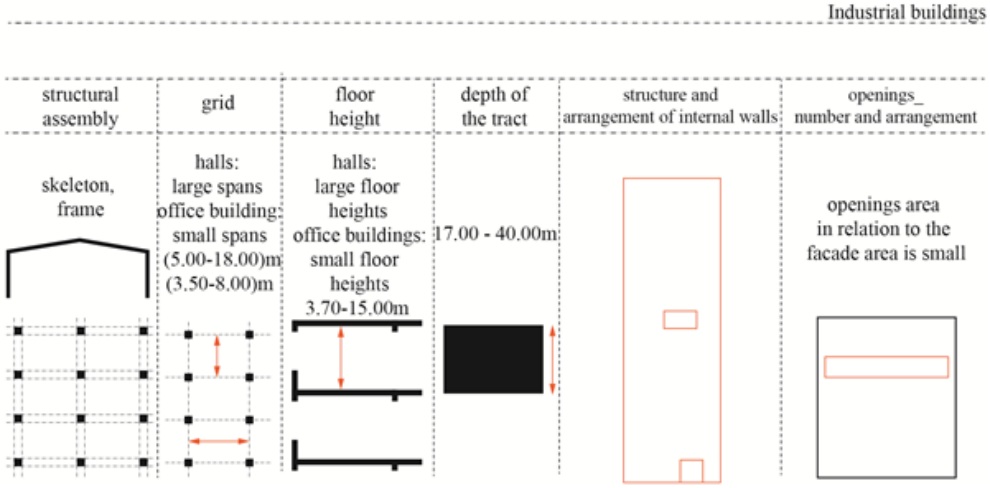


Figure 7. Analysis of the basic spatial characteristics of industrial facilities is significant for conversion, Authors

Figure 7 shows an analysis of the basic spatial characteristics of industrial buildings – industrial halls. Industrial halls are built in a skeleton and frame structure. The spans are large, and the grids range from 5.00m to 18.00m. The floor heights are not the same in all parts of the industrial building, so the range of floor heights is from 3.70m to 15.00m. The depth of the tract of buildings of this typology is large, from 17.00m to 40.00m. The interior space of industrial halls is a large, undivided space with separate cores (vertical communications), which provides many possibilities in terms of organizing the space for new uses. The area under the openings in relation to the facade area is small.

Figure 8 shows an analysis of the basic spatial characteristics of healthcare facilities. The largest number of facilities of this typology are built in a massive and/or skeleton structural assembly. The most common grid is 7.50m x 7.50m. The floor height is about 3.5m. The depth of the tract of healthcare facilities is greater, the circumference is between 14.00m and 18.00m. The interior space of these facilities is divided and consists of separate units of larger and smaller areas, depending on the purpose. As noted earlier in the pape, facilities with divided interior space, healthcare facilities are also characterized by a large area under openings in relation to the facade area.

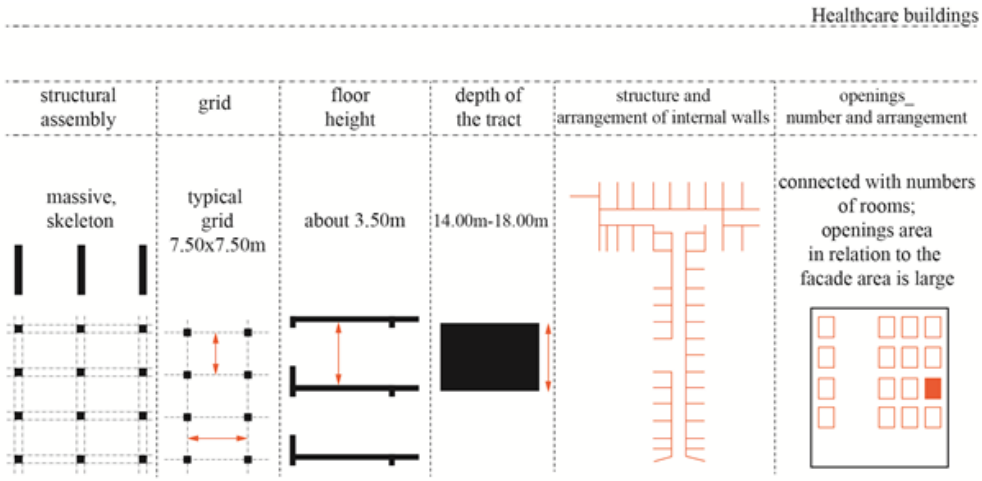


Figure 8. Analysis of basic spatial characteristics of healthcare facilities is significant for conversion, Authors

Figure 9 shows an analysis of the basic spatial characteristics of educational facilities (primary and secondary schools). The skeleton structure is dominant. The grid range is from 6.50m to 10.00m in one direction and from 6.50m to 7.50m in the other direction. Typical grids are distinguished: 7.50m x 7.50m and 6.50m x 8.50m. The minimum floor height is 3.00m, but varies in the range from 3.00m to 3.80m. The depth of the educational facility tract varies depending on the design solution (between 12.00m and 32.50m). The interior space is divided into units of different sizes, and the number of openings concerning the facade area is large.

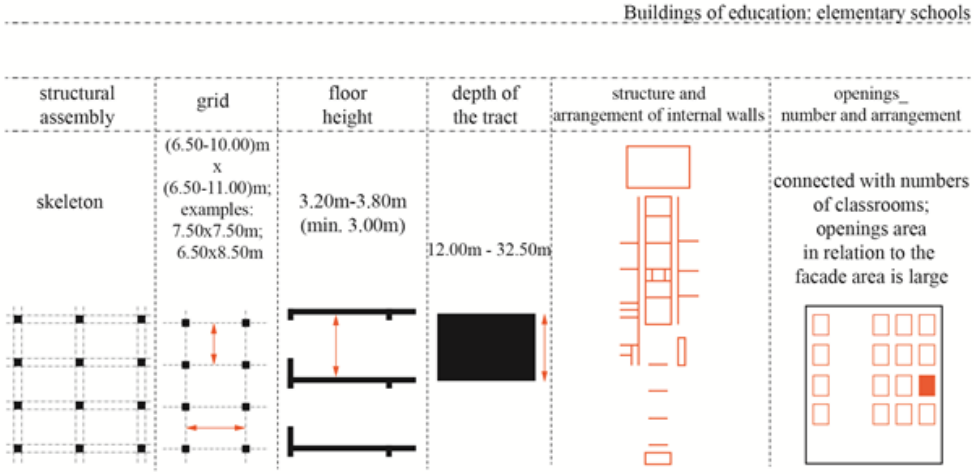


Figure 9. Analysis of the basic spatial characteristics of typical educational facilities (elementary schools) is significant for conversion, Authors

Figure 10 shows an analysis of the basic spatial characteristics of sports facilities. The structural assembly of sports facilities is skeleton or framed. These facilities are characterized by large spans that are determined by the type of sports activities for which they are intended. Although the minimum clear height is 2.50m, these facilities most often have large floor heights. The depth of the tract is different and is determined by the needs of the sports activities for which the facility is built. When it comes to the structure of the internal space, in most cases, larger undivided spaces (fields) and a series of smaller accompanying units next to them dominate. The area under the openings in relation to the surface of the facade of sports facilities is small.

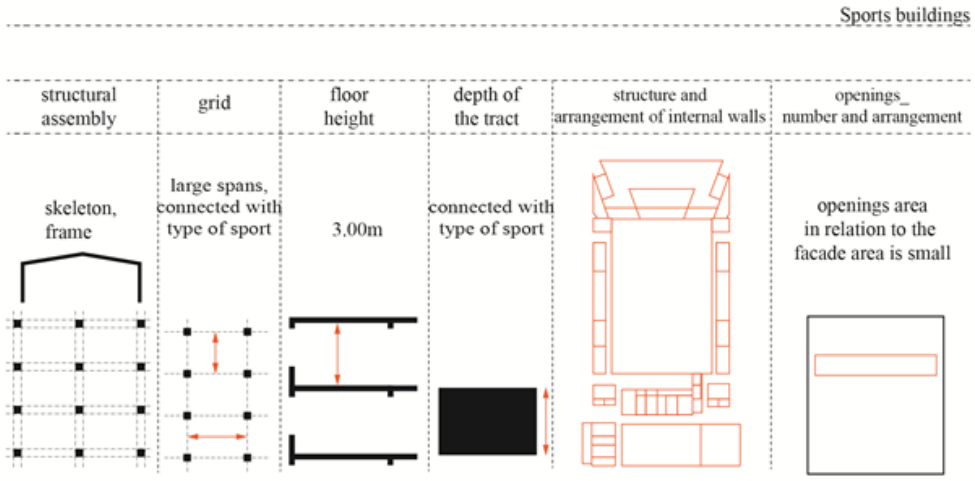


Figure 10. Analysis of the basic spatial characteristics of sports facilities is significant for conversion, Authors

3. CONCLUSION

The issue of potential new use is one of the most important factors in the entire conversion process. The presented analysis observed the basic spatial characteristics of typologies significant for conversion, the change of which during the potential conversion process would require more or less demanding structural interventions, which affect the duration and economic aspect of the conversion process as a whole. Compatible uses were considered to be those in which, during potential conversion, extensive and financially demanding structural interventions are not required. Given that the subject of the research is office buildings, uses compatible with these buildings were considered. The profile of a potential new use of a business office building based on the analyzed spatial characteristics (compatible uses) is as follows: **skeleton** or **frame structure**, **smaller spans**, **lower floor heights**, **smaller depth of the tract**, **cellular structure** of the interior space and **large opening area** in relation to the facade surface.

In this context, concerning the observed quantitative typological characteristics, it was established that office buildings can be most successfully adapted for the following purposes:

- **new office building** of a different structure (in line with modern ways of doing business that implies a greater degree of flexibility);
- **hotel** (taking into account the structure of office units, typical floors, and a larger number of floors), and
- **residential building** (in cases of adequate floor height and natural lighting).

The findings of this research make a significant contribution by laying the groundwork for developing mathematical tools to assess the potential for repurposing commercial buildings.

The conversion of unused commercial buildings into permanent or temporary residential buildings (tourist facilities, student and retirement homes) is a subject of research through theory and practice in a large number of cities. Several published publications describe the process of this type of transformation in the late twentieth and early twenty-first centuries in London, New York, Toronto, and Tokyo. In the case of London and Toronto, the conversion of commercial buildings into residential buildings was one of the ways to revitalize the central parts of these cities. In New York, in a part of Manhattan, and Tokyo, due to first the decline and then the dizzying economic development, new and better quality commercial buildings were built, so a large number of older commercial buildings remained unused. These buildings were transformed into smaller residential units as part of the strategy for the revitalization of this part of the city. In Amsterdam, the conversion of unused commercial buildings into permanent and temporary housing, predominantly social, was one of the solutions to the problem of insufficient available capacity of the existing housing stock. Numerous examples of good practice have been used to analyze various aspects of these conversions (economic, functional, environmental, etc.), which are most often determined by the characteristics of the buildings and their locations [15].

ACKNOWLEDGEMENTS

This research was done at the University of Belgrade – Faculty of Architecture, within the Research Laboratory: *Optimal lighting design in architecture.*

REFERENCES

[1] Damjanović, Vojislav. (1990). **Industrijski kompleksi i zgrade**. Beograd: Građevinska knjiga.

[2] Douglas, James. (2006). **Building adaptation**. Butterworth – Heinemann, Oxford.

[3] Neufert, Ernst. & Neufert, Peter. (Neufert, K.). (2012). **NEUFERT: Architects Data: Fourth Edition Chichester**, West Sussex: Wiley – Blackwell.

[4] Besaraba, Miloš. (1969). **Robna kuća u Zemunu**. *Arhitektura Urbanizam 53-54*, 61-63.

[5] Dumengjić, Selimir & Kosić, Ivan (1961). **Arhitektonske realizacije naše savremene izgradnje zdravstvenih ustanova**. *Arhitektura Urbanizam 8-9*, 11-55.

[6] Kabiljo, Leon (1960). **Izgradnja osnovnih škola**. *Arhitektura Urbanizam 6*, 4-23.

[7] Milićević-Nikolić, Olga (1960). **Robna kuća "Beograd"**. *Arhitektura Urbanizam 1*, 22-23.

[8] R.T. (1967a). **Zgrada "Jadran" u Beogradu**. *Arhitektura Urbanizam 44*, 12-13.

[9] R.T. (1967b). **Zgrada jugoslovenskog građevinskog centra u Beogradu**. *Arhitektura Urbanizam 44*, 14-15.

[10] R.T. (1967c). **Zgrada Politike u Beogradu**. *Arhitektura Urbanizam 44*, 16-17.

[11] R.T. (1967d). **Zgrada Društvenih organizacija u Novom Beogradu**. *Arhitektura Urbanizam 44*, 18-19.

[12] Šterić, Milica (1961). **Industrijski kompleks "Viskoza"**. *Arhitektura Urbanizam 7*, 7-12.

[13] Правилник о класификацији објеката, Службени гласник РС, 22/2015.

[14] Правилник о условима и нормативима за пројектовање стамбених зграда и станова. Службени гласник РС, бр. 58/2012, 74/2015 и 82/2015.

[15] Remoy, Hilde (2010). **Out of Office: A Study on the Cause of Office Vacancy and Transformation as a Means to Cope and Prevent**, *Doctoral Thesis*, TU Delft, Netherlands.

doi.org/10.62683/SINARG2025.029

Research paper

RESEARCH LINES IN THE FIELD OF CONVERSION OF VACANT OFFICE BUILDINGS: USE OF MULTI-CRITERIA DECISION-MAKING MODELS

Damjana Nedeljković[1], Tatjana Jurenić[2], Lidija Djokić[3]

Abstract

The field of conversion of vacant office buildings includes several aspects, and consequently, various research lines have been identified. The studies focus on the causes of abandonment of office buildings, possibilities for their conversion into temporary and permanent housing, analysis of desirable characteristics of office buildings from the users' perspective, the impact of land policies on the conversion process, the influence of the regulatory framework, the conversion of buildings with cultural heritage status, and so on. All research is aimed at improving the efficiency and cost-effectiveness of the conversion process of vacant office buildings in practice. The research relies on the analysis of existing multicriteria decision making models and the comparison of their structures and criteria. Based on the analysis of the selected models, a structure has been identified that can be applied to form new multi-criteria models of this type. The goal is to highlight the potential for applying such models in contemporary architectural and urban practice.

Key words: *office buildings, platform, criteria, evaluation*

[1] PhD, Teaching Assistant, University of Belgrade – Faculty of Architecture, Serbia damjana@arh.bg.ac.rs, ORCID 0009-0008-0597-293X

[2] PhD, Associate Professor, University of Belgrade – Faculty of Architecture, Serbia, tanja@arh.bg.ac.rs, ORCID 0000-0002-4340-2881

[3] PhD, Full Professor, University of Belgrade – Faculty of Architecture, Serbia, lidija@arh.bg.ac.rs, ORCID 0000-0003-2405-0670

1. INTRODUCTION

With the increasing number of different forms of reconstruction represented in contemporary architectural and urban practice, this topic has become the subject of interest of many researchers. Several different lines of research have been recognized in the field of repurposing. In Table 1 the lines of research related to office buildings out of use are presented.

Table 1: Research lines in the field of conversion of business facilities

Research lines	Authorities
Criteria for evaluating the potential of a business object for conversion	H. Remoy, T. J. M. Van der Voordt, H. de Jonge, T. P. Heath, R. Mackay
The impact of legislation on the process of office building conversion	H. Remoy, E. Street, P. A. Bullen, P. E.D. Love, J. Barlow, D. Gann, R. Olivadese, C. Berizzi, F. Hobma
Adaptability in the design of office buildings	H. Remoy, P. de Jong, W. Schenk, M. Ouf, W. O'Brien, B. Gunay, S. Slaugther, J. Gosling, P. Sassi, R. Lark, J. Douglas
Aspects of sustainability in the process of conversion of office buildings	H.Remoy, S. Wilkinson, E. H.K. Yung, E. H.W. Chan
Causes of the abandonment of office buildings	H. Remoy, P. Koppels, C. van Oel, H. de Jonge
Historical aspect – the development of conversion	B. Plevoets, J. Sowinska – Heim, K. Van Cleempoel
Multi-criteria models for evaluating the potential of office buildings for conversion	C.Langston, R. Geraedts, T. van der Voordt, D. Caccavelli, H. Gugerli, C.A. Balaras, G. Ding, F. Flourentzou, J.L. Genre, C. A. Roulet, A. Kaklauskas, E. Kazimieras Zavadskas, S. Wilkinson

Remoy investigates various aspects of the abandonment of commercial buildings and their conversion into temporary and permanent residential buildings, which relate to the necessary interventions on commercial buildings to adapt them to the needs of the new purpose, the causes of the general disuse of commercial buildings, the analysis of the supply and demand of the purpose in the market and the analysis of the desirable characteristics of the location and the commercial building as a physical structure [1]. Research of van der Voordt are focused on the benefits and risks of converting a commercial building into a residential building, legal, financial, technical, functional and architectural criteria based on which the potential of a commercial building for conversion into temporary or permanent housing can be assessed, economic feasibility and the influence of the target group of future users on decisions in the conversion process [2]. Heath deals with the revitalization of city centers by converting commercial buildings into residential ones, and examples include the cities of London and Toronto [3]. Mackay researches the costs of repurposing a business building through modeling, considering the share of the value of interventions on individual

elements concerning the final costs [4]. Remoy and Street consider the impact of land policies on the process of repurposing commercial buildings using the examples of England and the Netherlands [5], and Remoy, Olivadese, Berizzi and Hobma explore the advantages and disadvantages of regulations in Italy and the Netherlands concerning the efficiency of the process of converting commercial buildings into residential buildings [6].

Bullen and Love consider the conditions for the conversion of commercial buildings that have been declared cultural assets and are under a certain degree of protection, for example, in the city of Perth in Australia [7]. The influence of the legislative framework on the process of repurposing and the flexibility of regulation are among the focuses of the research by authors Barlow and Gann [8]. Remoy, de Jong and Schenk's research considers guidelines for designing commercial buildings to increase their potential for conversion into temporary or permanent housing in the future [9]. Ouf, O'Brien, and Gunay analyze the adaptability of objects to variability in purpose by measuring adaptability based on the characteristics of the object as a physical structure [10]. Slaughter examines design strategies that result in increased building flexibility [11]. Research by Gosling, Sassi, Naim, and Lark is aimed at considering the most important factors of a building's adaptability and developing an instrument for measuring adaptability and potential costs during conversion. [12]. Douglas considers the adaptability of a building from the aspect of the compatibility of spatial characteristics between typologies [13]. Another line of research in the field of commercial property conversion is the sustainability aspects. Remoy and Wilkinson [14] consider the environmental and sociological aspects of sustainability in the process of repurposing a commercial building. Yung and Chan explore an environmentally sustainable approach to repurposing and striking a balance between economic feasibility, environmental impact, and social benefits [15]. The reasons leading to the cessation of the use of a business facility were considered to identify the characteristics of business facilities that are considered advantages or disadvantages within the market and from the perspective of users, to their (changed) expectations directed towards the workspace. Remoy, Koppels, van Oel and de Jonge investigate the characteristics of business facilities using the Delphi method [16]. Researchers who analyze the historical aspect of conversion as a form of architectural and urban action, such as Plevoets, Sowinska-Heim and van Cleempoel, consider forms of planned and unplanned conversion throughout history and the presence of this form of recycling of the built stock [17-19].

In order to create a structural platform suitable for developing a new multi-criteria decision-making model, the focus of the research presented in this paper is on identifying key criteria and a structure of this type of model, based on comparative analysis of existing multi-criteria decision-making models.

2. EXAMPLES OF MULTI-CRITERIA DECISION-MAKING MODELS

Depending on the problem being solved, the number and characteristics of the solutions offered, and the differences in the interests of the participants, the decision-making process can be very complex [20]. In these cases, participants use techniques, which can be formal (cost analysis, multi-criteria decision analysis, decision trees, etc.) and informal (not covered by the research) to assist in decision making. All formal decision-making techniques are similar in that they contain a set of clearly defined rules based on which certain criteria are

selected and evaluated. Multi-criteria decision-making models are mathematical instruments that are one of the formal techniques used to solve problem tasks in various fields [21].

Multi-criteria decision-making models that are applicable in the processes of various adaptations of business facilities are presented.

2.1. Conversion meter model

The first version of this model, named the Transformation meter, was formed at the end of the twentieth century in the Netherlands when a large number of office buildings were out of use [22]. The model was tested through case studies by students of the Delft School of Architecture and other universities and then further developed. The structure of the model includes several checklists of criteria that are used to assess the potential of an unused commercial building for conversion into a residential building. The assessment takes place in the following steps:

- Database overview;
- The first, "quick" assessment, which includes four criteria, which have a "veto" character. If at least one of the criteria is assessed negatively, the facility is considered to have no potential for conversion and the assessment is not continued.
- The next step in assessing the potential for conversion of commercial premises into temporary or permanent residential premises is to complete two checklists of criteria relating to the location and characteristics of the facility. Positive responses are added up and multiplied by a specific weighting factor. The resulting value is recognized within one of the categories determined on the formed scale of potential for conversion. Belonging to one of the five categories represents the final result. Weighting factors and “veto” criteria are subject to change depending on the specifics of individual cases, and the criteria can be adapted to different target groups of potential users.
- The fourth step refers to the assessment of the financial feasibility of the conversion process of a specific business facility.
- The fifth step considers possible risks and problems that may arise during the conversion process itself [23].

The assessment of the potential for conversion of commercial to residential properties in this model is based on the evaluation of criteria related to the characteristics of the location and the property. The evaluation system is a method of assessment through checklist scales: each fulfilled criterion brings a point - the more fulfilled criteria, the greater the conversion potential [24].

2.2. TOBUS model

TOBUS is a multi-criteria model for assessing the current state of a business facility and evaluating the potential for different types of adaptation, estimating the cost of these processes and the amount of energy required. It was developed within the framework of the European research program *JOULE III* and is the result of joint research by experts from Denmark, France, Greece, Switzerland and the Netherlands [25]. The model contributes to a better organization of the adaptation process by the chosen method. Two basic tasks of the model have been recognized: diagnostics, the aim of which is to assess the current state of the business facility, and intervention, within which the type of adaptation is defined. In

order to simplify the use of this model, the software of the same name has been developed. The software uses data related to Switzerland, but the possibility of adapting the software to data from other countries that participated in the creation of this model has been left [26]. Choosing the appropriate type of adaptation of a business building takes place through four steps:

- *Assessment of the physical condition of the building* and the degree of degradation of the building's elements, which are grouped for easier consideration;
- *Assessment of the functional obsolescence of installation systems* in a building involves assessing the possibility of improving installation systems to meet current standards;
- *The assessment of the required amount of energy* is based on data on the current energy characteristics of the facility, to propose energy-saving measures, and
- *The assessment of the quality of the interior space* takes place through the evaluation of sub-criteria that describe comfort [27].

The selection of the appropriate type of adaptation is based on the assessment of criteria that are selected based on practical experience. The set of criteria contains quantitative criteria that are measurable and numerically expressed, but also qualitative criteria that are more flexible and immeasurable. To obtain a single result, it is necessary to translate qualitative values into a numerical and comparable form. In multi-criteria and multivariate models, such as this one, methods based on different families of algorithms are used to evaluate the proposed criteria and assign weighting factors. The evaluation of criteria in this model is carried out using the *COPRAS* method. The method was used to evaluate criteria that describe potential interventions for each segment of the facility [28]. The model was first tested within the framework of a pilot project for the development of the application process. It was then tested on individual buildings located in the countries participating in the study [27]. It is important to note that, since it suggests many different combinations of interventions, this model includes a large number of criteria and indicators that are not used every time, so the process of assessing the adequate type of adaptation of a business building is different for each building.

2.3. ARP model

This multi-criteria model is intended to assess the potential of a building for conversion and is based on an assessment of the lifespan of the building as a physical structure and its current age, expressed in years [29]. The assessment of the lifespan of a building as a physical structure is based on the consideration of a list of criteria related to the environment, the way the building is used and its structure characteristics. Individual criteria are separated and their values are duplicated [14]. A template from MS Excel is used to assess this part of the assessment. The assumed lifespan of the building as a physical structure is one hundred years, and then this time frame is reduced or increased depending on the value of the criteria. This assessment is based on a literature review, ISO standards, and the experiences of the model authors [30]. Further assessment is based on considering the period of use of the facility as the period of the facility's duration as a physical structure, reduced by different types of obsolescence, which are also the basic criteria of the model. The types of obsolescence that affect the period of use of the facility are proposed: physical obsolescence, economic

obsolescence, functional obsolescence, technical obsolescence, social obsolescence, legislative obsolescence, and political obsolescence [14].

The criteria are scored in percentages from 0% to 20%. This multi-criteria model is expressed in a diagram that shows that the maximum potential for conversion of each facility is at the end of the exploitation period of the original purpose [31].

Score values above 50% are interpreted as high potential, values between 20% and 50% as moderate potential, and values less than 20% as low potential for the facility to be converted [14]. When it comes to evaluation, this model uses the *SINDEX* methodology [32], which is based on multi-criteria analysis to calculate a sustainability index and rank projects [29].

2.4. iconCUR model

The multi-criteria model *iconCUR* uses criteria to visually present the characteristics and capabilities of an existing building at any point in its life, through a spatial diagram [14]. The model is based on three main criteria:

- *The current condition of the building* is a criterion that refers to the physical characteristics of the building;
- *Use value* is a criterion that describes the way an object is used;
- *Benefits* considered through *collective utility* and *stakeholder interests* (potential financial, social, and environmental benefits). *Collective utility* reflects the net benefit of the facility to all stakeholders, describing the level of financial contribution from the facility. *Stakeholder interests* are considered through a short-term perspective that considers utility in the first five years, a medium-term perspective that considers utility in the next fifteen years, and a long-term perspective that refers to the remaining life of the facility [33].

The evaluation is shown in a spatial model. The criteria are represented through axes with evaluation scales from 0 to 5. The values relating to the current state of the facility are on the x-axis, the utility value of the facility on the y-axis, and compliance with standards on the z-axis. Based on the consideration of the current state of the facility and its utility value, some type of intervention is proposed: maintenance, renovation, extension, reconstruction, conversion,... The third criterion evaluates the feasibility of the proposed intervention. If there are several facilities whose potential for some type of adaptation is assessed simultaneously, using this model, their results can be compared. It is also possible to show the change in the potential of the same facility after certain interventions. The spatial model has the shape of a cube. Each vertical edge of the cube represents one of the potential interventions. Each object is positioned within this spatial model by its coordinates – the values of the criteria. Given this, the criteria must be quantified in a certain way. For this reason, each of them is presented through several key sub-criteria that are evaluated according to a defined scale from 0 to 5 and within certain categories [14]. The model uses a weighted matrix approach that assigns weighting factors to each sub-criterion, according to their importance, proportionally to each group [33]. In different cases, the same sub-criterion may have a different share. By changing the share of the sub-criterion in the final value of the criterion, the value of the criterion itself changes [14]. The evaluation system used in this model belongs to the group of visual methods for multi-criteria decision-making and is based on the *PROMETHEE* family of algorithms [33].

2.5. PAAM *(Preliminary assessment adaptation model)* model

The *PAAM* model is a multi-criteria model designed to assess the potential of different types of commercial buildings for retrofitting [34]. Although the model focuses on a different type of adaptation than the one that is the subject of this research, the methodological approach applied in this model has an impact on the process of forming a new model [35].

Part of the research related to the development of this model is a very extensive literature review that identifies criteria that are significant for different types of adaptation. The criteria are grouped into six categories: economic, physical, location, legislative, social, and the category of criteria related to the environment [34]. Based on statistical analysis, criteria and indicators for this model were selected from the list of criteria that are significant for each type of adaptation of commercial buildings. The *PAAM* model contains three basic criteria: physical characteristics and size, land, and social factors.

The model does not consider criteria that, according to the model authors, equally affect the potential of the facility for this type of adaptation in all analyzed cases [34]. The valorization principle applied in this model is based on the statistical analysis of data collected from a large number of case studies of facilities that have already been treated with the type of adaptation in question (retrofitting). The starting point is a set of criteria, indicators, and the estimated impact of each indicator on the criterion, and then each criterion on the process of implementing the adaptation project as a whole. The impact of criteria and indicators is determined using the *PCA* method [34]. The basic idea of this technique is to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while preserving, to a large extent, the variations present in the data set [36]. The outcome of the analysis is a table of identified factors. Within the *PAAM* model, the qualitative assessment of the adaptation potential of each criterion is based on the percentage frequency of that attribute at a given value in many previous cases of adaptation. The percentage values of the identified potentials are standardized on a scale consisting of five levels. This scale valorizes all indicators to obtain the values of the individual criterion, and then valorizes the criterion to obtain the final assessment [34].

3. STRUCTURE OF MULTI-CRITERA MODELS

As a result of the analysis related to multi-criteria models used as an aid in the decision-making process and their elements, and the consideration of specific examples of multi-criteria models applicable in the process of adapting business facilities, a platform for creating a new model was formed, shown in Table 2. The platform represents a structure within which four parts are recognized, recognized as significant within the previous models. The established platform contains: influential factors, evaluation, defining the form of results, and the method of using the multi-criteria model.

3.1 Part I: Influential factors

The first part of the platform for the new multi-criteria model presents several factors that have an impact on the potential for conversion, selected based on the analysis of the presented multi-criteria models and relevant literature. General influential factors are grouped (location of the building, characteristics of the building, quality of the interior space, financial justification, energy sustainability and market), specific influential factors determined by the

type of adaptation (capacity of the building, current standards for the new purpose and expected profit during the exploitation period) and specific influential factors that are a consequence of the specificity of the context in which the multi-criteria model was developed and/or for which it is intended (location of the building in the context of the urban development in which the building is located and the surrounding area of the building) [35].

Table 2 shows the influential factors that were observed in the analyzed multi-criteria models, and may become (not necessarily all) parts of new multi-criteria models. It is expected that new multi-criteria models will contain a larger number of influential factors within each group, which will be defined through the specifics of the research that resulted in them.

3.2. Part II: Criteria evaluation

The second part of the platform presents the basic steps related to the evaluation of selected influential factors. The first step is to define the type of problem: is it a relative evaluation in which several options (alternatives) are compared to selected criteria and the most suitable solution for a given problem is selected among them, or is it an absolute evaluation, where one or more options are evaluated through selected criteria and compared with predefined categories or prototypes. The second step is to introduce a hierarchy among influential factors by assigning weights or determining priorities. This is followed by the selection of the appropriate *MCDA* method and determining preferences.

3.3. Part III: Defining the result form

Among the presented multi-criteria models, it was noted that the forms of the results are different. In the *Conversion meter* model, the result is numerical and represents the sum of points assigned to the selected answers (during the filling in of the checklists). In the *TOBUS* model, the result is a set of recommendations that suggest certain stucture interventions. In the *ARP* model, the result is shown numerically, as a percentage, but also through a two-dimensional graphic display. The spatial graphic display is the form of the result in the *iconCUR* model. The "qualitative" sum is the result of the evaluation in the *PAAM* model - descriptive values are summed up, and the result is one of the terms from a defined scale of possible results. Given that multi-criteria models of this type contain both quantitative and qualitative criteria and represent a type of assessment of a certain potential or opportunity, the numerical forms of the solution may be insufficiently precise and reduce the range of possible solutions and the differences between them. When defining the form of the results, it is necessary to consider which form of results is most suitable for potential users of the multi-criteria model. Depending on the specifics of the individual multi-criteria model, a set of recommendations, with the possibility of visual (two-dimensional or three-dimensional) display, is considered an adequate form of results.

3.4. Part IV: Method of application of multi-criteria decision-making models

As a way of applying the multi-criteria model, based on the conducted analysis of multi-criteria models and relevant literature, it is proposed to create software within which checklists composed of indicators and their proposed values will be filled out.

Table 2. Proposal for a platform for creating a new model

Part I: Influential factors		
Group 1: general influential factors	Location	Infrastructure
		Distance from different types of content
	Building's characterstics	Adaptability
	Quality of interior space	Several types of comfort
	Financial feasibility	Investments
	Energy sustainability	Possibilities for improving the energy properties of a building
	Market	Feasibility of a (new) use
Group 2: specific influential factors for a certain type of adaptation[4]	Building capacity	Number of units of a new use
	Current legislative standards for new use	Provisions from current legislative standards that may initiate (additional) structure interventions
	Expected profit during the exploitation period	Value per square meter (for sale and rent)
Group 3: influential factors based on the specificities of spatial context	Building location (urban area)	Distance from different types of content [5]
	Building environment	Presence of certain contents near the building
Part II: Evaluation		
Defining the type of problem	Relative (choice/ranking) or absolute (sorting) evaluation;	
Parameters: weights	Establishing a hierarchy among influential factors – assigning weights or priorities;	
Choosing a method for multi-criteria decision-making	The multi-criteria decision-making method (ELECTRE, PROMETHEE, phases,…) is determined based on the type of formulated problem;	
Preference system	Determining preferences regarding the selected method for multi-criteria decision making;	
Part III: Defining the result form		
Potential result form	Numerical values (sum of points or percentages); Visual representations – diagrams; Set of recommendations/ comments	
Part IV: Application of new multi-criteria decision-making models		
Potential way of application of new multi-criteria decision making models	Software – entering data about a building through checklists	

[4] Criteria and indicators within this group are proposed for conversion as a type of adaptation.
[5] It refers to distances that are considered acceptable, which varies depending on the regulations of a particular city.

4. CONCLUSION

Various aspects of repurposing brownfield sites are the focus of numerous researchers. In the *Introduction* several research lines were identified, clearly defined focus. One of the recognized lines of research is devoted to multi-criteria decision-making models, which represent formal decision-making techniques. In the second part of the paper, several multi-criteria models have been considered that are intended to evaluate the potential of office buildings for various types of adaptation. Groups of criteria (sub-criteria) and indicators have been identified, with their representation in the models. In the third part of the paper, the result of the comparative analysis of the selected multi-criteria models is a platform (shown in Table 2) that can be used for creating other multi-criteria models that are intended to evaluate the potential of different purpose buildings for various types of interventions.

The findings of this research establish a basis for future development of advanced MCDM models applicable in similar domains.

ACKNOWLEDGMENTS

This research was done at the University of Belgrade – Faculty of Architecture, within the Research Laboratory: *Optimal lighting design in architecture.*

REFERENCES

[1] Remoy, Hilde (2010). **Out of Office: A Study on the Cause of Office Vacancy and Transformation as a Means to Cope and Prevent**, *Doctoral Thesis*, TU Delft, Netherlands.

[2] Remoy, Hilde & van der Voordt, Theo J.M. (2014). **Adaptive reuse of office buildings: opportunities and risks of conversion into housing**, *Building Research and Information* 42 (3), 381–390.

[3] Heath, Tim (2001). **Adaptive re-use of offices for residential use: the experiences of London and Toronto**. *Cities* 18 (3), 173-184.

[4] Mackay, Roderick, Remoy, Hilde. & de Jong, Peter (2009). **Building Costs for Converting Office Buildings: Understanding Building Cost by Modeling**. *Conference paper*.

[5] Remoy, Hilde. & Street, Emma (2018). **The dynamics of post-crisis spatial planning: a comparative study of office conversion policies in England and The Netherlands**. *Real Estate Management* 77, 811-820.

[6] Olivadese, Rosamaria, Remoy, Hilde, Berizzi, Carlo & Hobma. Fred (2016). **Reuse into housing: Italian and Dutch regulatory effects**, *Property Management* 35 (2), 165–180.

[7] Bullen, Peter & Love, Peter (2010). **The rethoric of adaptive reuse or reality of demolition: views from the field**. *Cities* 27, 215-224.

[8] Barlow, James & Gann, David (1995). **Flexible planning and flexibile buildings: reusing redundant office space**. *Journal of Urban Affairs* 17 (3), 263-276.

[9] Remoy, Hilde, de Jong, Peter & Schenk, Wiechert (2011). **Adaptable office buildings**, *Property Management* 29 (5), 443–453.

[10] Ouf, Mohamed, O'Brien, Wiliam & Gunay, Burak. (2019). **On quantifying building performance adaptability to variable occupancy**. *Building and Environment* 155, 257-267.

[11] Slaughter, Sarah (2001). **Design strategies to increase building flexibility**. *Building Research & Information* 23, 208-217.

[12] Gosling, Jonathan, Sassi, Paola, Naim, M. & Lark, Robert (2013). **Adaptible buildings: A system approach**. *Sustainable Cities and Society* 7, 44-51.
[13] Douglas, James (2006). **Building adaptation**. *Butterworth – Heinemann*, Oxford.
[14] Wilkinson, Sara J., Remoy, Hilde & Langston, Craig (2014). **Sustainable Building Adaptation: Innovations in Decision-Making**.Wiley Blackwell.
[15] Yung, Esther H. K. & Chan, Edwin H.W. (2012). **Implementation challenges to the adaptive reuse of heritage buildings: towards the goals of sustainable, low carbon cities**. *Habitat International* 36, 352-361.
[16] Remoy, Hilde, Koppels, Philip W., Van Oel, C. & De Jonge, Hans. (2007). **Characteristics of vacant offices: a Delphi – approach**, *ENHR Rotterdam* 2007. Rotterdam.
[17] Plevoets, Bie & van Cleempoel, Koenraad. (2012). **Adaptive Reuse as a Strategy towards Conservation of Cultural Heritage: A Survey of 19th and 20th Century Theories**. In *Proceedings of the IE International Conference Reinventing Architecture and Interiors: The Past, the Present and the Future*, 29–30 March: London, UK. (3.1.2024.)
[18] Plevoets, Bie & Sowinska-Heim, Julia (2018). **Community initiatives as a catalyst fo regeneration of heritage sites: vernacular transformation and its influence on the formal adaptive reuse practice**. *Cities* 78, 128-139.
[19] Plevoets, Bie, & Van Cleempoel, Koenraad. (2013). **Adaptive reuse as an emerging discipline: an historic survey**. In G. Cairns (Ed.), *Reinventing architecture and interiors: a socio-political view on building adaptation*, 13-32. London: Libri Publishers.
[20] Nedeljković, Damjana, Jurenić, Tatjana. & Čabarkapa, Aleksandra (2023). **The multi-criteria decision making models in architecture: approach development throughout the history**. *Proceedings / 16th International Scientific Conference „Integration, Novelty, Design, Interdisciplinarity, Sustainability" iNDiS 2023*, Novi Sad, Serbia, 16-17 November, 2023, 760-767.
[21] Bouyssou, Dennis, Marchant, Thierry, Pirlot, Marc, Tsoukias, Alexis & Vincke, Philippe (2006). **Evaluation and decision models with multiple criteria: stepping stones for the analyst**. New York: *Springer Science+Business Media*, Inc.
[22] Geraedts, Robert & van der Voordt, Theo J.M. (2004). **Offices for living in. An instrument for measuring the potential for transforming offices into homes**, *Open House International* 28 (3), 80–90.
[23] Geraedts, Robert P., van der Voordt, Theo & Remoy, Hilde (2017). **Conversion Meter: a new tool to assess the conversion potential of vacant office buildings into housing**, in: *Proceedings of the International Conference on Advances on Sustainable Cities and Buildings Development* (SB-LAB 2017), Green Lines Institute for Sustainable Development.
[24] Geraedts, Robert & van der Voordt, Theo J.M. (2007). **A Tool to Measure Opportunities and Risks of Converting Empty Offices into Dwellings**, *Sustainable Urban Areas*, Rotterdam.
[25] Balaras, Constantinos A. (2002). **TOBUS – a European method and software for office building refurbishment**, *Energy Buildings* 34, 111–112.
[26] Flourentzou, Flourentzos, Genre, Jean-Louis & Roulet, Claude-Alain (2002). **TOBUS software – an interactive decision aid tool for building retrofit studies**, *Energy Buildings* 193–202.
[27] Caccavelli, Dominique & Gugerli, H. (2002). **TOBUS - a European diagnosis and decision-making tool for office building upgrading**, *Energy Buildings* 34, 113–119.

[28] Kaklauskas, Arthur, Kazimieras Zavadskas, Edmundas & Raslanas, Saulius (2005). **Multivariant design and multiple criteria analysis of building refurbishments**, *Energy Buildings* 37, 272–361.

[29] Langston, Craig & Shen, Li-Yin (2007). **Application of the adaptive reuse potential model in Hong Kong: a case study of Lui Seng Chun**, *International Journal of Strategic Property Management* 11 (4), 193–207.

[30] Langston, Craig A. (2011). **Estimating the useful life of buildings**, in: *Proceedings of the 36th Annual Conference for Australasian Building Educators Association (AUBEA).* AUBEA, 418–432.

[31] Langston, Craig, Yung, Esther H. & Chan, Edwin H. (2013). **The application of ARP modeling to adaptive reuse projects in Hong Kong**, *Habitat International* 40, 233–243.

[32] Farjami, Elnaz & Turker, Ozlem Olgac (2021). **The extraction of prerequisite criteria for environmentally certified adaptive reuse of heritage buildings**, *Sustainability* 13 (6), 3536, doi.org/10.3390/su13063536.

[33] Langston, Craig & Smith, Jim (2012). **Modelling property management decisions using 'iconCUR'**, *Automation in Construction* 22, 406–413.

[34] Wilkinson, Sara J. (2014). **Office building adaptation and the growing significance of environmental attributes**, *Journal of Corporate Real Estate* 16 (4), 252–265.

[35] Nedeljkovic, Damjana, Jurenic, Tatjana & Djokic, Lidija (2023). **Comparative analysis of multi-criteria models for decision-making in the process of building adaptation**. *Helyion* 9(6), doi. org/10.1016/j.heliyon.2023.e16620.

[36] Jolliffe, Ian T. (2002). **Principal component analysis**. Springer Series in *Statistics*, Springer.

doi.org/10.62683/SINARG2025.030

Preliminary report

INVESTIGATIVE WORKS TO DETERMINE THE NATURE OF CRACKS IN THE INTAKE TOWER OF THE ĆELIJE DAM

Uroš Mirković[1], Dušan Stevanović[2], Nikola Mirković[3]

Abstract

The Ćelije Dam is located in the municipality of Kruševac, built on the Rasina River near the village of Ćelije, approximately 30 km upstream from Kruševac. The construction of the dam was completed in 1978. Ćelije Dam is an earthfill dam, with a height of 51.5 m and a horizontal crest at an elevation of 285 m above sea level. The normal water level of the dam is at 277 m above sea level. The construction of the Ćelije Dam created a reservoir with a total volume of 64 million cubic meters. To extract water from the reservoir, a cylindrical intake tower was constructed with an internal diameter of 4.6 m. The tower is 46.0 m high, with cylindrical walls that are 1.0 m thick. A visual inspection of the intake tower, conducted after extreme hydrological events in the second half of 2019, revealed cracks along almost the entire height of the tower. The cracks are grouped into three vertical directions around the tower, positioned approximately 120° apart from each other. At the end of 2020, the Jaroslav Černi Water Institute initiated extensive investigative works to determine the extent of the damage to the concrete structure of the intake tower and the causes of its occurrence. The primary objective of the investigations was not only to assess the extent of the damage but also to identify the reasons for its occurrence and to predict the future behavior of the structure under operational conditions.

Key words: *Ćellije Dam, Intake Tower, Cracks, Investigative Works, Technical Monitoring*

[1] PhD, Research Assistant, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, uros.mirkovic@jcerni.rs, ORCID 0000-0001-6781-5798
[2] MSc Civ. Eng., PhD student, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, dusan.stevanovic@jcerni.rs, ORCID N/A
[3] PhD, Research Associate, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, nikola.mirkovic@jcerni.rs, ORCID 0000-0002-5980-3049

1. INTRODUCTION

With the construction of the “Ćelije” dam, a reservoir with a total volume of 64 million cubic meters was formed. The water from this multipurpose reservoir is primarily used for water supply, as well as for improving water quality downstream during low-flow periods. In addition, the reservoir provides storage capacity for flood wave retention and helps prevent flooding during high-water events.

The dam is 51.5 meters high, with a horizontal crest elevation at 285 meters above sea level. The crest is 8 meters wide, and the dam is 220 meters long. The normal water level of the reservoir is at an elevation of 277 meters above sea level.

At the upstream end of the tunnel, a cylindrical intake tower (Figure 1.) with an internal diameter of 4.6 meters was constructed to draw water from the reservoir [1], [2]. The tower has a height of 46.0 meters above the crown of the intake tunnel, with wall thickness of 1.0 meter.

Inside the tower, there are two vertical pipelines Ø900 mm used for water supply purposes. The intake pipes, with a diameter of Ø700 mm, are positioned at elevations 280, 277, 274, 271, 268, 265, and 255 meters above sea level [3], [4].

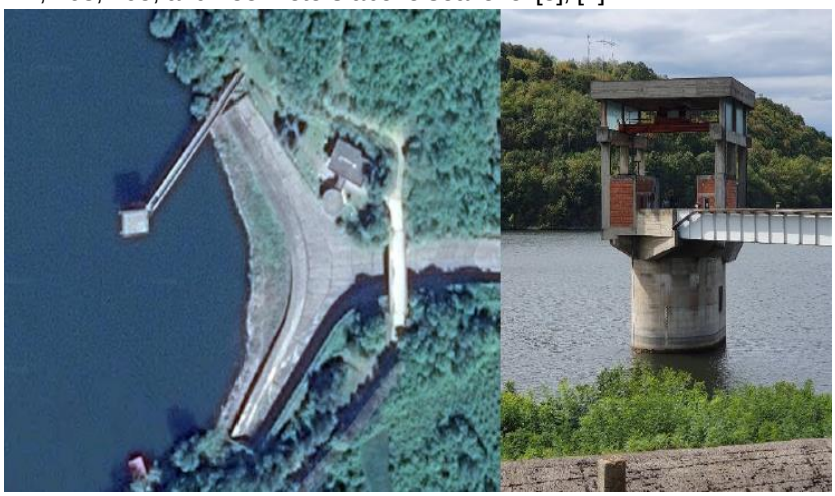


Figure 1. Intake tower with access bridge

A visual inspection of the intake tower, conducted following extreme hydrological events in the second half of 2019, revealed cracks along nearly the entire height of the structure. The cracks are grouped in three vertical directions, each oriented approximately 120° from the others. The crack openings are widest at mid-height, measuring between 1 and 2 millimeters.

In 2021, the Jaroslav Černi Water Institute initiated extensive investigative works with the aim of determining the extent of damage to the concrete structure of the intake tower and identifying the causes of its occurrence.

The primary objective of the conducted investigative works was not only to determine the extent of the damage, but also to identify its causes and assess the future behavior of the structure under operational conditions. For this reason, it was planned that all investigations be carried out over a one-year period, to monitor the behavior of the structure throughout an annual cycle.

The investigative works included the implementation of the following activities: geodetic monitoring of the tower, detailed visual inspection of the structure and equipment, exploratory drilling of the concrete lining to determine the depth of damage, ultrasonic measurement of crack depths using surface scanning of the concrete, continuous deformation monitoring within the intake tower and assessment of changes in the cylindrical contour of the structure, continuous air temperature monitoring, and the development and commissioning of a system for data collection, archiving, and storage.

The position and width of the crack openings were determined through a detailed visual inspection and mapping of the entire inner surface of the tower, as well as inspection of the visible part of the outer surface above the reservoir water level. To determine the depth of the cracks, two methods were used: a non-destructive method (ultrasonic scanning along all three crack systems) and drilling into the intake tower wall in the direction of the cracks to verify the results obtained by ultrasonic scanning, i.e., to calibrate the non-destructive measurement model.

A review of the documentation provided by the User [5] and measurements on-site revealed that the intake tower was constructed according to the planned dimensions, with minor deviations and modifications. The most significant deviation from the project was the absence of the reinforced concrete platform/landing, which was intended not only to facilitate movement through the tower but also to shorten the height of the tower's cylinder. Instead of the reinforced concrete platform, steel platforms were constructed.

This paper presents an overview of the conducted investigative works and the installed equipment, as well as the measurement results. Additionally, an analysis of the condition of the intake tower has been performed, with recommendations for further activities, including tower rehabilitation, and suggestions for ongoing monitoring.

2. METHODOLOGY OF CONDUCTED INVESTIGATIVE WORKS

To collect the necessary information for assessing the condition and behavior of the intake tower, it was necessary to develop a monitoring system for the tower, which would measure and track specific parameters.

The system was designed and implemented to collect most data automatically in real-time, ensuring continuous data flow. A smaller part of data and measurements, due to their nature, had to be taken manually with a predefined frequency. The monitoring system of the tower included several main groups of observations, which differ based on the applied methods: geodetic observations, physical observations, visual observations, and other observations.

While geodetic observations refer to measurements using exclusively geodetic methods, physical observations represent a group of various parameters (displacements, pressures, etc.) measured using different methods and instruments. Visual observations involve regular and emergency site visits, along with the inspection and recording of any noticed changes. Other observations relate to specific activities, such as testing of hydro-mechanical equipment and similar [6].

The technical solution for the monitoring system of the intake tower at the "Ćelije" dam includes the monitoring of the following physically measurable quantities, which serve as indicators of the behavior and condition of the structure: absolute horizontal displacements of the top of the intake tower, opening/closing of cracks in the inner wall of the intake tower,

concrete temperature, temperature of the vertical pipelines, relative displacement of vertical pipelines in relation to the concrete structure, and measurement of deformations (changes in the contour of the internal cylinder of the intake tower).

2.1. Overview of the Data Collected from the Facility

Considering that there is a technical monitoring system in place at the dam, for the purpose of analyzing the condition of the structure, all available measurement and observation data from the tower were collected. This includes data on the water level in the reservoir (Figure 2.) and the water temperature at the intake levels (Figure 3.).

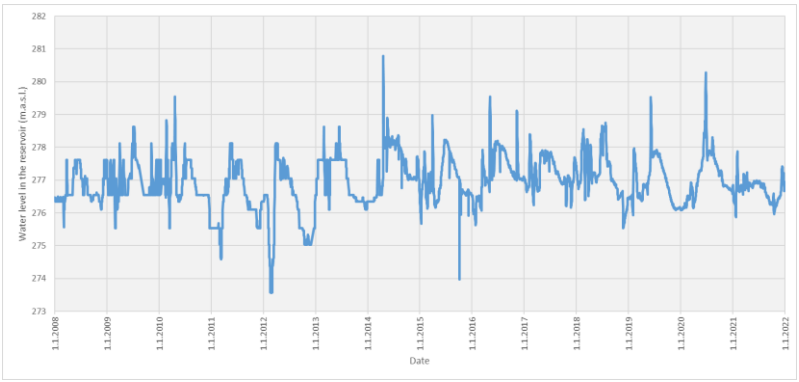


Figure 2. Water Level in the Ćelije Reservoir

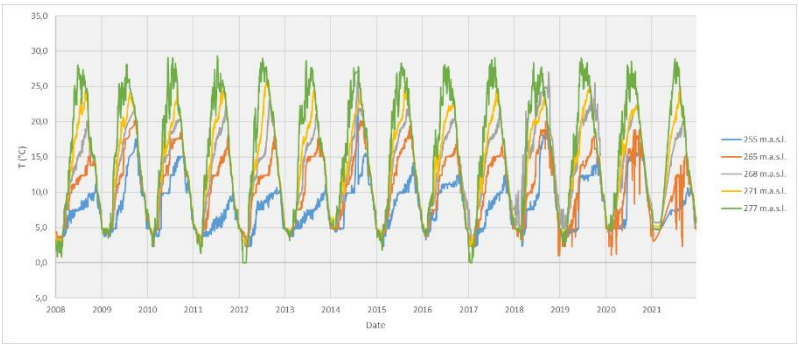


Figure 3. Water Temperature in the Ćelije Reservoir at the Intake Locations

2.2. Overview of the Conducted Research Works

2.2.1. Visual Inspection of the Structure

From December 15, 2020, to December 18, 2020, a visual inspection of the internal concrete surfaces of the intake tower was carried out to determine the position of all cracks. Following this, all observed cracks were mapped, and the crack openings were measured. A visual inspection of the external concrete surfaces above the water level in the reservoir was also performed. The mapping of cracks is graphically presented in Figure 4.

Among all the cracks, three vertical cracks are most prominent, extending throughout the entire height of the tower. The openings of these cracks vary, with the largest being in the central part of the cylinder's height. Since the cracks were dry and no leakage was detected through them, it was concluded that they do not extend through the full depth of the concrete, which was later confirmed by exploratory drilling.

No deformations or mechanical damage to the tower's equipment were observed during the visual inspection.

2.2.3. Geodetic Works

The goal of the geodetic observation was to monitor the movement of the tower between two epochs of measurements (observations) using characteristic points on the structure from a 2D reference network.

The results of the geodetic observation of the tower show cyclical movements throughout the year, but after the last measurement, the tower did not return to its original position when the measurements were initially taken. Due to the very small number of observations, it was not possible to draw a clear conclusion about the behavior of the tower and its relationship to the external influences acting on the structure.

2.2.2. Investigative drilling

The selection of drilling locations was made based on the requirement that drilling should not compromise the water tightness of the tower's structure, meaning that priority was given to locations above the normal level, and boreholes were located in areas where ultrasonic measurements indicated greater depths.

At crack no. 1 (Figure 4), borehole P1-K1 (K1) was drilled to a depth of about 450 mm. The borehole remained dry throughout its length, while the crack continued deeper. Subsequent drilling extended the borehole by 220 mm, after which the crack was observed to extend beyond the cross-section of the core of the borehole.

At crack no. 2, boreholes P2-K1 (K2), P2-K2 (K2’), and P2-K3 (K2") were drilled.

P2-K1 (K2) was a borehole with a depth of about 450 mm. This borehole remained dry throughout its length and continued further into the depth. P2-K2 (K2’) was a borehole with a depth of 115 mm, while P2-K3 (K2") was about 285 mm deep. Both cracks extended beyond the cross-sections of these boreholes, which remained dry throughout their length.

At crack no. 3, borehole P3-K1 (K3) was drilled to a depth of about 460 mm. The crack continued further into the depth of the concrete. The borehole remained dry throughout its length.

The results of the exploratory drilling, along with the measured but not final depths of the cracks, indicated that all three vertical cracks extend beyond half the thickness of the tower's cross-sectional profile.

2.2.5. Ultrasonic measurement

The goal of using ultrasonic measurements was to gain a more detailed insight into the condition and quality of the concrete, but primarily to determine the depth of the cracks. The individual locations of the measurement points are shown in Figure 4. Field measurements were performed using modern digital ultrasonic equipment from TICO Proceq testing instruments [7].

In the areas where ultrasonic measurements were conducted, measurements were also carried out using a Schmidt hammer to define the concrete's strength.

2.2.6. Testing of strength

Schmidt hammer testing represents a fast and non-destructive method used to assess the compressive strength of concrete in the intake tower. The measurements were carried

out with the modern digital Schmidt hammer Silver Schmidt 8200 [8]. This method is classified as non-invasive, meaning there is no destruction of the tested concrete, and no repairs are required after the test.

At each measurement location, several cycles of testing were performed, which involved between 9 and 11 impacts, as prescribed by European standards, in order to obtain the most representative data.

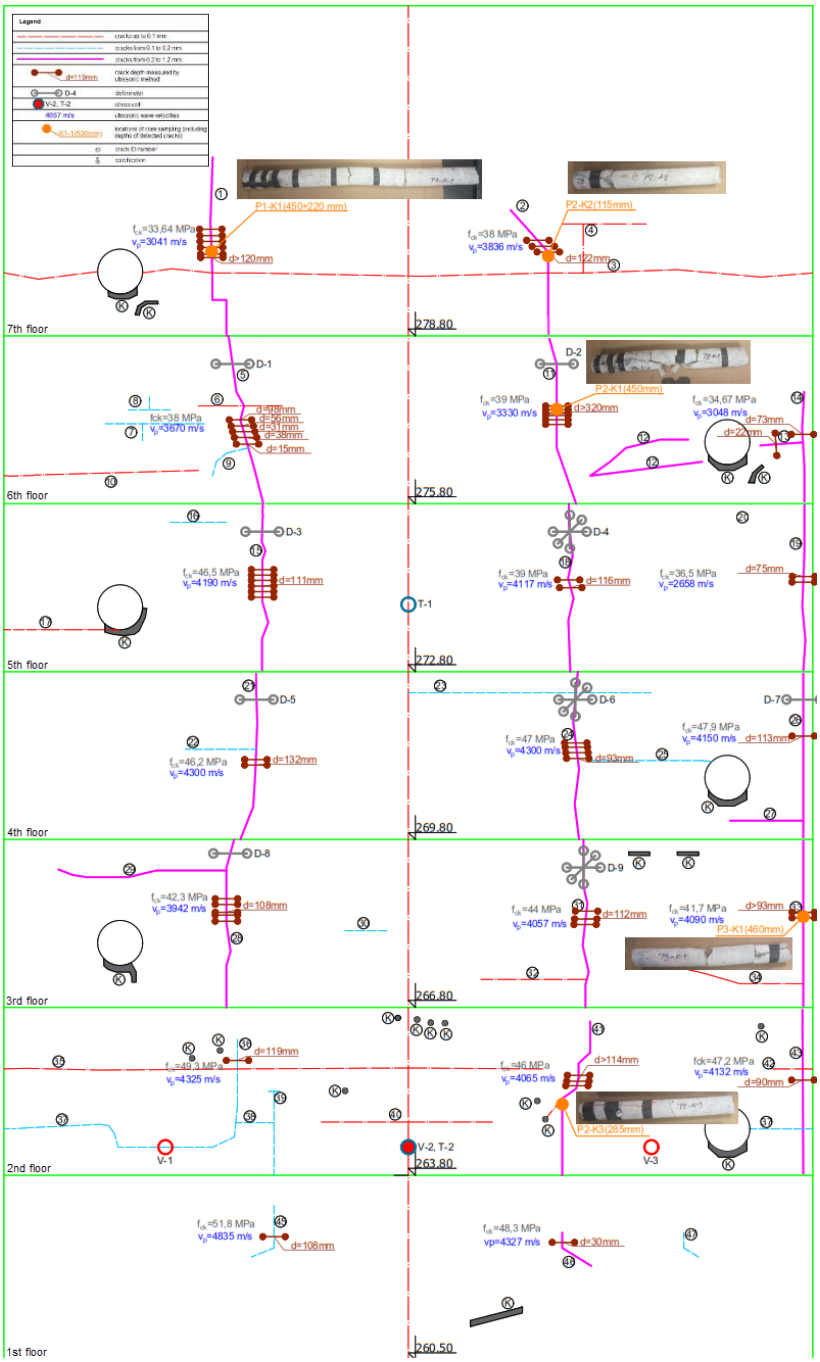


Figure 4. The unwrapped profile of the cylinder of the intake tower with the instruments and research results shown

2.2.4. Convergence measurement

Convergence measurement serves as an indicator of deformation of the internal profile of the intake tower.

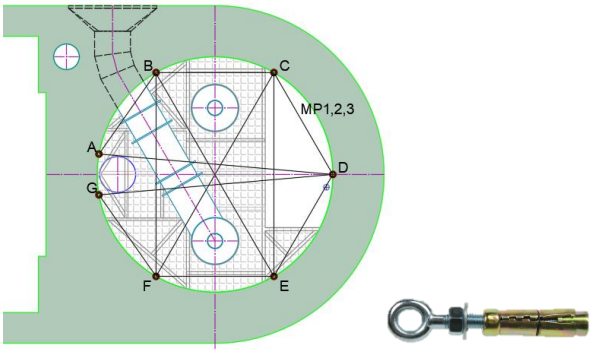


Figure 5. Measurement profile and benchmark for convergence monitoring

The benchmarks for convergence monitoring were embedded in the concrete of the intake tower's inner wall, with a total of 7 benchmarks installed on each of the 3 measurement profiles (at elevations 280.65, 274.80, and 268.60 meters above sea level). The distances between pairs of benchmarks are measured, and by subtracting the results from the previous measurement series, relative changes in distance are obtained (Figure 5.). These values are used to monitor the behavior of the tower profile over time. A total of 12 measurement directions were established for each profile.

2.2.7. Measurement of Crack Width Changes

The opening and closing of cracks on the inner wall of the intake tower of the "Ćelije" dam was monitored using electrical crack gauges (teledeformeters, Figure 6.). A total of 9 teledeformeters were installed on the structure, including 6 uniaxial and 3 triaxial devices.

In uniaxial teledeformeters, measurements are taken in the principal direction of crack activity, i.e., perpendicular to the direction of the crack. A triaxial teledeformeter is essentially a set of three uniaxial sensors installed and measured along three orthogonal directions: direction "T" (crack opening/closing), direction "R" (displacement along the crack line), and direction "V" (displacement perpendicular to the inner wall plane of the tower).

The installed teledeformeters are manufactured by SisGeo, model D313 [9].



Figure 6. Installed Teledeformeters (Triaxial and Uniaxial)

2.2.11. System for Data Acquisition, Archiving, and Transmission

Automatic and telemetry-based data acquisition on the installed instruments is carried out using a special data acquisition system, the central part of which is a data logger with an appropriate extension in the form of a twenty-channel multiplexer, allowing the connection of all existing electrical instruments in the observation system (Figure 7.).



Figure 7. Layout of the measurement cabinet with data logger and accompanying equipment

3. ANALYSIS OF THE MOST IMPORTANT OBSERVATION RESULTS

The results of the ultrasonic testing allowed for the determination of the ultrasonic wave velocities in the immediate nearness of the crack (m/s) as well as the estimation of the crack depth (mm), which are shown in Figure 4 at the testing locations. Additionally, the dynamic modulus of elasticity of the concrete (MPa) was obtained. The crack depths were determined using the standard method, which involves measuring the transit time across the crack for two positions of the piezoelectric transducer, with the crack always located in the middle of the measuring device. Also, based on the conducted exploratory drilling, the calibration of the ultrasonic method during testing was performed [10].

Based on the obtained values from the Schmidt hammer test, a diagram was constructed indicating the established correlation between the concrete strength and the ultrasonic wave velocity (Figure 8.).

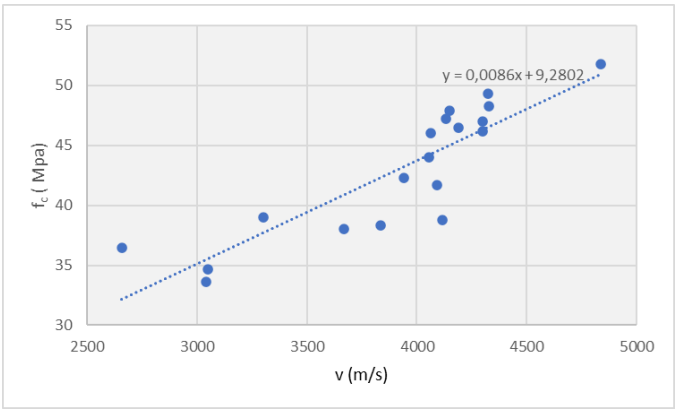


Figure 8. The relationship between the ultrasonic wave velocity and concrete strength

Considering the obtained results, it can be said that the concrete strength is in the range of 34.0 to 51.0 MPa, with an average of around 43.0 MPa.

The results of convergence measurements showed millimeter changes in the diameter of the intake tower and even larger changes in the circumference of the inner wall. These displacements are consistent with the external influences acting on the structure, primarily the changes in the water level in the reservoir and temperature changes. Namely, with the lowering of the water level in the reservoir, greater convergence was observed, which simultaneously coincided with an increase in both air and water temperatures. The increments of measurements on one of the profiles (MP1 at elevation 280.65 m.a.s.l.) are shown in the following image, where positive values represent the divergence of the reference points, and negative values represent their approach.

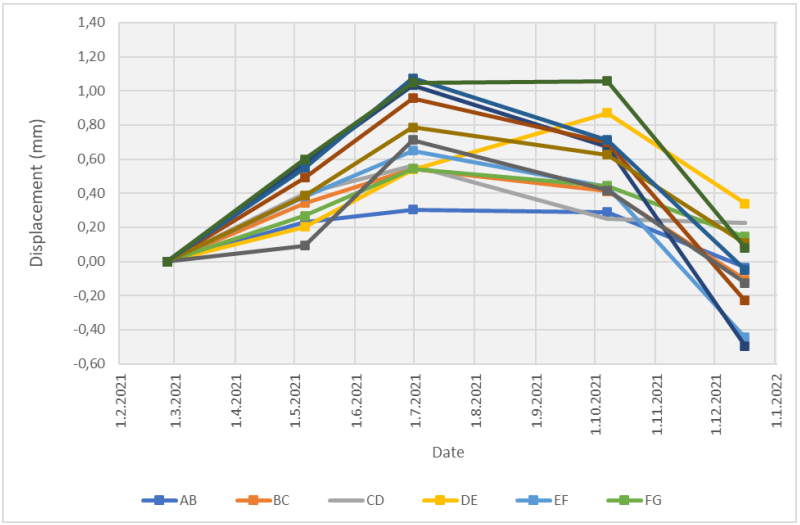


Figure 9. The change in the contour of the cylinder on one measurement profile (MP1)

The results of measuring the crack opening indicate cyclic deformations of the intake tower. The measured change in the opening is consistent with the results of the cylinder convergence measurements, meaning that the reduction in the crack opening coincides with the expansion of the tower's cylindrical contour. Positive values in the diagrams below refer to the upward movement of the right end of the crack relative to the left (D-4R, Figure 10.), the opening of the crack (D-4T, Figure 11.), and the lifting of the right end of the crack relative to the left (D-4V, Figure 12.).

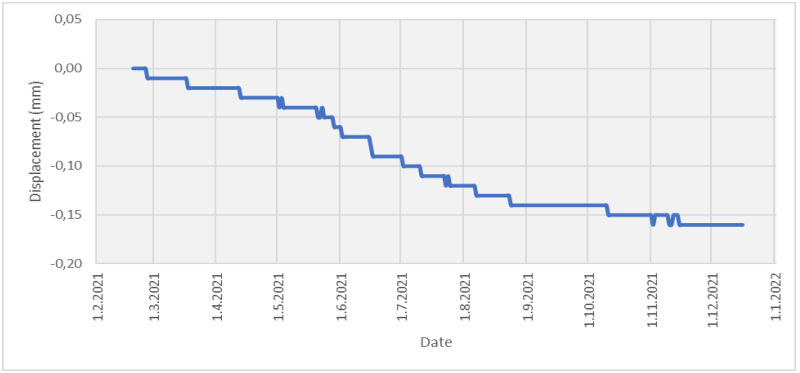


Figure 10. The diagram of crack behavior (deformeter D-4R)

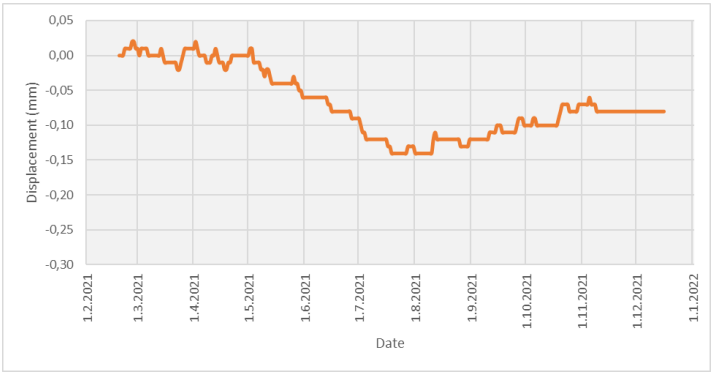


Figure 11. The diagram of crack behavior (deformeter D-4T)



Figure 12. The diagram of crack behavior (deformeter D-4V)

4. DISCUSSION AND CONCEPT OF THE SOLUTION FOR THE REHABILITATION

Based on the previously mentioned information, in the next period, it is necessary to prepare the technical documentation for the rehabilitation of the structure and begin the rehabilitation works to ensure the permanent safety and functionality of the structure.

It is recommended that the calculation analyses be performed using one of the FEM software packages that have the ability to model the complex geometry of the structure (Figure 13.), taking into account all combinations of actions acting on the structure, as well as boundary conditions. This type of modeling allows the designer, based on the presented measurements, to calibrate the parameters of the tower model and perform stress-strain analyses (for the case before and after rehabilitation) along with calculating the safety factor of the structure.

Considering that, according to the results of the investigative works, the cracks were caused by various deformations due to the complex actions acting on the tower, and taking into account the lack of the RC platform whose task was to tension the structure in multiple places along the height, the concept of the technical solution should be based on a solution that will bring the tower to the condition foreseen by the project.

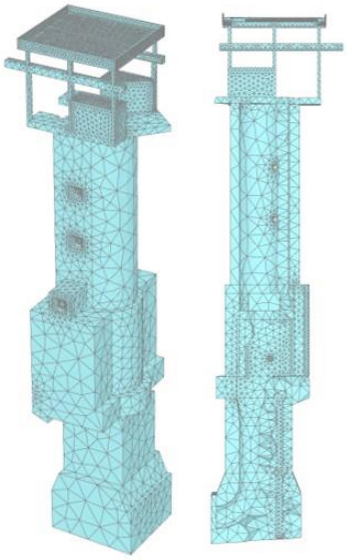


Figure 13. FEM model of the water intake tower

As an additional measure to tension the tower and ensure cooperation between the existing structure and the newly designed RC platforms, the technical solution needs to consider additional tensioning of the structure on the external side with RC pre-stressed beams at the levels of the new RC platforms or according to the results of the rehabilitation analyses. These works would be partly performed underwater, with the pre-stressing of beams being carried out after the construction of the RC platforms.

5. CONCLUSION

Based on the analysis of all the data obtained in the previous period, as well as the review of the available documentation about the facility, the following conclusions can be drawn:

- A visual inspection of the water intake tower revealed that the tower was not fully constructed according to the project documentation. The most significant deviation is the absence of the reinforced concrete platform/landing, which was intended not only to provide movement through the tower but also to stiffen the tower's cylinder along its height.
- The results of the observations and measurements indicated deformations in the concrete structure of the water intake tower, which may have caused the observed damage in the form of three vertical cracks along the height of the tower. This primarily refers to the results of convergence measurements and the crack width changes, which correspond to fluctuations in the water level in the reservoir and temperature variations. Particularly concerning are the drilling results, which revealed that the cracks extend through more than half the thickness of the concrete section.

The integrity of the tower at the given moment was not threatened, but the unfavorable operational conditions in which the tower might be subjected (earthquake, fluctuations in the water level in the reservoir, extreme temperatures, etc.) could lead to further development of

damage, which could result in water leakage into the tower, making water intake from the reservoir difficult or nearly impossible.

The future technical solution needs to consider the possibility and effects of implementing an RC platform entirely according to the water intake tower project (removing the existing steel platforms or connecting it with the existing steel structure) as well as the execution of RC pre-stressed beams on the outside of the tower.

REFERENCES

[1] **MHPP „Ćelije“ - Conceptual design and feasibility study - Book 1**, Energoprojekt Hidroinženjering, Belgrade, 2009.

[2] **„Ćelije“ Reservoir - Conceptual design - Book I.1 - Evacuator - Hydro-construction part**, Energoprojekt, Belgrade, 1974.

[3] **„Ćelije“ Resevoir - Evacuator - Main Project - 5460- XГ/VI - Volume VI - Static and Hydraulic Calculation**, Serbia Project, Hydrosector, Belgrade, 1970.

[4] **"Ćelije" Reservoir - Main Project - Book IV, Volume 2/2 - Evacuator - Intake Tower and Inlet Tunnel - Formwork and Reinforcement Plans**, Energoprojekt, Belgrade, 1975.

[5] **"Ćelije" Reservoir - Detailed Design - Book IV, Volume 2/2 - Hydro-construction part - Evacuator - Intake Tower**, Energoprojekt, Belgrade, 1978.

[6] "Jaroslav Černi" Water Institute, **Bureau for Structures and Geotechnics: Instructions for technical inspection of high dams**, special book, Book 24, Belgrade, 1982.

[7] https://www.iziis.ukim.edu.mk/wp-content/uploads/labs/ndt/Proceq_Tico_Ultrasonic_Operating_Instructions.pdf (29.04.2025.)

[8] https://www.screeningeagle.com/en/products/silver-schmidt-os8200 (29.04.2025.)

[9] https://sisgeo.com/wp-content/uploads/Prodotti/Crackmeters%20and%20Joint%20meters/Electrical%20Crackmeters%20and%20Jointmeters/EN/Datasheet/D313_EN_16_electrical_and_vibrating_wire_crackmeters.pdf (29.04.2025.)

[10] **“Ćelije” Dam - Urgent Research Works with the Procurement and Installation of Equipment on the Water Inlet Tower of the "Ćelije" Dam** - *Final Report with Measurement and Observation Results and the Concept of the Technical Solution for Remediation*, Belgrade, 2022.

doi.org/10.62683/SINARG2025.031

Research paper

PRESERVING THE ARCHITECTURAL HERITAGE OF SMALL TOWNS IN SERBIA: VLASOTINCE

Ivana Cvetković[1], Ana Momčilović Petronijević[2], Đorđe Stošić[3], Mirko Stanimirović[4]

Abstract

Due to a lack of understanding of monumental and other values, and an inappropriate approach to heritage, Vlasotince, as well as other numerous small towns in Serbia, are at risk of completely losing their identity. The level of threat to architectural heritage in cities across our country highlights the need for defining a clear strategy for the preservation of historical cores. Architectural heritage represents one of the most important categories of cultural heritage, and as such, it is an integral part of the spatial and cultural identity of the country. Its sustainable use and restoration represent an economic potential that significantly impacts spatial development and the preservation of the place's identity. This paper aims to draw the attention of the scientific public to the valuable architectural heritage found in small towns in southern Serbia, using Vlasotince as an example, and to offer basic guidelines for future planning documents based on inherited values.

Key words: *architectural heritage, heritage preservation, sustainable development*

[1] The Institute for Cultural Heritage Preservation Niš, ICHP Niš, senior conservator, architecture, Serbia, ivana.cvetkovic.ct@gmail.com
[2] Faculty of Civil Engineering and Architecture, University of Niš, Serbia, associate professor, ana.momcilovic.petronijevic@gaf.ni.ac.rs, https://orcid.org/0000-0001-7224-5590
[3] The Institute for Cultural Heritage Preservation Niš, ICHP Niš, senior conservator documenter, Serbia,djordje.stosic@zzsknis.rs
[4] Faculty of Civil Engineering and Architecture, University of Niš, Serbia, associate professor, mirko.stanimirovic@gaf.ni.ac.rs, https://orcid.org/0000-0001-6201-5855

1.INTRODUCTION

In order to assess the overall condition of cultural heritage and to develop clear guidelines for its protection within historic urban areas, the Institute for the Cultural Heritage Preservation Niš (ICHP Niš) conducted systematic field research across selected areas of several small towns. Comprehensive studies have been prepared for Knjaževac, Dimitrovgrad, Surdulica, Vučje, Leskovac, Vlasotince, Vranje, Niš, Aleksinac, Sokobanja, and Bor. Heritage assets were mapped, identified, and evaluated, and proposals for spatial organization, protection measures, and guidelines for incorporation into planning documents were provided. Through these efforts, attention has been directed toward the valuable architectural heritage preserved within the small towns of southern Serbia.

Meanwhile, a new Law on Cultural Heritage (Zakon o kulturnom nasleđu: 129/2021-120, “Službeni glasnik RS”, broj 129/2021) was adopted and came into force in 2023, introducing minor improvements to the heritage protection system. This law recognizes cultural heritage in a broader sense, encompassing not only formally protected assets but also those of potential heritage value. That same year, the Republic of Serbia adopted the National Architectural Strategy (Nacionalna arhitektonska strategija, 2023-2035, "Službeni glasnik RS", br. 48/2023), which places particular emphasis on the preservation of built heritage. The Strategy acknowledges built heritage as one of the most significant categories of cultural heritage, recognizing its essential role in shaping the spatial and cultural identity of the country. Furthermore, the 2023 amendments to the Law on Planning and Construction (Zakon o planiranju i izgradnji, “Službeni glasnik RS”, br. 72/2009, 81/2009 - ispr., 64/2010 - odluka US, 24/2011, 121/2012, 42/2013 - odluka US, 50/2013 - odluka US, 98/2013 - odluka US, 132/2014, 145/2014, 83/2018, 31/2019, 37/2019 - dr. zakon, 9/2020, 52/2021 i 62/2023) mandated the preparation of Heritage Protection Studies as an obligatory component of urban planning documents. Collectively, these developments have provided a stronger legal framework for the protection and strategic management of heritage, while granting heritage protection services enhanced legal instruments for more effective action.

2. METHODOLOGY

The researchers conducted several studies based on core conservation principles: documenting before any intervention, conducting preliminary research and evaluation, making professionally grounded decisions, proposing sustainable restoration while preserving authenticity, maintaining spatial integrity, considering the broader environmental context, and raising public awareness of cultural heritage value.

Fieldwork and research activities facilitated the direct collection of empirical data, which is essential for developing a comprehensive understanding of the town and its historical evolution. The documentation gathered for the most significant individual structures—comprising historical data, textual descriptions, graphic representations, archival records, and historical photographs—forms the foundational material for the entire research. Through the systematic organization, analysis, and synthesis of this data, a deeper understanding of the town’s historical and spatial context is achieved. This process also reveals the urban and architectural transformations that have occurred over time. The interrelationships of the preserved material remains are carefully defined and mapped. Such a holistic approach not only offers insights into the processes and nature of heritage degradation but also leads to

professionally grounded proposals for improving the condition of the heritage and its integration into future planning.

3. KEY STUDY - VLASOTINCE

Vlasotince is a small town in southeastern Serbia, located in the Jablanica District. It lies at the point where the Vlasina River emerges from mountainous gorges into the wide Leskovac Field, gradually changing from a swift mountain stream into a calm and slow-moving river.

The architectural and urban morphology of Vlasotince developed spontaneously during the 18th and 19th centuries. The town center, or čaršija (bazaar), evolved around old inns and caravanserais, which functioned as important places of trade and were strategically located along caravan routes.

Throughout the 19th century, the town experienced several peasant uprisings, during which the settlement suffered considerable damage [1]. The Ottomans set fire to Vlasotince in 1809, during the First Serbian Uprising; again in 1821; a third time in 1841, during the so-called Bojadži Revolt (Bojadžijska buna); and once more in 1860, during the event known as the Sadrazam Plunder (Sadrazam Pljačka) [2]. The period between 1850 and 1890 was marked by lively and flourishing trade, craftsmanship, agriculture, and viticulture [3]. From 1847 onwards, the development of the čaršija intensified, assuming the form of an elongated linear structure, with a mixed commercial-craft and residential function. The town's central place was occupied by a spacious marketplace, located at the site of today's triangular main town square stands [4]. Vlasotince was declared a varošica (small town) in 1878, following the liberation of southern Serbia from Ottoman rule. By then, It had already achieved the appearance of a developed town, as described by Mita Rakić: "...when I entered the town, which was so clean, white, polite, and orderly, it seemed as if it had been under Serbia for thirty years. There are no Turkish walls here, houses face the streets, they are beautiful and clean, many of them two-storied, looking like villas" [5]. Following liberation, Vlasotince's growth slowed somewhat due to disrupted trade routes after the Berlin Congress and the establishment of the border between Serbia and Bulgaria. Nevertheless, certain branches of industry soon developed in the region, particularly textile, milling, and viticulture industries, in which the people of Vlasotince played a significant role. Brick and tile production, as well as ceramics manufacturing, also became prominent [6].

At the turn of the 20th century, Vlasotince developed under Western European influences, with architecture modeled on European urban styles, shaping the town's present-day identity. Architectural activity significantly increased, resulting in a greater diversity of styles. Its urban form evolved spontaneously, with more structured regulation beginning in 1912, based on Franc Bartoš's 1893 plan, which was fully implemented by 1923 [7]. Architectural heritage is evident in the densely built houses along the old bazaar (čaršija), marked by narrow façades on deep, narrow lots combining residential and commercial functions. Though altered, parts of this core still retain their original character. Another distinctive element of Vlasotince's architectural heritage is the presence of elegant family residences situated on side streets with spacious green courtyards.

After World War II, changes in the political system, the structure of authority, and the functioning of the local community influenced the spatial development of the town. The inherited condition during this period consisted of a dense lineary formed market area with

single-story or multi-story buildings and streets radiating from the central town square [8], a layout that is still recognizable today. By the late 1950s, urban planning and development in Vlasotince took on a revolutionary and destructive character. These tendencies resulted in the construction of several multi-story buildings, which continue to shape the town's residential core, particularly around the Liberation Square and Dušanova Street [9].



Figure 1. Libération Square, before World War II, Vlasotince that I love, 2010.



Figure 2. Liberation Square, in the 1960s (left) and in 2023 (right), National Library of Vlasotince and the ICHP Niš, A. Nikšić, 2023.

The development of Vlasotince after World War II, particularly during the 1970s, was subject to a "destructive" influence on the inherited urban fabric. New construction was carried out under the influence of the urban doctrine of "total reconstruction" of city cores, which had a profoundly negative effect on the architectural heritage. Regulatory plans failed to recognize the existing values and preserved architectural heritage, treating buildings in these parts of the town as "structures of poor quality, with inadequate access routes" [10]. The 1977 plan concluded that additional interventions were necessary to achieve the structure of a "modern" city, in line with the ideals of urban industrial society. This process involved the transformation of the Vlasotince market core area, particularly in Nemanjina Street, through the demolition of old shops and the construction of multi-story buildings [11]

Decisions made by spatial and urban planners and the local authorities, which overlooked the town's inherited values, led to the gradual loss and degradation of the old čaršija's identity, once known for its unique architecture and authenticity. These decisions had serious and largely irreversible consequences.

Although severely affected by post-war urban planning policies and inappropriate construction interventions, the čaršija of Vlasotince has been preserved as a significant part of the town's identity and urban landscape. During the comprehensive research conducted in 2023–2024, over 50 valuable buildings, two significant historic zones, and one war memorial complex were mapped within the historic center of the town. The cultural and historical significance of the identified heritage assets was established through historical and scientific evaluation [12].

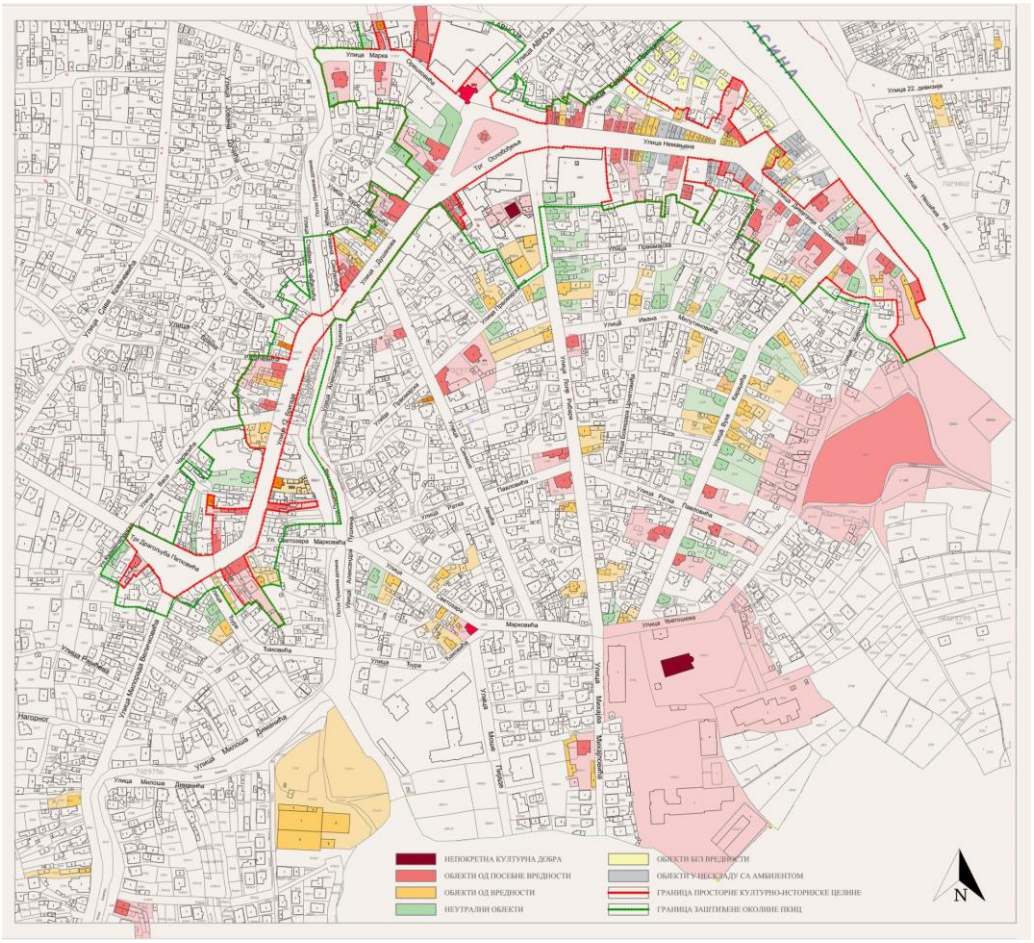


Figure 3. Architectural heritage of Vlasotince, ICHP Niš, drawing by I. Cvetković, 2024.



Figure 4. The surroundings of the Old Mill, ICHP Niš, photogrammetry by A. Nikšić, 2023.

In recent decades, however, this landscape has been increasingly disrupted by individual developments that have compromised the architectural character of the area. There has been a lack of thoughtful adaptation to the local architectural context, the typology of the inherited structure, and the existing conditions. Whether through the reconstruction and extension of modernist or classical buildings, or through new construction within the now recognized historical ensemble, there is a noticeable absence of contextual design that respects the architectural and stylistic qualities of the built environment.



Figure 5-6.Municipal building, appearance in the 1980s and after extension in the late 20th century, https://www.vlasotince.info/ and https://toovlasotince.rs/

4. DISCUSION

In the town center, by modern principles of heritage protection, significantly more buildings and urban units should have been preserved than is the case today. While some structures were lost due to war and natural disasters, a far greater number were destroyed by aggressive and indifferent urban policies. Numerous important buildings, or even entire blocks, that would today constitute the town's cultural heritage were demolished. Post-war urban planning largely distanced itself from the inherited urban structure and legacy. The construction of buildings with inappropriate scale in the heart of the town has led to a town center whose balanced and harmonious character has been compromised.

A careful assessment of Vlasotince's urban transformations reveals that most multi-family residential buildings, built at an inappropriate scale, were constructed in a short post-World War II wave. This was driven by the ambition to transform Vlasotince into a “modern” town, an approach that is no longer pursued today. In recent decades, new constructions have emerged that, in terms of scale, could potentially integrate with the surrounding area and

existing structures. However, these buildings are in significant stylistic and material discord with their context. Today, the remaining architectural heritage is increasingly vulnerable to disappearance due to pressures from new construction, small changes, the use of inappropriate materials, and poorly designed additions, all of which undermine the architectural integrity, authenticity, and overall coherence of the environment.



Figure 7. Odd side of Nemanjina Street, ICHP Niš, photogrammetry by A. Nikšić, 2023.

The first form of degradation is the neglect of buildings, leaving them to deteriorate. Degradation then progresses from the mildest forms, where facades are preserved but show signs of damage due to decay, color changes, or dirt. The second degree involves facades that are preserved with only minor changes but have significantly diminished aesthetic value due to inappropriate (partial) interventions and the way advertising signs are displayed. Next, we find facades from which facade details have been partially or completely removed, the appearance of portals, windows, and shop windows has been altered, yet their original shape and dimensions have been preserved. The following level of degradation involves changes in the shape and size of openings, as well as modifications in materials and original finishes. In the next stage, the type of roof covering has been changed, or extensions or modifications have been made to the building, changing its volume both horizontally or vertically. The most drastic forms of degradation involve complete replacement of buildings with new ones that have inappropriate architectural finishes or unsuitable dimensions [13].



Figure 8-9. Dušanova Street No. 8, before and after replacement, National Library of Vlasotince and ICHP Niš, photo by I. Cvetković, 2023.

The historic čaršija has been subjected to the inconsiderate forces of investor-driven urban development and construction practices, which fail to contribute to the cohesive layout and compliance with the area's original architectural and urban principle. From both an urbanistic and architectural standpoint, "modern" investors and architects design and implement buildings that are introducing disharmony and degradation of the environment and the existing architectural heritage. Consequently, it is imperative to plan the restoration of the built heritage based on expert decisions, supported by thorough analyses, and accompanied

by clearly defined protective measures, building regulations, and guidelines for the overall urban development.

Construction activities within the historic spatial unit of the Vlasotince old bazaar should be carried out based on professionally grounded proposals aimed at improving the condition of the built heritage. Urban planning and design guidelines primarily address the use of appropriate finishing materials, architectural design, and the maintenance of horizontal and vertical regulation. The prescribed protection measures encompass the preservation, maintenance, and use of buildings and spaces in accordance with established conservation principles, with the goal of safeguarding the authenticity, identity, and visual integrity of the historic area. These measures are defined individually for each building. Structures of particular cultural value must be subject to conservation-based interventions. Controlled new construction may be allowed on vacant lots or parcels containing structures without heritage value, provided that the new development is stylistically and volumetrically compatible with the surrounding context and architectural typology. Special attention should be given to the planning and improvement of public spaces, greenery, and transportation infrastructure to enhance the overall quality of the urban environment. This includes the integration of pedestrian-friendly streets, small plazas, parks, tree-lined avenues, and outdoor café gardens.

Consistent implementation of the proposed measures and devotion to the professional recommendations of the competent heritage institutions can ensure the long-term protection and affirmation of Vlasotince's unique identity recognized for its cultural and architectural heritage. The restoration and preservation of valuable buildings would not only contribute to improving the quality of life but also enhance the character and atmosphere of the place, making it attractive for living, working, and visiting. In order to integrate the protection of the historic core into contemporary development processes, it is essential that the old town center be reestablished as a recognizable and integral part of the town's identity. A key step in this direction is restoring the trust of the local population and encouraging their willingness to actively participate in the preservation and valorization of cultural heritage. With the aim of expanding knowledge and raising awareness of heritage values, the Institute for Cultural Heritage Preservation Niš, in collaboration with the Faculty of Civil Engineering and Architecture at the University of Niš, organized the student architectural workshop *Preservation of Architectural Heritage: Old Bazaar of Vlasotince* [14]. Also the exhibition *Architectural Heritage of Vlasotince,* as well as a roundtable discussion titled The Disappearance of Small Towns — Challenges of Preserving Identity and Cultural Heritage, were organized as part of a broader cultural heritage promotion program.



Figure 10. Even side of Dimitrije Stojanović Street, ICHP Niš, photogrammetry by A. Nikšić, 2023.



Figure 11. A Student's Proposal for Improving the Appearance of the Historic Area, Kulić Lazar, Šaković Anja, Momirović Miona, 2024.

An additional incentive for investing in the preservation of Vlasotince's architectural heritage lies in the fact that this region has a centuries-old tradition of master builders who participated in the construction of numerous significant buildings across Serbia and region. This is also illustrated by the exhibition "Crnotravci, the Builders of Belgrade: The Construction Work of Seasonal Builders from the Crna Trava Region in Belgrade During the 19th and First Half of the 20th Century", authored by Tatjana Videnović, senior conservator, and Ognjen Tutić, art historian, held in Belgrade in 2024. This legacy offers a potential basis for the region's economic development. Contemporary craftsmen could be recognized as restorers of historic buildings constructed by their ancestors. Restoring valuable architecture to revive the identity of the old Vlasotince čaršija should go hand in hand with training skilled craftsmen in traditional building techniques. This synergy can help establish a recognizable identity for local artisan workshops and support sustainable economic development. Considering that Vlasotince today has a well-organized technical high school with a developed methodology for both theoretical and practical education, further investment in training related to traditional crafts and construction techniques for conservation and restoration could contribute to the revitalization of the local community. In addition to restoring and highlighting the beauty of individual buildings and the entire urban silhouette, this initiative could serve as a unique platform for preserving and transmitting knowledge of traditional craftsmanship, especially in preparing artisans for work on historic structures. Students from the Technical School could carry out their internships in real-life settings and contribute to the restoration of their hometown, thus gaining a deeper understanding of its history and identity.

5. CONCLUSION

Architectural heritage is a key element in preserving local identity, as its value lies not only in its aesthetic and historical qualities, but also in its social function, as a symbol of continuity, the preservation of tradition, and local distinctiveness. It fosters a sense of belonging, collective identity, and pride among local residents, and plays a vital role in safeguarding historical integrity and cultural continuity [15].

The level of endangerment facing architectural heritage as a non-renewable resource in towns across the country underscores the urgent need to define clear strategies for preserving the historical cores of small towns. It is essential to introduce effective mechanisms and detailed guidelines to support heritage conservation. Through careful research, evaluation, and assessment prior to the drafting of planning documents, and by implementing active protection measures, it is possible to contribute meaningfully to the preservation and enhancement of the identity of both the town and the wider region. Architectural heritage must be preserved primarily from an urban planning perspective, not

only through the protection of individual legally safeguarded buildings but also by considering the broader environmental and contextual framework. Urban planners carry a crucial responsibility in this process. They are not only tasked with identifying the typology and respecting cultural values of the built environment but are also accountable for translating these insights into concrete urban planning parameters. This includes establishing urban parameters, construction guidelines, and design regulations that align with and reinforce the cultural character of the urban fabric. Inconsistencies arise when planning documents fail to define parameters consistent with the existing typology of areas. A common issue is the planning of large-scale developments without justification, particularly in towns where population growth is not a factor. Such plans often overlook the unique characteristics of the space, leading to inconsistency, disharmony, and a loss of identity. The degradation of heritage values is also intensified by the lack of detailed guidelines, clear mechanisms, and regulations for municipal and city administrations, which issue permits and oversee inspections of construction works.

Architects and designers responsible for preparing project documentation for investors frequently represent a significant obstacle to the integration of heritage protection measures. Due to a lack of expertise in this field, they often fail to recognize the importance of preserving inherent values of buildings. They are also unfamiliar with the appropriate techniques and methodologies for working on built heritage. Additionally, in their interactions with investors, these professionals do not prioritize the public interest in cultural heritage preservation, instead fostering a degree of animosity that is subsequently transferred to the investors. Although architects, as experts in the field, should be aware of the importance of cultural heritage preservation, their indifference is not surprising, considering that this topic is insufficiently studied within educational systems. For example, the Faculty of Civil Engineering and Architecture at the University of Niš does not offer specialized courses on the protection and conservation of immovable cultural heritage at the master's level.

The role of the state in the systematic degradation of cultural heritage should not be underestimated. To date, the state has failed to establish an effective and comprehensive framework for heritage preservation. Existing legislation places full responsibility for the care of immovable cultural heritage on property owners. However, once a site is designated as cultural heritage, it is only reasonable to expect corresponding incentives to support its preservation. There is a clear need for mechanisms that offer subvention for restoration and maintenance work, accompanied by strict quality control of the interventions carried out. Such an approach would ensure that heritage assets receive the attention they deserve, property owners would gain material support, and heritage protection authorities would no longer be seen as adversaries or obstacles to development.

While there are several reasons for the poor treatment of heritage, all of them can be traced back to an insufficient understanding of the significance of cultural heritage preservation by all parties involved in the planning and construction process.

ACKNOWLEDGMENTS

The project is financially supported by the Ministry of Culture of the Republic of Serbia in 2023. During the same year, a memorandum of cooperation was signed between the Institute for the Protection of Cultural Monuments of Niš and the Faculty of Civil Engineering and Architecture at the University of Niš, with the aim of jointly working on the development of a

Conservation Study for the Old Čaršija in Vlasotince, as well as the implementation of the student workshop 'Preservation of Architectural Heritage: The Old Bazaar (Čaršija) of Vlasotince.

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] Бишевац Славиша, Светозаровић Милена: **Власотиначка мушка основна школа 1878-1903. године**, Годишњак Педагошког факултета у Врању, књига IX, 181-194, 2018. https://scindeks-clanci.ceon.rs/data/pdf/2466-3905/2018/2466-39051801181B.pdf
[2] Стојанчевић, Владимир: **Власотиначки крај у Првом српском устанку**, Власотиначки зборник 2, Власотинце, 7-12, 2006.
[3] Валчић, Даница: **Градитељско наслеђе Власотинца**, Власина, Власотинце, 7, 2018. https://digitalnabibliotekavlasotince.org.rs/wp-content/uploads/2024/05/Graditeljsko-nasledje-Vlasotinca-drugo-dopunjeno-izdanje.pdf
[4] ibid, 12.
[5] Ракић Мита: **Из Нове Србије**: (Отаџбина, књ. 4, 5 и 6, 1880-1881), Народни музеј Лесковац, Власотинце, 593, 1987. https://istorijskenovine.unilib.rs/view/index.html#panel:pp|issue:UB_00020_18800701|page:599
[6] Уредник Такић Срба: **Власотиначко предузетништво, сведок времена**, Власотинце, 15, 2016.
[7] Nikolić Olivera, Nikolić Vladan, Marković Biserka, Petrović Nemanja, Marković Predrag: **Franc (Franja) Bartoš - srpski inženjer u 19. veku**, Zbornik radova građevinsko arhitektonskog fakulteta, broj 30, Niš, 229-234, 2015. https://gaf.ni.ac.rs/nip/dc1/Zbornik%20radova%20GAF%20Vol.%2030%20-%202015.pdf
[8] Валчић Даница: **Градитељско наслеђе Власотинца**, Власина, Власотинце, 12, 2018.
[9] **Vlasotince - Detaljni urbanistički plan**, Jugoslovenski institut za urbanizam i stanovanje, Beograd, 14, 1977.
[10] ibid, 14.
[11] ibid, 10.
[12] Цветковић Ивана, Момчиловић Петронијевић Ана, Стошић Ђорђе, Станимировић Мирко: **Власотинце - студија заштите градитељског наслеђа, заштита старе чаршије**, Ниш, 81-83, 2024. https://digitalizacija-zzsknis.rs/zzsk/vlasotince/
[13] ibid.
[14] Stanimirović Mirko, Momčilović Petronijević Ana, Cvetković Ivana, Stošić Đorđe: **Arhitektonska radionice - očuvanje graditeljskog nasleđa: Stara čaršija Vlasotinca**, Nauka+Praksa, br. 27/2024, 76-85, 2024. https://project.gaf.ni.ac.rs/epub/index.php/nip/article/view/42
[15] Urednički tim Kler Žiro-Labalt ... [et al.]: **Kulturno nasleđe vredi Evropi, rezime i strateške preporuke**, Evropa Nostra Srbija, Beograd, 30-31, 2017. http://blogs.encatc.org/culturalheritagecountsforeurope/wp-content/uploads/2017/06/CHCfE_Report_EXS_Serbia.pdf

doi.org/10.62683/SINARG2025.032

Research paper

RAISING ENVIRONMENTAL AWARENESS IN THE URBAN CONTEXT USING GEOSPATIAL AUGMENTED REALITY

Petar Vranić[1], Dušan Tatić[2]

Abstract

Environmental awareness is crucial for fostering sustainable urban development and enhancing citizens' engagement with their surroundings. In this study, we developed a mobile application based on geospatial augmented reality to promote environmental awareness in outdoor urban spaces. The application aims to immerse users in multimedia interactive content related to the environmental benefits of urban green spacecs (UGS), on-site and in real time. The application aims to assist individuals in understanding the ecosystem services of UGS and its potential future scenarios. The research highlights the potential of geospatial augmented reality (AR) in smart cities, emphasizing its role in education, citizen participation, and sustainable urban planning.

Key words: *Urban Green Space, Augmented Reality, Environmental Ecosystem Services, Participatory Urban Planning, Environmental Awareness, Geospatial*

[1]PhD, Research Associate, Mathematical Institute SANU, petarvvv@mi.sanu.ac.rs, https://orcid.org/0000-0002-9671-992X
[2]PhD, Research Associate, Mathematical Institute SANU, dusan.tatic@mi.sanu.ac.rs, https://orcid.org/0000-0002-9228-6020

1. INTRODUCTION

The interrelated themes of urbanization and climate change are among the greatest challenges facing humanity on a global scale. The anticipated impacts of climate change include an increase in the average global temperature, a decrease in average rainfall, and a rise in sea levels, potentially coupled with an increase in extreme storm events [1]. In this context, urban areas are recognized as the greatest contributors to all global energy-related carbon emissions [1]. In recognition of these trends, the three core priorities for sustainable urban development are recognized: the improvement of urban life, the minimization of ecological footprints, and the improvement of urban resilience to climate change [2,3].

UGS—parks, tree-lined avenues, urban forests, green roofs, and walls—have the potential to enhance the ecological balance within cities and also improve the quality of life among citizens. Besides cultural and social ecosystem services, UGS performs many important ecosystem functions like carbon sequestration, pollutant filtration, mitigation of the urban heat island effect, and preservation of biodiversity [4]. UGS are of much more significance in a changing climate environment, as they contribute to the resilience of urban areas from severe weather events [5]. Because of evidence that nature improves human well-being [6,7], UGS research is being pushed by an increasing interest in the environmental, social, and economic advantages of its use in urban areas, while the demand for more UGS is high on the political agendas of cities all over the world.

It has become more and more important that, in this new age of rapid urbanization and the relentless whirlwind of climate change and environmental degradation, people have a better understanding of their relationship with their habitat. These contorted challenges should be tackled through sustainable governance of natural resources and the conservation of the ecological balance [8,9]. The aforementioned goals do not come easily, as they require much human energy and systemic change, especially in how urban spaces are planned and managed. Increasing environmental awareness among citizens, coupled with their active participation in participatory planning processes, is increasingly recognized as a prerequisite for cities that are more disaster resilient and at the same time more efficient, inclusive, and sustainable [10,11]. Thus, a future-proof city is one with inclusive governance structures that empower communities against social and ecological disaster.

Environmental awareness is defined as the ability of an individual to recognize and understand the significance of natural processes as well as ecosystem services and their dependence on people's activities. In urban settings, this increasing population severity distance from the natural values has caused a growing danger of the separation of the urban population from natural values [12]. This fact affects the population's inactivity concerning issues of spatial planning and environmental preservation. Research from the studies shows that knowledge about environmental ecosystem services like air filtration, microclimate control, and permeable water surfaces contributes to more environmental care by urban citizens and participation in the planning process [13,14].

Participatory planning is the process of involving citizens in the entire phases of urban planning, from problem identification to implementation and evaluation. This has made it possible to mainstream citizens' needs and aspirations in spatial policy, thereby improving acceptance of, and thus effectiveness in, implementation of plans [15,16]. However, without proper information, public decisions cannot be made, and meaningful critiques and recommendations should not arise.

Technology brings about the aspect, especially AR, which very well suffices as a tool used for education through visualization. In this context, AR can be a solution to the gap between abstract planning and designing concepts and the effective perception of space by the citizens. This technology can enable users to visualize complex environmental data at the given location in real time, including air quality data, the degree of green coverage, species types, and their role in the ecosystem. In that way, users can directly experience the role of UGS in real space and time.

As an interactive technology, augmented reality can provide quick contextual information about environmental awareness in urban spaces. Using hardware such as a mobile device, users can engage interactively with their surroundings while virtual information overlays the physical environment through the device's display. This effect is possible through various techniques for recognizing and tracking the environment. Image tracking enables the recognition of flat image objects, achieving high precision under stable lighting conditions. However, since this technique is sensitive to lighting variations, it is best suited for indoor environments. Similarly, object tracking is used for recognizing physical 3D objects and is best performed indoors. This technology is precise but requires effort to generate 3D models or scan objects. For outdoor environments, location-based tracking utilizes GPS coordinates to position virtual materials. A limitation of this technology is that the precision of aligning virtual objects depends on the GPS signal and hardware quality.

2. MATERIALS AND METHODS

2.1. Data visualization method: Geospatial AR

In our work, we used a hybrid type of geospatial tracking to achieve higher precision in an outdoor environment. This type of tracking combines solutions such as Global Positioning System (GPS) and Visual Positioning System (VPS). The sensor of the device and the GPS are used for location-based tracking to detect the user's environment. VPS is used to improve the precision of tracking based on computer vision algorithms. These algorithms are used to match visual features with previously stored images in the database.

We use AR Core Geospatial API to determine the precise location of the user's device and anchor virtual content. Device sensors and GPS data are used to detect the visitor's device location, while Google’s VPS is used to determine a more precise location. The VPS detects the device location by comparing the data captured by the camera with feature points from the VPS localization model. This VPS localization model is realized as a 3D model point cloud generated using Street View images from Google Maps. Therefore, this tracking solution does require the creation of additional markers in contrast to other tracking solutions. Also, ARCore Geospatial API can be used in any outdoor environment where the location of the device can be determined.

2.2. Data

The assessment of ecosystem services provided by green areas, specifically trees within schoolyards, comprised a point of interest during this study via the i-Tree tool [17].. Seven urban elementary schools are selected for this study (Table 1, Figure 1). Average tree circumference was measured per dominant species; the total number of trees was estimated

per site; and the overall tree condition was evaluated based on variables defined for the i-Tree tool (Table 1). Carbon sequestration, stormwater runoff interception, and air purification were determined from the i-Tree assessments of the major tree species in each site. The results were extrapolated to simulate possible green infrastructure improvement scenarios, wherein calculated values were increased by either 30, 50, or 100 percent, thereby portraying possible scenarios of increased green coverage. It is emphasized that ecological service valuations obtained from i-Tree for a certain stand are for a 20-year projection period and thereby offer some pointers regarding the long-term benefits of the concerned tree and shrub cover that may need recognition for management improvements.

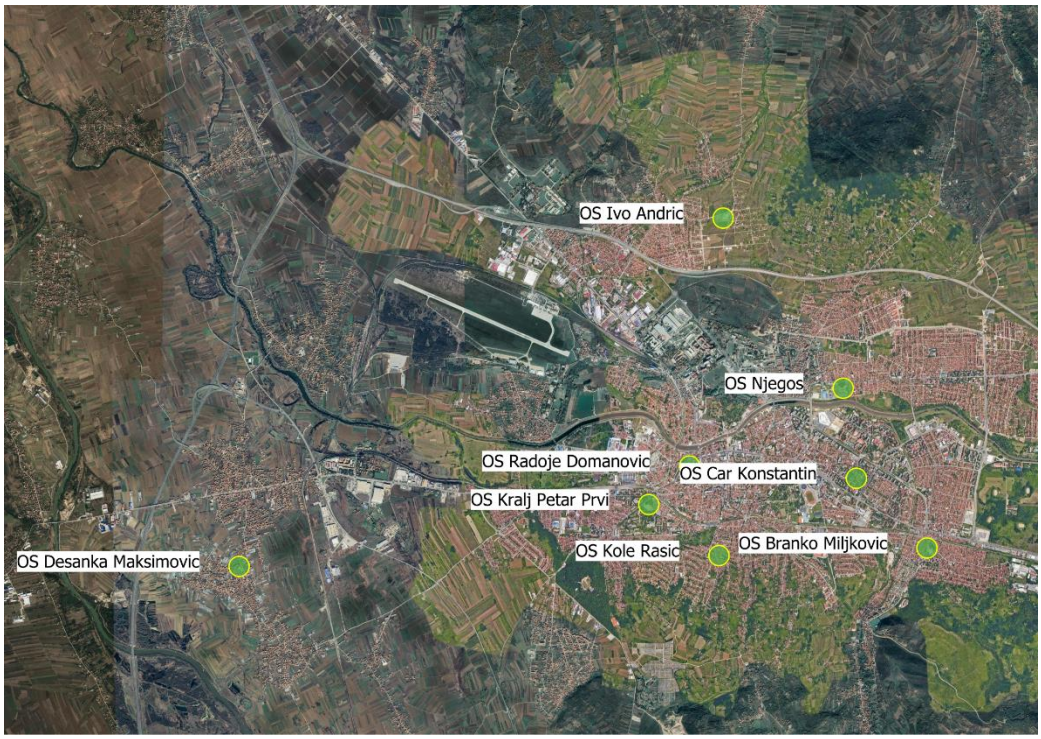


Figure 1. Selected elementary schools

The i-Tree tool is a software developed by the USDA Forest Service to estimate, in terms of dollars and cents, the environmental and economic benefits offered by trees and urban forests. It operates through a field-based data collection procedure that includes species of trees, tree size (for instance, circumference at standard height), tree health, and local environmental conditions. Carbon storage and sequestration, stormwater attenuation, and air quality improvement are some key services and benefits assessed by i-Tree by applying scientifically proven models and extensive databases. The i-Tree uses basic tree inventory data and translates this into much more detailed output on ecosystem services involving ecological valuation and monetary estimates. This makes the i-Tree an important tool in urban green-space management and planning with regard to evidence.

Table 1. Entry data for selected elementary schools

Name	Spices	Number of trees	Condition	Circumference
Radoje Domanovic	Betula pendula	27	11-25%	112
Kole Rasic	Acer sp.	15	11-25%	100
Kralj Petar Prvi	Tilia sp.	145	1-10%	135
Car Konstantin	Betula pendula	78	1-10%	135
Ivo Andric	Betula sp.	69	1%	90
Njegoš	Pinus nigra	65	11-25%	99
Branko Miljkovic	Abies alba	67	11-25%	88

3. RESULTS: REALIZATION OF THE AR APPLICATION

The aim was to develop an interactive application based on geospatial AR that will provide environmental data directly at the location of the user.

The application is realized using the Unity engine as a multimedia cross-platform tool for developing interactive solutions [18]. Using this tool application can be published on various mobile devices based on platforms such as Android and iOS. Also, Unity integrates AR Foundation [19] as a framework for developing augmented reality applications for multiple platforms and devices. For using AR Foundation, various package extensions are available that depend on the platform. For the development of the application, we used the ARCore [20] package, which has various tracking features. The ARCore Geospatial API [21] tracking feature is used to develop an application that visualizes data in an outdoor environment. This tracking technology, based on GPS and VPS, is used to anchor virtual content at the location of the primary schools. This virtual content is based on the environmental data given in Table 1.

When a user is at the location of the primary school, he opens the application and points the camera of the mobile device toward the garden. The augmented reality application using GPS and VPS determines the position of the user device. Then, on the mobile device screen, show the virtual overlay over the image captured by the camera. This virtual overlay shows the environmental data about the schoolyard in the user's surroundings. For this exercise we presented results for two elementary schools. Figure 2 shows the usage of an AR application that provides environmental ecosystem services information about the park in the primary school Kole Rasic. The information’s presented are calculated using iTree tool. The resulted

information about ecosystem services involving ecological valuation and monetary estimates is presented in Table 2.

Table 2. Ecosystem services ecological valuation and monetary estimates for elementary school Kole Rasic

	Current Value	30% increase	50% increase	100% increase
Amount of stored carbon dioxide equivalent expressed in RSD per tree over a 20-year period.	8132	10571.6	15857.4	31714.8
Benefit of absorbed pollutants expressed in RSD per tree over a 20-year period.	8346	10849.8	16274.7	32549.4
Benefit of flood prevention expressed in RSD per tree over a 20-year period.	3	3.9	5.85	11.7
Total benefit expressed in RSD for all trees over a 20-year period.	249417	324242.1	486363.15	972726.3



Figure 2. AR application shocase environmental ecosystem services information about the trees in the elementary school Kole Rasic

Also, the visualization of environmental data about the park in the primary school Radoje Domanovic is given in Figure 3, and output iTree information in Table 3.

Table 3. Ecosystem services ecological valuation and monetary estimates for elementary school Radoje Domanovic

	Current Value	30% increase	50% increase	100% increase
Amount of stored carbon dioxide equivalent expressed in RSD per tree over a 20-year period.	10058	13075	19613	39226
Benefit of absorbed pollutants expressed in RSD per tree over a 20-year period.	9368	12178	18267.6	36535
Benefit of flood prevention expressed in RSD per tree over a 20-year period.	3	4	6	12
Total benefit expressed in RSD for all trees over a 20-year period.	525156	682702	1024054	2048108

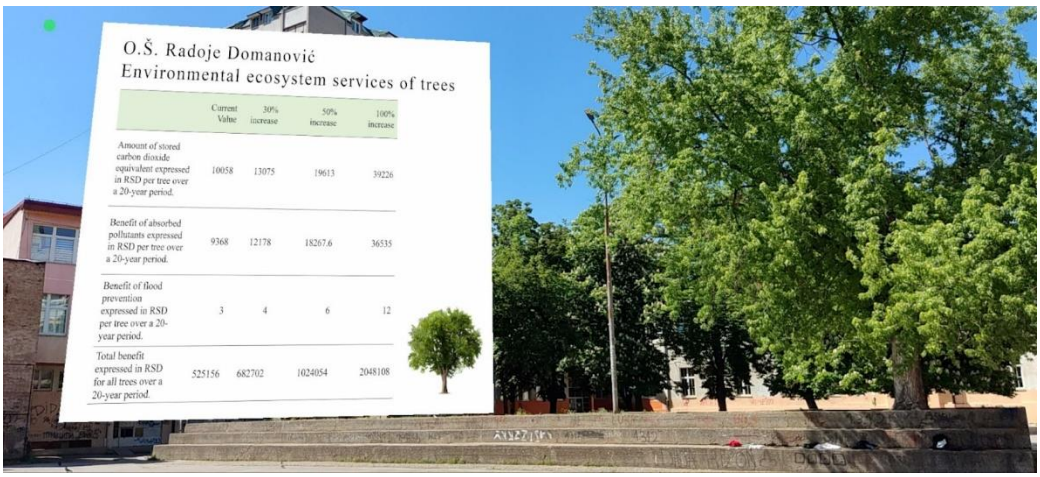


Figure 3. AR application shocase environmental ecosystem services information about the trees in the elementary school Radoje Domanovic

The finding comparison between elementary school Radoje Domanovicand Kole Rasic portrays a very important impact of the number and type of species of trees, as well as its condition towards the value of the ecosystem services they generate. With 27 Betula pendula trees, elementary school Radoje Domanovicoffers very high ecological and monetary benefits compared to those of Kole Rasic, which is equipped with 15 Acer sp. trees. Although both share similar conditions of health for their trees (11-25%), the greater number of trees

at Radoje Domanovic directly contributes to the total benefit amounting to 525,156 RSD compared with 249,417 RSD for a 20-year period. Also, other species differences and size or circumference of the trees affect rates of carbon stored and pollutants absorbed: the Betula pendula, despite its condition and circumference not being very impressive, seems to do better than Acer sp. regarding total services delivered.

Seeing such a comparison in an AR setting is one way for users to understand the impacts that different trees and conditions have on their lives. With AR, learners would interact with overlays of ecosystem service values right on the schoolyards, enabling intuitive comparisons and active learning. Observing the variations in carbon, pollution, and flood prevention, among other things, truly lets users internalize the characteristics and quantity of trees in place and how these lead to certain environmental outcomes. This, at scale, could enhence participatory city planning, empowering citizens—especially young ones—to directly learn about the ecological values of urban greenery and make informed decisions and proposals for the future urbanization based on real, localized data.

4. CONCLUSION

Increasingly, UGS are showing their influence on environmental resilience in sustainable urban living within the pressing challenges of climate change and urbanization. This study introduced a novel and accessible means of communicating the ecological value of UGS through the combination of ecosystem service evaluation using the i-Tree tool with the creation of an AR application. The i-Tree assessment quantified key ecosystem services as carbon sequestration, air purification, and stormwater management, demonstrating the direct environment benefits from urban trees. The AR application allowed users to interactively "receive" such data within real-world urban settings and in such a manner rendered more complex ecological processes clear and relatable.

In fact, this approach narrows the gap between the scientific information and the citizenry by converting much of the solid data into public awareness and highly stimulating participation in urban planning. The study highlights the modalities that should be adopted in future integrative frameworks to align data-driven environmental management with citizen-centered technological tools in empowering the urban population and provide adaptability for cities to future-proof their planning.

It must be pointed out that several limitations exist. The ecological service valuations provided by iTree are based on model projections and assumptions that sometimes do not represent the on-the-ground realities of local environmental dynamics, especially on horizons spanning a number of years. The other constraint of the study is that it has focused only on several elementary school sites, which limits the generalization of the results across wider urban contexts. Although the AR application makes one aware, it does not necessarily induce behavior change or active civic participation without supplementary curricula and policy initiatives.

Broadening the application of the approach to diverse urban locations with diverse ecological, social, and spatial characteristics would be an appropriate extension of this methodology for further validation and refinement. Advances in AR technology, especially in improving outdoor tracking accuracy and user interface design, would also enhance the user experience and educational impacts. Likewise, linking AR visualizations with participatory workshops and some feedback mechanisms would further fortify citizen engagement and

create a sense of environmental ownership. Finally, it is hoped that policy-makers and urban planners will include such technology in wider sustainability education campaigns and participative planning processes.

ACKNOWLEDGMENTS

This work was supported by the Serbian Ministry of Science, Technological Development and Innovation through the Mathematical Institute of the Serbian Academy of Sciences and Arts.

REFERENCES

[1] International Panel on Climate Change: Climate Change 2014 Synthesis Report. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf
[2] UN-Habitat: **Annual Report 2010**. https://unhabitat.org/sites/default/files/download-manager-files/Annual%20Report%202010.pdf
[3] UNDP, 2015: **Sustainable Development Goals 2030.** https://www.undp.org/sustainable-development goals/nopoverty?gclid=EAIaIQobChMIws63t4NwIVlMF3Ch1xHwZIEAAYAiAAEgI4KDBwE (8.6.2023.)
[4] Zhang Fan, Haochen Qian: **A comprehensive review of the environmental benefits of urban green spaces**. *Environmental research* Vol. 2024, No. 118837, 2024, https://doi.org/10.1016/j.envres.2024.118837
[5] Nadja Kabisch, Salman Qureshi, Dagmar Haase: **Human–environment interactions in urban green spaces – A systematic review of contemporary issues and prospects for future research**. *Environmental Impact Assessment Review*, 50, 25–34, 2016, https://doi.org/10.1016/j.eiar.2014.08.007
[6] Taylor Lucy, Dieter F. Hochuli: **Defining greenspace: Multiple uses across multiple disciplines**. *Landscape and Urban Planning*, Vol. 158, 25-38, 2017, https://doi.org/10.1016/j.landurbplan.2016.09.024
[7] Frumkin Howard: **The Evidence of Nature and the Nature of Evidence**. *American Journal of Preventive Medicine*, Vol. 44, No. 2, 196-197, 2013,
[8] LeeTaedong: **Global cities and climate change: The translocal relations of environmental governance**. *Routledge*, London and New York, 2014.
[9] IPCC: **Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. *IPPC*, Geneva, 2022.
[10] Meerow Sara, Joshua P. Newell, Melissa Stults: **Defining urban resilience: A review**. *Landscape and urban planning,* Vol. 147, No. 2016, 38-49, 2016, https://doi.org/10.1016/j.landurbplan.2015.11.011
[11] **World Cities Report 2020: The Value of Sustainable Urbanization**. *United Nations Human Settlements Programme*, Nairobi, Kenya, 2020. https://unhabitat.org/sites/default/files/2020/10/wcr_2020_report.pdf
[12] Maleknia Rahim, Mohammad Reza Pakravan-Charvadeh: **Green minds lead to green actions? Studying media literacy's role in fostering visitors' environmental behavior in urban forests in Tehran**. *City and Environment Interactions*, 100199.v, 2025, https://doi.org/10.1016/j.cacint.2025.100199

[13] Gómez-Baggethun, E., Barton, D. N. (2013). **Classifying and valuing ecosystem services for urban planning**. *Ecological Economics*, Vol.86, 235–245, 2013, https://doi.org/10.1016/j.ecolecon.2012.08.019

[14] Haase Dagmar, Niki Frantzeskaki, Thomas Elmqvist: **Ecosystem services in urban landscapes: practical applications and governance implications**. *Ambio*, Vol. 43, No. 4, 407–412, 2014, https://doi.org/10.1007/s13280-014-0503-1

[15] Marondedze Andrew Kudzanayi, Onisimo Mutanga, Matilda Azong Cho: **Promoting inclusion in urban land use planning using participatory geographic information system (PGIS) techniques: A systematic review**. *Journal of Environmental Management*, Vol. 370, 123099, 2024, https://doi.org/10.1016/j.jenvman.2024.123099

[16] Seo Bo Kyong: **Co-creation of knowledge in the urban planning context: The case of participatory planning for transitional social housing in Hong Kong**. *Cities*, Vol, 122, 103518, https://doi.org/10.1016/j.cities.2021.103518

[17] Nowak David J. : **Understanding i-Tree: summary of programs and methods. General Technical Report NRS-200**. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station, 2020. [plus 14 appendixes]. https://doi.org/10.2737/NRS-GTR-200.

[18] **Unity Technologies**. Unity. https://unity.com/

[19] **Unity Technologies. AR Foundation.** https://unity.com/solutions/xr/ar

[20] **Google. ARCore.** https://developers.google.com/ar

[21] **Google. ARCore Geospatial API.** https://developers.google.com/ar/develop/geospatial

doi.org/10.62683/SINARG2025.033

Review paper

IMPLEMENTATION OF SUSTAINABLE TRANSPORT MODELS IN INNOVATIVE AND ENVIRONMENTALLY FRIENDLY URBAN ENVIRONMENTS THROUGH ANALYSIS OF COPENHAGEN AND PARIS

Marko Jeremić[1], Natalija Stanković[2]

Abstract

Rapid urbanization and population growth create significant challenges in the field of transport, especially in the context of sustainability and environmental friendliness. Modern cities face increasingly serious problems of pollution, traffic congestion and excessive energy consumption, which further exacerbate the impact on climate change. In order to ensure the long-term sustainability of urban environments, it is necessary to adopt innovative transport models that reduce pollution, optimize mobility and increase the resilience of cities to environmental challenges. The paper explores innovative approaches in the planning and implementation of sustainable transport systems, with a particular emphasis on the integration of public transport, the development of cycling and pedestrian corridors, as well as the use of smart technologies to improve transport. Concepts such as "smart cities" and "15-minute cities" will be analyzed, which enable efficient and environmentally friendly population movement. The comparative analysis method will present examples of cities that have successfully implemented sustainable transport solutions, such as Copenhagen and Paris, in order to identify best practices and opportunities for application in different urban environments. Through this analysis, the aim is to highlight the importance of sustainable transport as a key factor in reducing pollution, improving the quality of life of citizens and building dynamic, resilient and more environmentally friendly cities of the future.

Key words: *Sustainable transport, Smart cities, 15-minute cities, Sustainable development, Climate change*

[1] Master Engineer of Architecture, Faculty of Civil Engineering and Architecture, University of Niš, Serbia, markojeremica@gmail.com, ORCID N/A
[2] PhD Student, Junior Researcher, Innovation Center University of Niš, Serbia, natalija.stankovic@icun.ni.ac.rs, ORCID 0009-0009-3532-8878

1. INTRODUCTION

Contemporary urban environments stand at a crossroads, facing the growing demand for space and the necessity for adaptable, sustainable solutions in response to rapid urbanization and technological advancement. Traditional transport models, primarily based on the individual use of motor vehicles, contribute to excessive air pollution, climate change, traffic congestion, noise, degradation of public spaces, and a general decline in the quality of life in urban areas. In this context, sustainable transport models are gaining increasing importance as societies around the world become more aware of the negative impacts of conventional transportation methods on the environment and public health. The primary goal of these models is to provide reliable, energy-efficient, and affordable transport solutions while minimizing adverse effects on ecosystems. In addition to reducing greenhouse gas emissions, sustainable transport models also promote physical activity, healthier lifestyles, and greater social inclusion.

Modern concepts such as smart cities and 15-minute cities represent innovative approaches to urban planning that encourage improved spatial and transport structures, where everyday needs can be met within short distances. In this context, sustainable transport refers to green, energy-efficient, and accessible modes of mobility with minimal environmental impact, such as walking, cycling, public transit, electric and hybrid vehicles, as well as alternative fuel-powered transportation. The overall sustainability of a transport system is evaluated based on the efficiency of its components, their environmental and climate impacts, and the structure and functionality of infrastructure (roads, railways, terminals, etc.). Data indicate that transport systems account for approximately 20% to 25% of global energy consumption and CO_2 emissions [1]. At the same time, transport remains a vital driver of economic development and human mobility, making the adoption of sustainable transport models not only an ecological but also a socio-economic imperative for all urban communities striving toward a better future.

The subject of this research is the analysis of sustainable transport models and their implementation in innovative and environmentally adaptive urban settings, with a particular focus on the integration of public transportation, bicycle and pedestrian corridors, and smart technologies within transport infrastructure. The aim of the study is to highlight, based on an analysis of best practice examples, specific models and strategies that enhance sustainability in urban environments. Special attention is given to identifying the key success factors in cities that have achieved significant progress in this area, as well as the potential applicability of these principles in other urban contexts. The research methods employed in the paper include data collection, data analysis, descriptive method, comparative analysis and synthesis, as well as the inductive–deductive method to formulate conclusions based on concrete examples.

2. CONCEPT AND PRINCIPLES OF SUSTAINABLE TRANSPORT MODELS

Sustainable transport models represent a systemic approach to the planning, organization, and improvement of transport infrastructure and services, with the aim of meeting mobility needs in an environmentally friendly, socially equitable, and economically efficient manner [2]. Sustainable transport seeks to fulfill transportation needs while

preserving human health and ecological balance by utilizing renewable resources at a rate that does not exceed their natural regeneration and using non-renewable resources at levels below the development rate of renewable alternatives.

A sustainable transport system is defined as one that: enables the safe fulfillment of individual and societal transportation needs without compromising human health or ecosystems, while respecting the principle of equity both within and between generations; ensures economic accessibility and efficiency, provides a diversity of transport modes, and supports the flexibility of modern economies; reduces emissions and waste within the planet's ecological capacity, minimizes the use of non-renewable energy sources, and controls the consumption of renewables within sustainable limits; applies principles of recycling and reuse of its components, while minimizing land use and noise pollution [3].

Key characteristics of sustainable transport systems include: reducing harmful emissions and air pollution through a shift to electric vehicles, cycling, and walking; promoting public transportation as the primary mode of mobility, with improved frequency, reliability, and accessibility; integrated planning of transport and urban development to align mobility with spatial organization; multimodality, i.e., the ability to seamlessly switch between different modes of transport without loss of time or comfort; social inclusivity, ensuring equal access to transport services for all population groups; and energy efficiency through reduced fossil fuel consumption and support for renewable energy sources [3].

Sustainable transport aims to meet society's current mobility needs without compromising the ability of future generations to meet theirs. The concept is based on the application of environmentally sound technologies, alternative fuels (such as electricity, gas, and biodiesel), and the development of intelligent transport systems (Fig.1) [4].

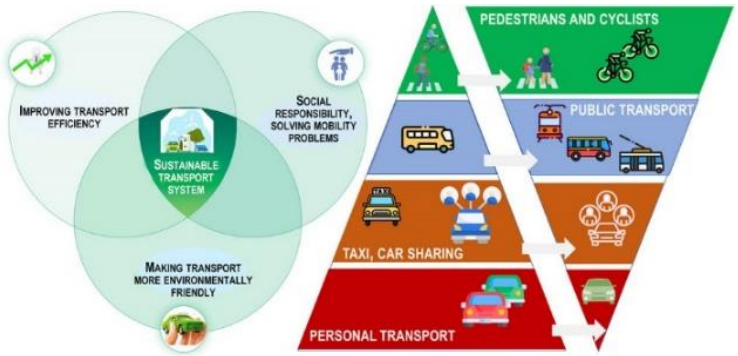


Figure 1. Goals and ways towards sustainable transport, https://www.frontiersin.org/journals/built-environment/articles/10.3389/fbuil.2023.1161361/full

Contemporary concepts such as smart cities, which rely on digital technologies for more efficient traffic management, and 15-minute cities, where all essential services are available within a short walking or cycling distance, are significant tools for building sustainable transport systems. The idea of sustainable transport is closely linked to the notion of intergenerational justice, which implies that the needs of present generations should not be met at the expense of future ones.

3. GOOD PRACTICE EXAMPLES

The successful implementation of sustainable transport models in various cities around the world demonstrates the potential of such approaches to transform urban environments toward ecological resilience, energy efficiency, and improved quality of life. Among the most prominent examples are Copenhagen and Paris, which represent two distinct yet equally inspiring models of urban mobility—one based on a long-standing culture of cycling, and the other on a comprehensive transformation aligned with the concept of the “15-minute city.” In addition to these examples, numerous other cities around the world have demonstrated significant progress in implementing sustainable transport solutions:

- Amsterdam, Netherlands – A city where bicycles dominate daily transportation, supported by outstanding cycling infrastructure and a strong cycling culture
- Tokyo, Japan – Renowned for having one of the most advanced public transportation systems globally, alongside a growing number of electric vehicles
- Stockholm, Sweden – An example of a city utilizing biofuels in public transport and maintaining an extensive network of bicycle and pedestrian paths
- Portland, USA – Known for actively promoting cycling, electric vehicles, and sustainable urban planning practices
- Zurich, Switzerland – A model of efficient, integrated public transport, with strong measures aimed at reducing pollution, noise, and energy consumption

3.1. City of Copenhagen

Copenhagen, as the capital of Denmark, has for decades been committed to improving the quality of life for its residents through the integration of environmentally responsible transport, urban planning, and advanced technological solutions. The city implements multiple models of sustainable transport that together form a functional, ecological, and inclusive mobility system:

- Public transport powered by renewable energy – The city employs electric and biogas-powered buses, as well as metro systems running on green energy
- Integrated cycling system – With more than 400 km of dedicated cycling lanes, special bridges for cyclists, bicycle “highways,” and bike-sharing schemes, cycling has become the dominant mode of transport [5]
- Green pedestrian zones and urban planning – The promotion of walkability and traffic-free public spaces, with a strong focus on safety and accessibility
- Car-sharing and micromobility – A well-developed network of shared electric vehicles, e-scooters, and bicycles
- Reduction of car traffic – High parking fees, restricted access to the city center, and planning mechanisms that prioritize public transportation and cyclists [5].

The smart city concept encompasses the use of information and communication technologies (ICT) and innovations in urban governance to improve quality of life, reduce resource consumption, and enhance public services [6]. Copenhagen is a leading example in this domain, with a model that includes:

- Sensor networks for monitoring pollution, noise, and traffic – Data are used in real time to optimize traffic flow and plan urban interventions
- Smart lighting and energy systems – Devices that automatically respond to environmental conditions to reduce energy consumption

- Open Data platform – Public access to city data encourages innovation, transparency, and citizen participation
- Smart mobility – Applications that integrate real-time information on all modes of transport, enabling more efficient travel planning for citizens.

One of the most striking features of Copenhagen is its well-developed cycling culture (*Fig. 2a*). The city boasts over 400 kilometers of specially marked and physically separated bike lanes, as well as several bridges dedicated exclusively to pedestrians and cyclists, such as the famous Cykelslangen - The Bicycle Snake (*Fig. 2b*). The so-called "super bicycle highways" connect Copenhagen with neighboring municipalities, promoting intercity mobility without reliance on cars [7].

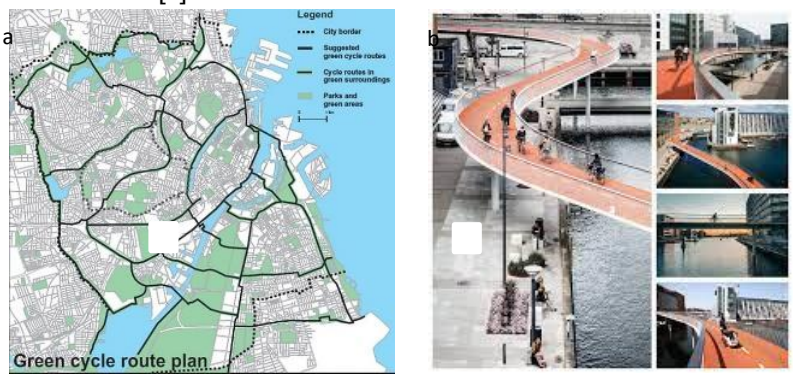


Figure 2a - Green cycle route plan of Copenhagen and 2b - Bridge Cykelslangen - The Bicycle Snake bridge https://www.slideshare.net/slideshow/sustainable-transport-system-of-copenhagen-citypdf/266559943

3.2. City of Paris

Paris is one of the most prominent examples of a European metropolis that systematically implements innovative and sustainable transport models. The city is investing substantial resources in ecological transition and reducing dependence on private vehicles, with the aim of improving quality of life and combating climate change [8].

Sustainable transport models implemented in Paris include:

- Public transport powered by electric and hybrid energy – The Paris metro system, one of the most advanced in the world, increasingly relies on electric and energy-efficient trains. The bus system is also undergoing gradual electrification, with a goal to achieve a mostly zero-emission fleet by 2030
- Cycling infrastructure – Paris has significantly expanded its network of bike lanes through the "Plan Vélo" program. Many streets have been redesigned to prioritize cyclists and pedestrians. The Vélib' public bike-sharing system is one of the largest in Europe, with over 20,000 bicycles, a large portion of which are electrically assisted
- Pedestrian zones – The city center is progressively becoming a car-free zone. A notable example is the transformation of the Seine riverbanks into public pedestrian spaces, closed to motorized traffic
- Electric and shared vehicles (car-sharing) – Paris supports the expansion of electric vehicles through a dense network of charging stations and services such as Autolib' and Zity that offer electric car-sharing options

- Micromobility – Electric scooters, small electric motorcycles, and similar vehicles are regulated under sustainable mobility policies and integrated into the broader transportation system

Paris is also developing the smart city concept through the adoption of digital tools and systems that enhance urban efficiency, transparency, and environmental sustainability. Through the “Paris Smart City 2050” platform, the city integrates innovations in energy efficiency, resource management, and urban mobility [9]. The use of smart lighting that adapts automatically, digital signage, and real-time air quality and traffic monitoring systems enable better control of urban processes and reduce energy consumption. Interactive applications provide citizens with information on public transport arrival times, traffic conditions, air pollution levels, and parking availability. The city actively involves citizens in decision-making through digital participatory platforms, a fundamental feature of smart and democratic urban communities.

The 15-minute city is an urban planning concept that promotes the idea that all residents should be able to access essential services—such as work, education, healthcare, recreation, and shopping—within a 15-minute walk or bike ride from their home (Fig. 3a). The concept, developed by Professor Carlos Moreno, has been adopted by the Mayor of Paris as a core element of the city’s sustainable urban development agenda [10].

The goal of this approach is to reduce the need for long commutes and automobile reliance, increase social interaction, boost the local economy, and enhance overall quality of life. In practice, it involves redistributing urban functions, increasing the presence of public and community facilities across all neighborhoods, redesigning streets to favor pedestrians and cyclists, and introducing multipurpose facilities (e.g., schools that function as cultural or sports centers in the afternoons) [11].

By applying the 15-minute city concept, Paris aims to decentralize urban services, reduce traffic congestion, improve public health, increase energy efficiency, and encourage local communities to play a more active and responsible role in city life. This model of urban development is already showing results in Paris and is inspiring other cities around the world seeking to combine urban compactness, social equity, and environmental sustainability (Fig. 3b).

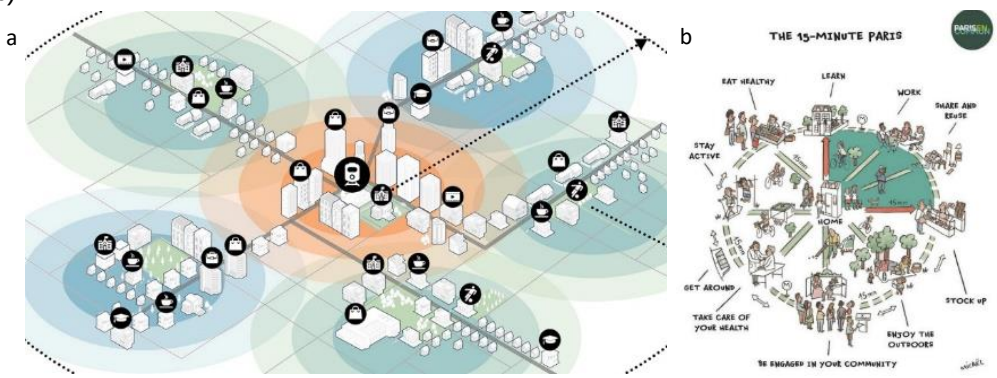


Figure 3a - The concept of the 15-minute city and 3b - Paris as a 15-minute city, https://resistire-project.eu/better-stories/paris-as-a-15-minute-city/

3.3. Comparative Analysis of Urban Sustainable Transport Strategies in Copenhagen and Paris

In order to better understand how different cities address the challenges of urban mobility, it is particularly important to compare the strategies and outcomes in cities that lead in the implementation of sustainable transport models (*Table 1*). Paris and Copenhagen represent two distinct but successful approaches to urban development—one based on a decades-long cycling culture and technological innovation, and the other on the integration of the "15-minute city" concept.

Table 1. Comparative Analysis of UST Strategies in Copenhagen and Paris

Criteria	**Copenhagen**	**Paris**
Main Strategy	"City for Cyclists"	"15-Minute City"
Public Transport	High-quality metro and bus network with electric buses	Metro, buses, and trams – electrification in progress
Cycling Infrastructure	400 km of lanes; mandatory cycling planning	Expanded network of lanes; Vélib' public bike system
Pedestrian Zones	Numerous streets prioritized for pedestrians and cyclists; low-motorized city center	Central areas closed to traffic; Seine riverbanks turned into pedestrian spaces
Electric and Shared Vehicles	Support for EVs and car-sharing, though to a lesser extent than Paris	Developed charging network; systems like Autolib' and Zity
Citizen Participation in Planning	Moderately high; inclusion through community dialogues and city workshops	High; participatory budgeting and platforms for citizen proposals
Smart Technologies	Smart traffic management, IoT devices, intersection sensors	Digital panels, apps, air quality and traffic monitoring

4. IMPLEMENTATION OF SUSTAINABLE TRANSPORT MODELS

The implementation of sustainable transport models in urban environments represents a complex and long-term process that requires coordination among various stakeholders, as well as the application of innovative technologies and principles of urban planning. The primary goal of this process is to create transport systems that reduce negative environmental impacts, improve the quality of life for citizens, promote economic development, and ensure social equity in mobility.

The adaptability of urban environments to ecological challenges involves implementing measures that not only mitigate the effects of climate change but also promote the role of transport in preserving the environment. Transport systems can be adapted to ecological challenges through various strategies, such as:

- Green infrastructure: the development of public transport networks that utilize environmentally friendly energy sources, such as electric buses or trains, as well as the creation of cycling and pedestrian zones
- Urban zone adaptation: planning cities in such a way that most essential services are accessible by walking or cycling, thereby reducing car dependency and lowering pollution levels
- Rehabilitation of vulnerable areas: transforming former industrial zones into green and urban parks that support biodiversity and improve air quality [3].

The task of urban planners and city authorities is to design transport strategies that simultaneously address traffic congestion and pollution, while also preparing cities for future climate challenges [12].

Technological innovations are playing an increasingly important role in creating sustainable and environmentally adaptive transport solutions. The integration of smart technologies into transport systems enables improved efficiency, safety, and sustainability, while also reducing negative environmental impacts.

Key technological innovations contributing to transport sustainability include:

- Electric and hybrid transport: the increased use of electric cars, electric bicycles, and public transport powered by clean energy significantly reduces CO_2 emissions
- Autonomous vehicles: self-driving vehicles using optimized algorithms for navigating cities can significantly reduce traffic congestion and energy consumption, as they operate according to real-time needs and pre-defined routes
- Traffic management systems: smart systems that leverage big data and the Internet of Things (IoT) enable better traffic flow and improved public transport management, thereby reducing delays and energy usage
- Green and smart charging stations: the development of electric vehicle charging infrastructure that integrates solar panels and other renewable energy sources allows for energy savings and CO_2 emission reduction

By applying these innovations, cities can significantly improve their transport systems, making them more efficient and environmentally friendly, while also creating new opportunities for local economic development and employment in the technology sector [4].

5. CONCLUDING CONSIDERATIONS

The implementation of sustainable transport models in urban environments is not merely a necessity, but a responsibility in the face of climate change, urbanization, and the social challenges confronting contemporary cities. Sustainable transport represents not only a technical challenge but also a social and political process that demands the cooperation of multiple stakeholders including local governments, urban planners, engineers, and citizens as active participants in the transformation of urban space [4]. Based on the analysis of best practice examples from Copenhagen and Paris, it can be concluded that successful implementation requires a comprehensive approach that integrates transport systems with other dimensions of urban life, such as public space, infrastructure, environmental protection, and social equity. The true strength of these models lies in their capacity to transcend traditional concepts of transportation and offer innovative, holistic solutions that enhance quality of life, reduce pollution, and increase urban resilience to current global challenges.

The key findings emphasize the multidimensional nature of sustainable urban transport development. Technological innovation constitutes one of the core elements of this process: the introduction of electric vehicles, smart traffic management systems, and the integration of public transport with active mobility modes such as walking and cycling play a crucial role in shaping sustainable transport solutions. Equally important is the need for long-term urban planning policies that reduce dependence on private cars, strengthen public transport, and improve pedestrian and cycling infrastructure. Sustainable transport must also be grounded in the principles of inclusivity and social equity. Furthermore, sustainable mobility should be an integral part of climate adaptation strategies, reducing cities' carbon footprints and accelerating the transition to renewable energy sources within the transport sector. While each city possesses unique characteristics and local challenges, concepts such as “smart cities” and the “15-minute city” offer valuable and adaptable frameworks for transport development aligned with the principles of sustainability. Cities like Copenhagen and Paris serve as inspiring examples and strategic models for other urban environments aiming to improve quality of life, enhance environmental resilience, and promote social justice through sustainable transport.

REFERENCES

[1] https://www.iisd.org/articles/deep-dive/road-sustainable-transport *(05.05.2025.)*
[2] Radičević Veljko, Subotić Marko, Milić Dragana: **Sustainable urban transport promotion as a function of sustainable development**. *FBIM Transactions*, Vol.2 No. 2 pp. 279-289, 2014, doi: 10.12709/fbim.02.02.02.28
[3] Komal Kanwar Korawat, Bharathi M., Mishra ankur: **Sustainable transportation systems**. *Swami Keshvanand Institute of Technology Management and Gramothan (SKIT)*, 2023, doi: 10.13140/RG.2.2.14203.69920
[4] Makarova Irina, Buyvol Polina, Shubenkova Ksenia, Fatikhova Larisa, Parsin Gleb: **Editorial: Sustainable transport systems**. *Frontiers in Built Environment*, 2023, doi: 10.3389/fbuil.2023.1161361
[5] Peštová Viktória: **Sustainable Urban Development: Case Study Copenhagen**. *24th International Scientific Conference for Doctoral Students and Post-Doctoral Scholars*, Bratislava, 2022, doi: 10.53465/EDAMBA.2021.9788022549301.390-399
[6] https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/city-initiatives/smart-cities_en *(09.05.2025.)*
[7] https://www.slideshare.net/slideshow/sustainable-transport-system-of-copenhagen-citypdf/266559943 *(09.05.2025.)*
[8] https://itdp.org/2008/02/03/the-greening-of-paris/ *(11.05.2025.)*
[9] https://amazingarchitecture.com/futuristic/paris-smart-city-2050-by-vincent-callebaut-architectures *(11.05.2025.)*
[10] Moreno Carlos: **Definition of the 15-minute city**. The Obel Award Jury, 2021
[11] Marzolla Francesco, Bruno Matteo, Loreto Vittorio, Hygor Piaget Monteiro Melo: **Compact 15-minute cities are greener**. 2024, doi: 10.48550/arXiv.2409.01817
[12] : Hapriyanto Aditya Restu, Azmi Hafidzul**: Implementation of Green Infrastructure in Sustainable Transportation in Supporting Urban Mobility: A Literature Review**. *Engineering Proceedings*, Vol. 84 No. 1 pp.25, 2025, doi: 10.3390/engproc2025084025

doi.org/10.62683/SINARG2025.034

Research paper

INFLUENCE OF DRAINAGE MEASURES ON THE UPLIFT RESISTANCE OF THE FOUNDATION JOINT OF A GRAVITY CONCRETE DAM

Dušan Stevanović[1], Nikola Mirković[2], Uroš Mirković[3]

Abstract

A common characteristic of concrete as a material used in the construction of dams and the surrounding rock mass, on which such structures are typically founded, is the presence of voids within the material. Buoyancy, as the load exerted by water in the voids of the foundation medium and concrete that presses against the structure, must be reduced and kept at a level where the stability and performance of the structure will not be compromised. The methods most commonly applied to reduce the buoyancy at the foundation interface include the use of an injection curtain on the upstream face and drainage boreholes downstream of the curtain.

The seepage pattern analysis presented in this paper is illustrated through different calculation scenarios and under varying boundary conditions. The analysis was conducted on the structure of the additional hydropower plant of the gravity concrete dam "Iron Gate II," where the initial seepage pattern was analyzed using the finite element method (FEM) model, composed of the concrete section of the additional plant and the associated rock mass. Quantitative parameters illustrating the effects of seepage pattern improvement in other calculation scenarios were obtained after incorporating elements such as the injection curtain and drainage boreholes into the FEM model.

A comparative analysis, conducted under two different boundary conditions, compared the buoyancy values in five different calculation scenarios and calculated the safety factors for the analyzed scenarios. Based on the results, conclusions regarding the effects of changes in the seepage pattern were drawn. In addition to the calculations, the paper also presents a theoretical review of the Eurocode standard, specifically focusing on the calculation of safety coefficients for flotation, which was implemented in the software and used during the analysis presented in this paper.

Key words: *Dam Stability, Safety Factors, Buoyancy, Injection Curtain, Drainage Boreholes, FEM Analysis*

[1] MSc Civ. Eng., PhD student, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, dusan.stevanovic@jcerni.rs, ORCID N/A
[2] PhD, Research Associate, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, nikola.mirkovic@jcerni.rs, ORCID 0000-0002-5980-3049
[3] PhD, Research Assistant, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, uros.mirkovic@jcerni.rs, ORCID 0000-0001-6781-5798

1. INTRODUCTION

Materials used for the construction of hydraulic structures, as well as the media in which such structures are founded (soil or rock), are porous materials characterized by the presence of micro- and macro-voids (pores, joints, and cracks). As a direct consequence of these material characteristics, uplift occurs - an action whereby water exerts pressure on the voids within hydraulic structures and foundation interfaces, pushing the structure upward. Uplift, as a load, acts both when water is at rest and when it is seeping; in other words, uplift is present under both hydrostatic and hydrodynamic conditions.

According to the literature [1], uplift can be divided into two components:

- Base uplift U_{BAZ} which represents the hydrostatic pressure of the upstream water;
- Differential uplift U_{DIF} which represents the piezometric difference between the upstream and downstream water levels ($\Delta H = H_G - H_D$).

When considering structural measures to reduce or limit uplift, it is important to note that the base component of uplift cannot be eliminated in an economically feasible way. Therefore, structural measures aimed at reducing uplift are primarily focused on the differential uplift. Engineering solutions adopted in practice depend on the type of foundation medium (soil or rock), the homogeneity or heterogeneity of the considered layer, the geometric characteristics of the structure, the water level in the reservoir, and the elevation of the downstream water.

By analyzing the uplift problem at the foundation interface, an effective reduction of the differential component of uplift can be achieved through the application of grouting methods or drainage.

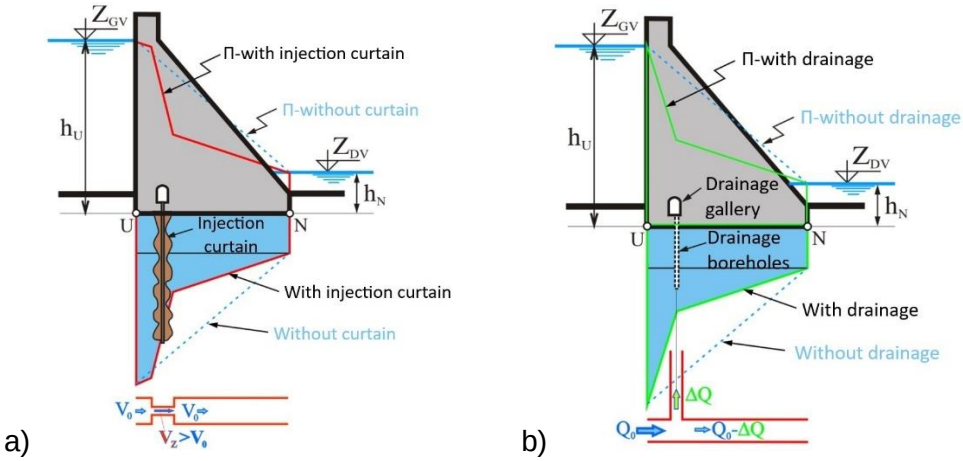


Figure 1. Anti-seepage measures for reducing uplift: a) injection curtain, b) drainage boreholes [1]

The impermeability of rocky media is increased through grouting. The grouting process involves injecting the grout material through pre-drilled boreholes, from which the grout penetrates into cracks, filling them and creating a high impermeability barrier in the form of a vertical seal. Another anti-seepage measure in rocky media is drainage, which is most commonly implemented by a network of boreholes. The boreholes extend to a drainage gallery, from where the infiltrating water is discharged outside the body of the dam [1].

On the dam section of the "Iron Gate II" Hydroelectric Power Plant, in the area between the Romanian Island Mare and the Serbian shore, the following structures are located:

powerhouse buildings with the assembly block, the spillway section of the dam, and the non-spillway section of the embankment dam. The segment encompassing the non-spillway section of the embankment dam consists of three zones, between which are the ship lock structures and the auxiliary power plant [2].



Figure 2. Photo of the HPP Iron Gate II Dam [3]

The subject of the analysis conducted within this paper is the auxiliary power plant, which is positioned on the previously constructed embankment dam, between the lock chamber and the right bank. The auxiliary power plant consists of two units: the turbine-generator block and the assembly block. The plant houses two units, each with a capacity of 27 MW [2].



Figure 3. Photo of the additional hydropower plant [3]

2. FEM MODEL

In the conducted analysis, a three-dimensional FEM model was developed for the marked part of the structure, where the red-marked portion of the structure represents the concrete part of the auxiliary power plant, while the yellow-marked portion represents the modeled corresponding segment of the rock mass.

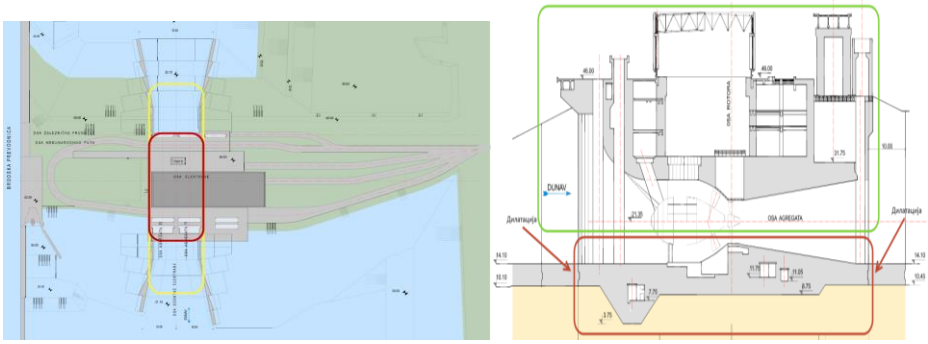


Figure 4. Representation of the boundaries of the modeled part of the additional hydropower plant [2]

The FEM model shown in Figure 5 covers a part of the foundation interface of the auxiliary power plant and the corresponding rock mass (Figure 4). The model dimensions at the base are 128.4 x 38.0 m (marked in red in Figure 4). The green-framed portion of the power plant is excluded from the seepage calculations as it is not considered significant for the filtration processes, while in the uplift safety calculation, the actual value of the total weight of the structure, as well as the corresponding live load, was taken into account. The boundaries of the model were extended 25.0 m upstream and downstream from the outer edges of the foundation interface of the modeled structure, in order to set realistic boundary conditions (marked in yellow in Figure 4) [2].

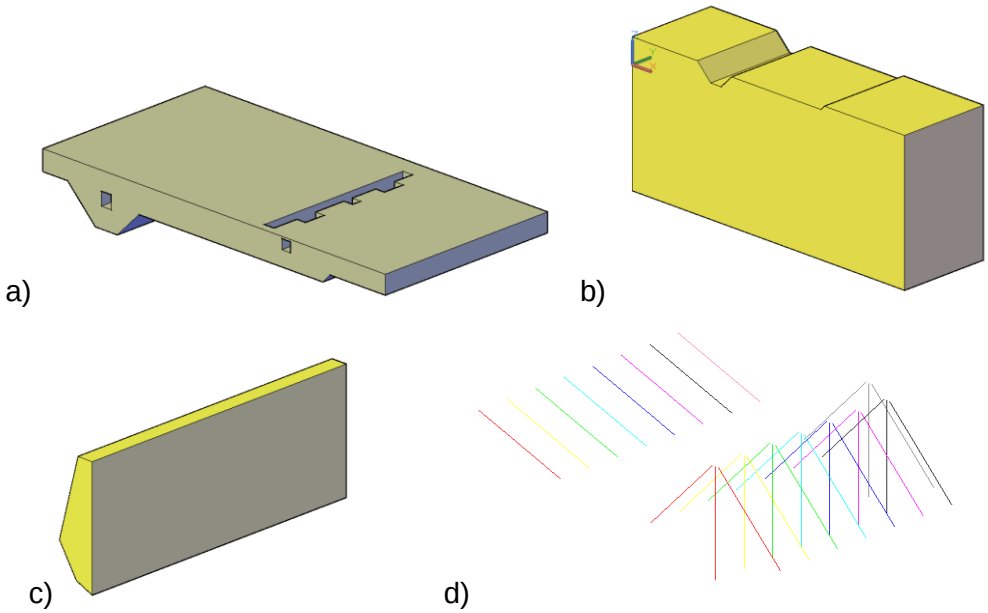


Figure 5. Representation of the FEM model elements: a) foundation joint of the additional hydropower plant; b) rock mass; c) injection curtain; d) drainage boreholes [2]

In addition to the aforementioned parts of the foundation interface and rock mass, the elements of the grouting curtain and drainage boreholes were also modeled for the purpose of analyzing uplift and safety factor calculations. The conducted calculations enabled a comprehensive assessment of the seepage conditions of the considered structure.

The foundation interface of the auxiliary power plant was modeled as a volumetric body using a 3D solid [2]. The corresponding rock mass and grouting curtain were modeled in the same way. The depth of the modeled grouting curtain is 15 m. The drainage boreholes were modeled as linear elements. The FEM model contains 32 boreholes, each 15 m long, distributed across 9 profiles [2].

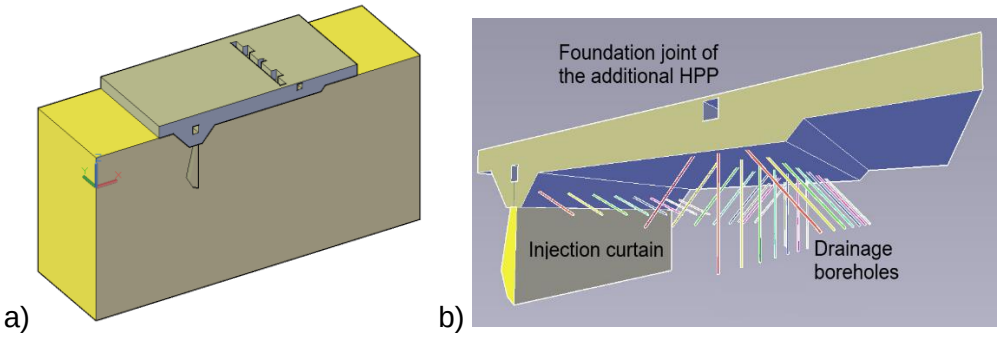


Figure 6. Appearance of the FEM model: a) with the attached rock mass; b) position of the modeled injection curtain and drainage boreholes relative to the 3D solid foundation interface. [2]

The finite element mesh of the considered structure was created using tetrahedral finite elements with mid-nodes (10 nodes per element). The model consists of 280,255 nodes and 205,894 elements [2].

For the purpose of analyzing the seepage conditions on the upstream face of the terrain and the concrete part of the foundation interface, the potential was set equal to the elevation of the upstream water, while on the downstream face of the structure and terrain, the potential was set equal to the elevation of the downstream water (Figure 7) [2].

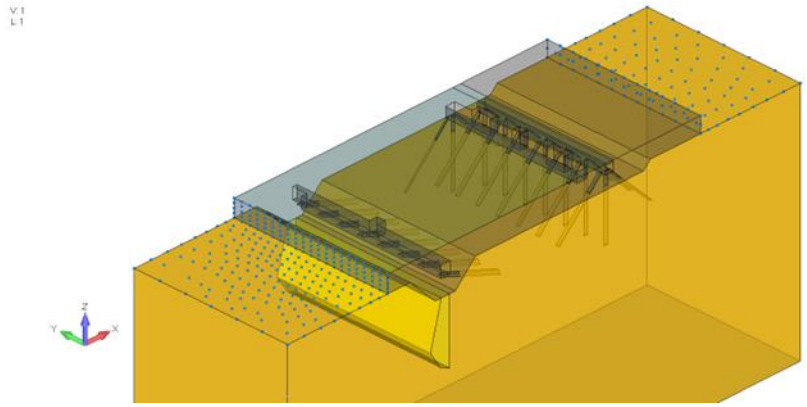


Figure 7. Representation of the assigned potentials corresponding to the upstream and downstream water elevations [2]

At the outlets of the drainage boreholes, the values of the seepage potential corresponding to the coordinates of the nodes at the top of the boreholes are assigned [2].

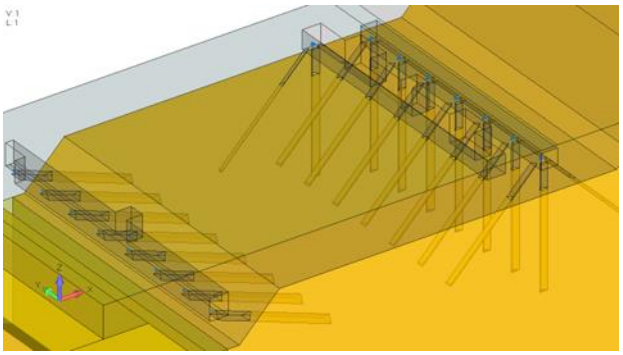


Figure 8. Representation of the assigned potentials at the outlets of the drainage boreholes [2]

On the surfaces of the galleries, the seepage potential values are also assigned, which correspond to the coordinates of the nodes on those surfaces [2].

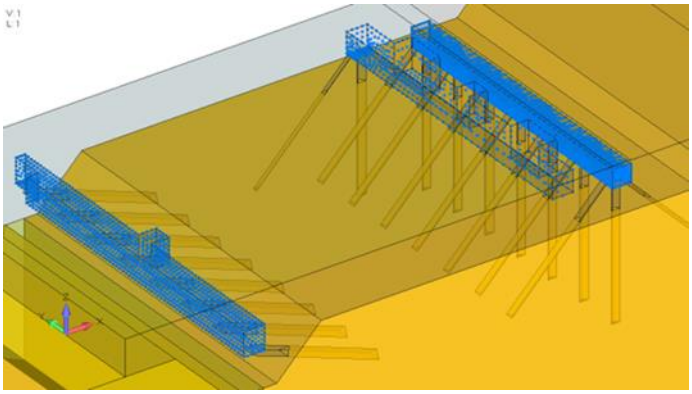


Figure 9. Representation of the assigned potentials on the surfaces of the galleries [2]

The theoretical basis of the seepage process in the considered software is thoroughly explained in the paper [4]. Given this fact, it will not be repeated in this work.

3. ASSESSMENT OF THE SAFETY FACTOR AGAINST UPLIFT OF THE STRUCTURE ACCORDING TO EUROCODE

The inclusion of standardized procedures according to the applicable Eurocode [5] implies that the verification related to uplift must be carried out by checking that the design value of destabilizing actions is ($V_{dst;d}$) smaller than the design values of stabilizing permanent vertical actions ($G_{stb;d}$) and the design values of any additional resistance to uplift. (R_d).

$$V_{dst;d} \leq G_{stb;d} + R_d$$

$V_{dst;d}$ – the design value of the combination of destabilizing permanent and variable vertical actions,

$G_{stb;d}$ – the design value of stabilizing permanent vertical actions,

R_d – additional resistance to uplift

For the foundation interface of the auxiliary power plant, the stabilizing vertical forces are determined, which include the self-weight of the dam and the weight of the additional equipment. The weight of the water over the wetted surface of the dam, which acts favorably

in the vertical direction, has been excluded from the analysis in this work, with a detailed explanation in Chapter 4. The destabilizing forces include the buoyant vertical forces acting on the foundation interface, which are a result of seepage forces.

In the case where there is no additional resistance to uplift, the check for the limit state of uplift can be written using the following relation:

$$\frac{G_{stb,d}}{V_{dst,d}} = F_s$$

The conducted seepage calculation aimed to determine the value of $V_{dst,d}$ for different calculation scenarios, depending on the application of anti-seepage measures.

The value of $G_{stb,d}$ was obtained by summing the calculated value of the total weight of the auxiliary power plant structure (1 100 000 kN) and the additional equipment (1 000 kN).

4. DESIGN SITUATIONS WITHIN THE SAFETY ANALYSIS OF THE ADDITIONAL HYDROPOWER PLANT STRUCTURE

In this chapter, Figure 10 shows an illustration of the conditions under which the calculation is performed within the tool. It is important to emphasize that the results presented in this study represent the seepage conditions in a predefined calculation scenario, which corresponds to the moment when the operational gate on the upstream side and the siphon gate on the downstream side are lowered, and there is no flow through the power plant turbines. The authors selected this calculation scenario as the most unfavorable, because at that moment, there is no favorable effect of the water weight on the uplift.

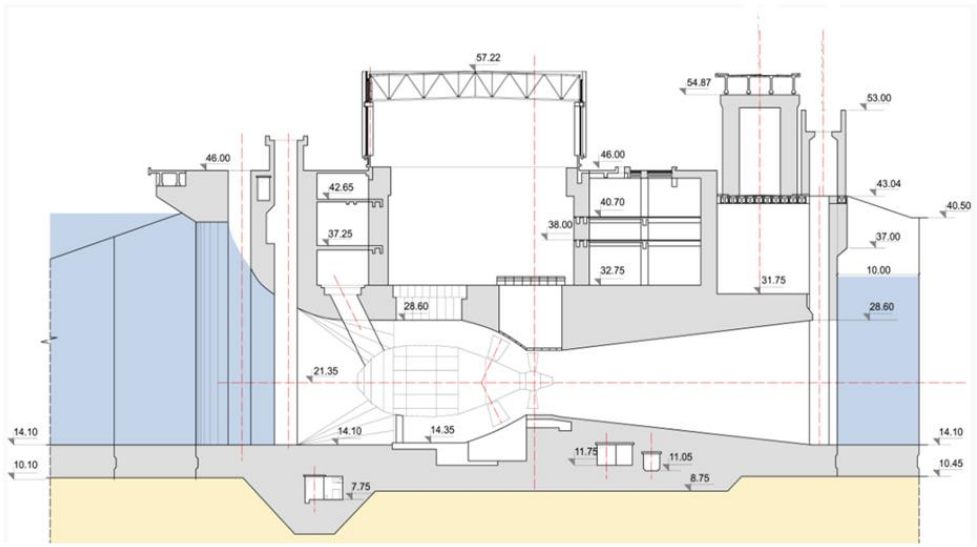


Figure 10. Boundary conditions for which the calculation is performed [2]

For modeling seepage processes in the rock mass within the analysis in this work, the filtration coefficients are defined as the rock parameters, which are given in the following Table 1. The parameters were adopted based on the available documentation about the structure as well as from the technical literature [2].

Table 1. Filtration coefficients of the modeled elements [2]

Material	Filtration coefficient (m/s)
Concrete part of the additional hydropower plant - foundation	10^{-11}
Rock mass	10^{-7}
Injection curtain	10^{-9}
32 drainage boreholes	10^{-3}

It is assumed that the diameter of all drainage boreholes is 85.0 mm. In the performed calculation, the foundation of the auxiliary power plant and the surrounding terrain, i.e., the rock mass, represent elements that had a constant filtration coefficient in all performed calculation scenarios (Table 1). Depending on the combination of including the injection curtain and drainage boreholes, the calculation scenarios were formed, and in them, these elements had different filtration coefficients, depending on whether they were included in the performed calculation or not. The injection curtain was excluded from some seepage calculations by assigning the same filtration coefficient as the surrounding terrain, i.e., the rock mass (10^{-7}). Boreholes were excluded from the seepage calculation by assigning an extremely low filtration coefficient (10^{-13}). Table 2 shows the different calculation scenarios depending on which anti-seepage measures were included. The symbol "✓" indicates that the element is included in the calculation (the filtration coefficients are identical to those in Table 1), while the symbol "✗" indicates that the element is excluded from the calculation, applying the previously mentioned changes in the filtration coefficients.

Table 2. Overview of the considered calculation scenarios of the seepage calculation

Calculation scenarios	Injection curtain	Drainage boreholes
1th	✗	✗
2th	✓	✗
3th	✗	✓
4th	✓	✓
5th	✓	✓*

The first calculation scenario represents the most unfavorable case in terms of the seepage condition and the calculation of the safety factor, as it excludes both the injection curtain and the drainage boreholes from the analysis. The second scenario represents a more favorable case, allowing the assessment of the effects of the injection curtain. The third scenario includes all drainage boreholes while excluding the injection curtain, enabling the evaluation of the effects of drainage boreholes based on the results.

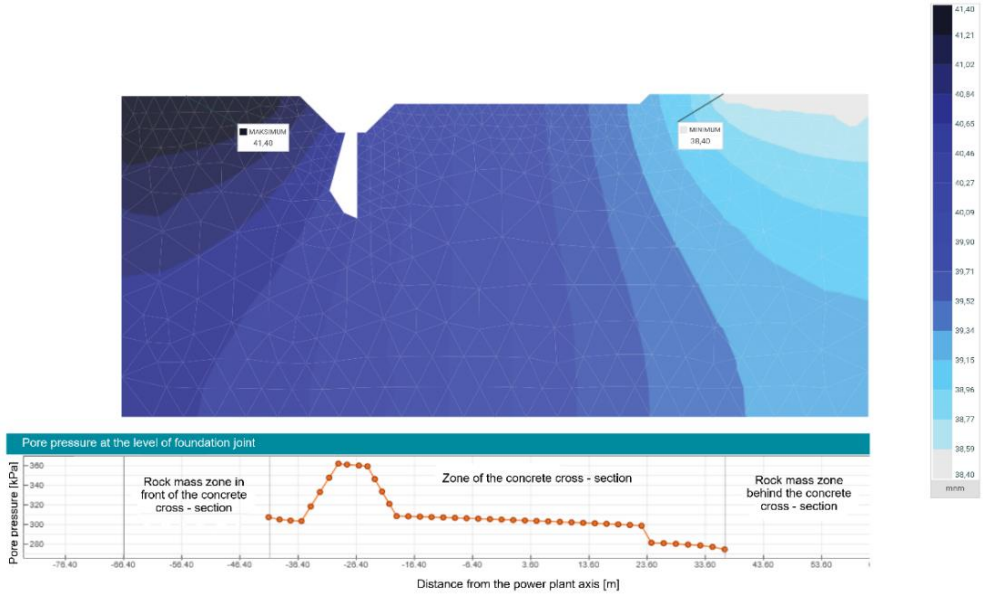
The fourth calculation scenario, which includes both the injection curtain and drainage boreholes, represents the most favorable case and illustrates the extent to which anti-seepage measures can improve the safety factor and seepage behavior of the structure in this specific example.

The fifth scenario involves the inclusion of the injection curtain and boreholes in the downstream gallery in selected profiles only, while all boreholes in the upstream gallery at a given elevation are excluded from the analysis.

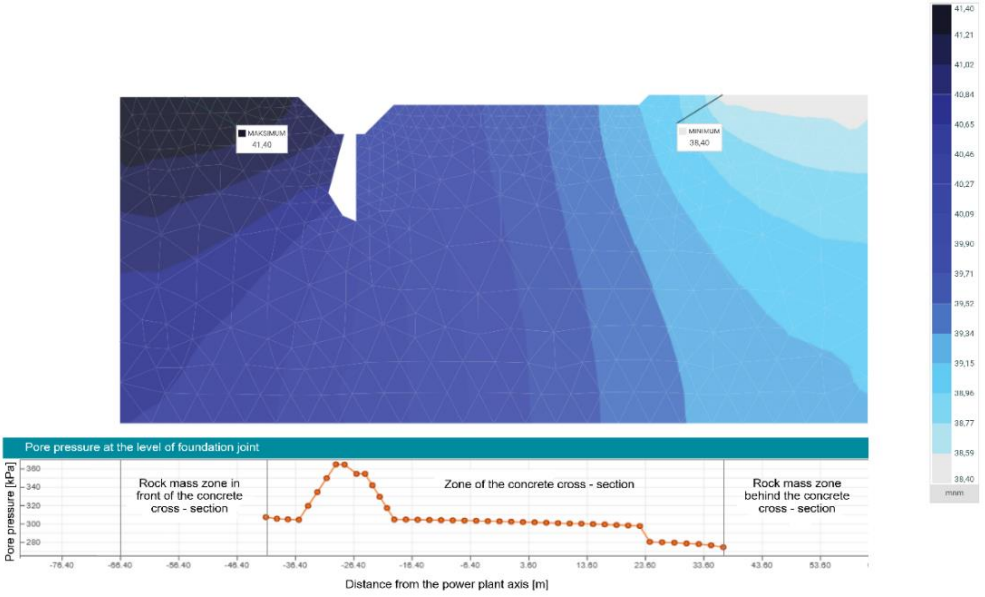
5. RESULTS OF THE SEEPAGE ANALYSIS

The results of the seepage calculations are presented in two parts within this chapter. The seepage analysis was conducted using the User Tool for the analysis of the condition and safety verification of the additional power plant, which is used during the calculations and analysis at the Jaroslav Černi Water Institute. The calculation was performed in the PAK software package [6, 7].

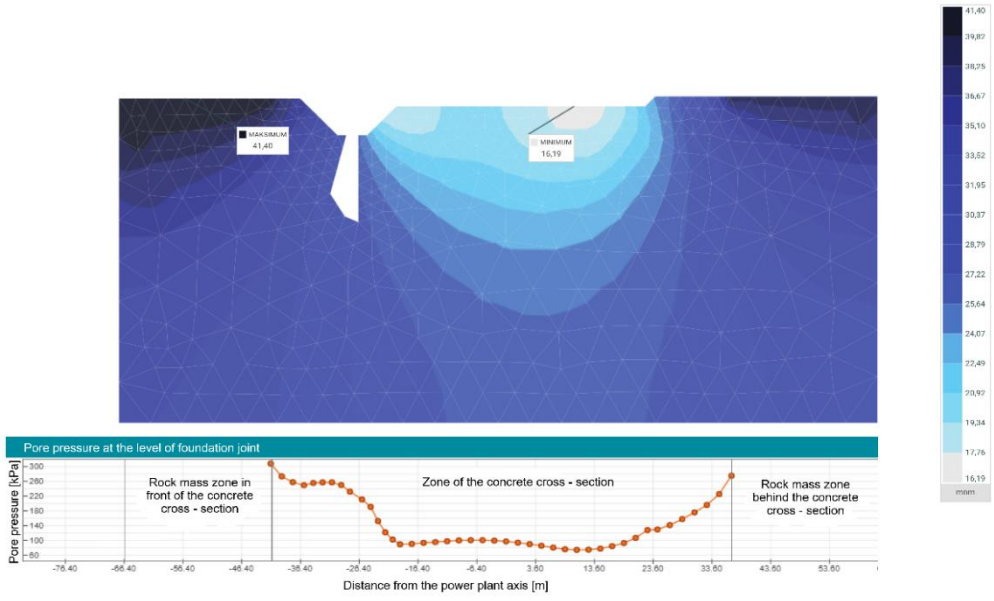
The first part of the chapter presents the values of piezometric levels and seepage behavior in the form of diagrams for the cross-section along the turbine axis (Figure 11) for calculation scenarios with water levels in the reservoir and the elevation of the downstream water level at 41.40 m a.s.l. and 38.40 m a.s.l., respectively.



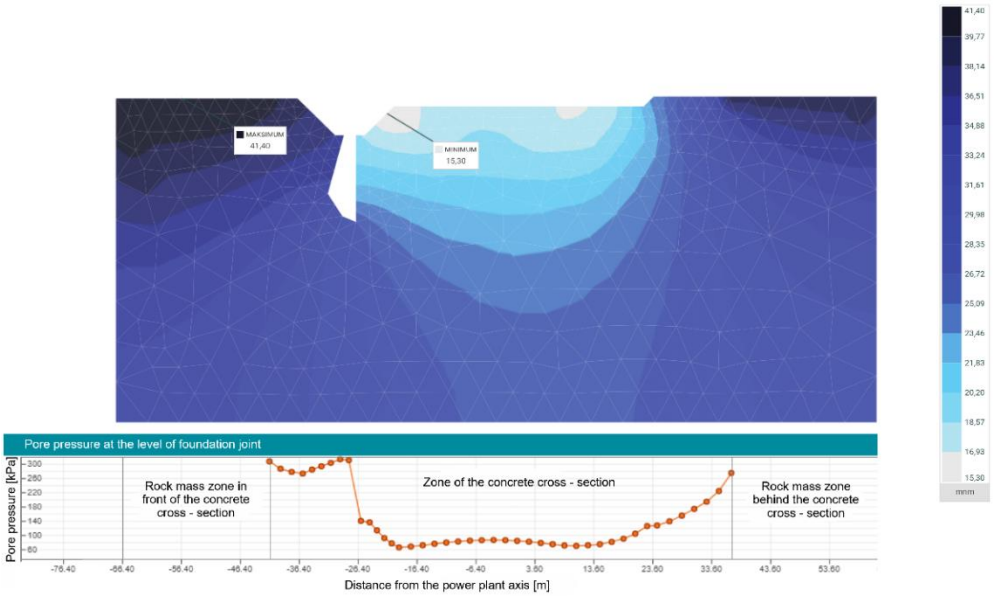
a)



b)


MAKSIMUM
41,40
MINIMUM
16,19
41,40
39,82
38,25
36,67
35,10
33,52
31,95
30,37
28,79
27,22
25,64
24,07
22,49
20,92
19,34
17,76
16,19
mnm
Pore pressure at the level of foundation joint
Pore pressure [kPa]
300
260
220
180
140
100
60
Rock mass zone in front of the concrete cross - section
Zone of the concrete cross - section
Rock mass zone behind the concrete cross - section
-76.40
-66.40
-56.40
-46.40
-36.40
-26.40
-16.40
-6.40
3.60
13.60
23.60
33.60
43.60
53.60
Distance from the power plant axis [m]

c)


MAKSIMUM
41,40
MINIMUM
15,30
41,40
39,77
38,14
36,51
34,88
33,24
31,61
29,98
28,35
26,72
25,09
23,46
21,83
20,20
18,57
16,93
15,30
mnm
Pore pressure at the level of foundation joint
Pore pressure [kPa]
300
260
220
180
140
100
60
Rock mass zone in front of the concrete cross - section
Zone of the concrete cross - section
Rock mass zone behind the concrete cross - section
-76.40
-66.40
-56.40
-46.40
-36.40
-26.40
-16.40
-6.40
3.60
13.60
23.60
33.60
43.60
53.60
Distance from the power plant axis [m]

d)

e)

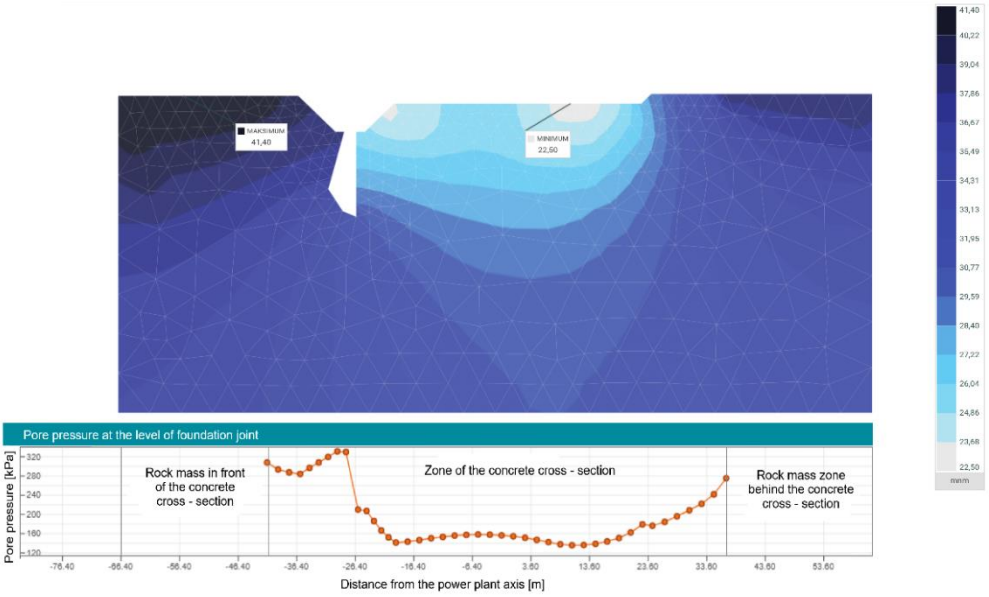


Figure 11. Potential (m.a.s.l.) and pore pressure at the foundation joint for: a) Calculation Scenario I, b) Calculation Scenario II, c) Calculation Scenario III, d) Calculation Scenario IV, e) Calculation Scenario V

The second part of the chapter presents in Table 3 the results in the form of values for the buoyant force and safety factor for different calculation scenarios. The results are separated into two different section of table, depending on the water level in the reservoir and the elevation of the downstream water level.

Table 3 Values of Buoyancy Force and Safety Factor for the Considered Calculation Scenario

Calculation scenarios	Water level in the reservoir [m.a.s.l.]	Lower water level [m.a.s.l.]	Buoyancy [kN]	Safety Factor [-]
1th	41.40	38.40	716 731	1.54
2th	41.40	38.40	712 674	1.54
3th	41.40	38.40	276 197	3.99
4th	41.40	38.40	265 049	4.15
5th	41.40	38.40	415 058	2.65
1th	40.50	32.00	636 405	1.73
2th	40.50	32.00	625 018	1.76
3th	40.50	32.00	255 636	4.31
4th	40.50	32.00	244 682	4.50
5th	40.50	32.00	372 710	2.95

6. CONCLUSION

In this study, in addition to the results presented in the work [4], the analysis was expanded by considering the parameters as a function of the safety factor. The objective of this study was to demonstrate the increase in the safety factor depending on the applied anti-

seepage measures. The presented results are part of an ongoing research project at the Jaroslav Černi Water Institute, related to the development of the Dam Safety Management System for HPP “Iron Gate II”.

Based on the results shown in Table 3, it can be concluded that all calculated safety factors for the auxiliary power plant structure exceed 1.5, clearly indicating that the uplift forces are lower than the stabilizing vertical forces. Acceptable minimum values of the safety factor for structures that have been in operation for a prolonged period are currently the subject of ongoing research and will be published in future studies, building upon the findings presented in this paper.

The presented diagrams of seepage behavior and safety factor values, as well as their increase after the implementation of anti-seepage measures, highlight the importance of applying injection curtains and drainage wells for a more favorable situation regarding buoyancy calculations.

7. REFERENCES

[1] Savić M. Ljubodrag, **Uvod u hidrotehničke građevine**, *Građevinski fakultet Univerziteta u Beogradu*, Beograd, 2009

[2] Institut za vodoprivredu „Jaraoslav Černi“, Sistem za upravljanje bezbednošću brane HE „Đerdap 2“ v2023, **Knjiga 3 – Izveštaj o analizama izvršenim primenom MKE modela filtracionih i naponsko – deformacionih procesa na dodatnoj elektrani**, Beograd, 2024

[3] https://www.eps.rs/lat/djerdap/Stranice/Galerija.aspx?folder=Galerija%2f2+-+He+%c4%90erdap+2 (24.04.2025.)

[4] Mirković Uroš, Radovanović Slobodan, Divac Nikola, Vulović Snežana: **Uticaj zavese i drenažnih bušotina na filtracionu sliku u temeljnoj spojnici gravitacionih brana**. *Zbornik radova sa nacionalnog simpozijuma DGKS*, Beograd, 2021

[5] **SRPS EN 1997-1:2017, Evrokod 7 – Geotehničko projektovanje – Deo 1: Opšta pravila**, *Institut za standardizaciju Srbije*, Beograd, 2017

[6] Živković Miroslav, Vulović Snežana, Kojić Miloš, Slavković Radovan, Grujović Nenad, **Program for FE Analysis of Flow Through Porous Media**, 2019

[7] Živković Miroslav, Vulović Snežana, Kojić Miloš, Slavković Radovan, Grujović Nenad, **User manual and examples for PAK-P – Program for FE Analysis of Flow Through Porous Media**, *Faculty of Engineering University of Kragujevac*, Kragujevac 2019

doi.org/10.62683/SINARG2025.036

Research paper

A METHOD FOR SEISMIC PROTECTION OF BRIDGES USING NEW UPGRADED NVF-ISOLATION SYSTEM: SHAKING TABLE TESTS OF BRIDGE MODEL

Jelena Ristic[1], Danilo Ristic[2]

Abstract

Presented in this paper is a new method representing efficient innovative system for seismic protection of bridges, created with upgrading of isolated bridge with developed specific uniform NVF devices. Capability of the new NVF seismic protection system for bridges was fully demonstrated with the conducted extensive seismic shaking table tests of large-scale bridge prototype model. The constructed bridge prototype model was assembled based on optimal upgrading of its basic isolation system, comprised of specific double spherical rolling seismic bearing (DSRSB) devices, with the originally created efficient uniform vertical fixed (NVF) complementary upgrading devices. The specific research segment devoted to development of the present NVF upgraded bridge system was originally created and realized by the authors as a part of an innovative research project. The presented research segment was realized at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, North Macedonia, within the innovative NATO Science for Peace and Security Project "Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828)", involving five European countries. The composed upgraded isolated rolling system with uniform NVF energy dissipation (ED) devices represent suitable integrated passive mechanical bridge system providing harmonized response of integral bridge structure subjected to strong earthquakes. The adopted system is based on global optimization of seismic energy balance, achieved through utilization of newly designed dissipation devices as a supplementary damping to the bridge isolation. The new NVF seismic protection system is based on incorporation of the following three integrated complementary systems: (1) Double spherical rolling seismic isolation (DSRSB) system, (2) Created NVF energy dissipation (ED) system and (3) Displacement limiting (DL) system. The created NVF bridge system represents a qualitatively new construction strategy providing upgraded structural seismic safety and efficient modification of the seismic response in bridges located in seismically active regions.

Key words: *bridge, seismic safety, seismic response, seismic isolation, energy dissipation*

[1] Coordinator & Lead Researcher, PhD, RESIN Laboratory of Industrial Sciences and Technology, Republic of N. Macedonia, jelena.ristic@resinlab.mk, https://orcid.org/0009-0002-3283-917X

[2] Prof. PhD, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje, Republic of N. Macedonia, danilo.ristic@gmail.com, ORCID: https://orcid.org/0009-0007-7293-4514

1. INTRODUCTION

Extensive studies in the field of seismic isolation of bridges have been mostly performed in the world's renowned research centers in Japan, USA, Italy, and New Zealand. However, in the recent years, contributions from many other countries are increased and have resulted in proposing of many new ideas and concepts. The intolerable severe impacts to modern bridge systems during strong recent earthquakes [1, 2], have been observed. It has given rise to strong arguments about the further needs for development and practical implementation of seismic isolation systems in seismic protection of bridges, [3, 4, 5, 6, 7]. This paper shows the obtained important results from the realized creative research part of the innovative long-term study devoted to development of a new, experimentally verified, advanced NVF system that can provide qualitative seismic upgrading of isolated bridges by using of innovative NVF energy dissipation devices [8]. The tested uniform upgrading system for seismic protection of bridges, NVF system, utilizes originally produced double spherical rolling seismic bearings (DSRSB) as seismic isolation system, while qualitative improvement of seismic performances is achieved through the use of uniform new vertical fixed (NVF) energy dissipation devices.

2. CONCEPT OF NVF BRIDGE SYSTEM

The NVF bridge system was created as a novel adaptable technical option incorporating three specific complementary and obligatory systems:

Seismic isolation system: The implemented seismic isolation (SI) system was selected to respectively assure safe vertical load carrying capacity resulting from the super-structure weight and low cumulative stiffness in horizontal direction effective for seismic isolation.

Energy dissipation system: The new vertical fixed energy dissipation devices (NVF devices) represent a novel technical structural option created with advanced hysteretic response performances and implemented for assembling of the bridge energy dissipation system. The NVF devices had to be designed with respect to the performances of the seismic isolators, successfully creating conditions for their optimal interactive response.

Displacement limiting system: The displacement limiting (DL) system was created using the developed specific DL devices capable of reducing or eliminating a critical earthquake impact effect. The DL system actually represents the last line of defense.

2.1. Concept of multi-directional NVF energy dissipation devices

Structural system: The created new vertical fixed energy dissipation devices (NVF devices) consist of eight main structural parts, Figure 1a).

- Bottom fixing plate (for bottom fixation of eight vertical NVF components);
- Fixing segment of NVF component;
- Vertical fixed multi-directional NVF component;
- Curved segment of NVF component;
- Upper fixing and activating plate (for upper fixation of NVF components);
- Welding-based component fixation;
- Stiff upper segment fixed to the super-structure;
- Locations for possible installation of additional eight NVF components (left).

Geometrical characteristics of the created and used NVF energy dissipation components are presented in Figure 1b). (right).

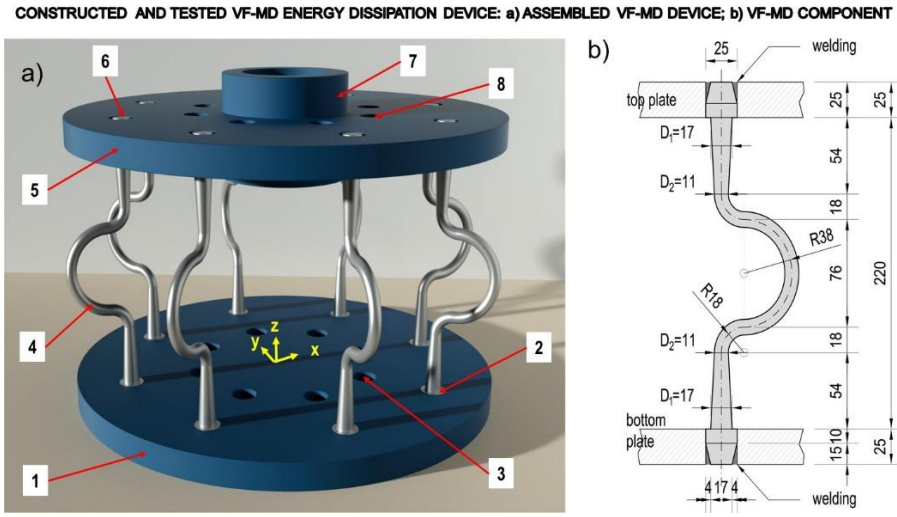


Figure 1. Originally designed and constructed prototype model of NVF device consisting of: 1. Bottom fixing plate; 2. Fixing segment of NVF component; 3. Vertical fixed multi-directional NVF component; 4. Curved segment of NVF component; 5. Upper fixing and activating plate; 6. Welding-based component fixation; 7. Stiff upper segment fixed to the super-structure; 8. Locations for possible installation of additional eight vertical fixed NVF components (left) and geometrical characteristics of created NVF energy dissipation component (right).

3. EXPERIMENTAL TESTING OF NVF BRIDGE SYSTEM

Shaking table testing program and set-up of bridge model: To obtain a reliable and relevant evidence on the seismic performances of the created NVF bridge system, an integral study comprising specifically targeted and extensive experimental research was adopted:

a) Bridge model testing program: The integral shaking table testing program included realization of different types of shaking table tests on a large-scale bridge model, including: (1) Sine-sweep tests on the bridge model with mounted isolation only. The programmed sine-sweep tests were conducted to confirm the actual recorded initial value of the fundamental vibration period and damping of the base isolated, not upgraded, bridge model; (2) Seismic test on the basic bridge model having isolation only. This seismic test was considered as referent, providing evidence on the seismic response of the bridge system without NVF upgrading devices; (3) Seismic tests on the NVF bridge model under simulated near-field earthquakes. The tests were performed to investigate the response of the upgraded bridge under simulated strong near-field earthquakes with different frequency content; (4) Seismic tests on the NVF bridge model under simulated semi-resonant earthquakes. Actually, these series of tests were carried out to investigate the response of the upgraded bridge under simulated semi-resonant or far-field earthquakes with different frequency content.

b) Set-up of bridge model: To provide simulation of the seismic response in longitudinal and transversal direction, the bridge model was spaced diagonally on the IZIIS seismic shaking table, Figure 2. It was composed of a stiff RC model sub-structure (SUB-S), model super-structure (SUP-S) in the form of an RC slab, left (abutment) support (LS), right

(abutment) support (RS), shorter middle piers (SMP), longer middle piers (LMP), two DSRSB devices at the left support (1,2), two DSRSB devices at the right support (3,4), location for the NVF device at the left support (A), location for the NVF device at the right support (B), a steel frame for installation of two DL devices above the left support and a steel frame for installation of two DL devices above the right support.

The typical full-scale prototype bridge was selected with configuration suitable for the proposed seismic upgrading. The three-span bridge superstructure had a total length of 58.5m (15.75+27.0+15.75), while the piers had different heights (9.50 and 11.70m). Formed between the RC bridge deck and the sub-structure supports was a seismic gap suitable to accommodate seismic isolation and energy dissipation devices. The constructed bridge model was geometrically reduced in respect to the prototype bridge based on an adopted geometric scale factor of 1:9 in order to match the dimensions and the load capacity of the shaking-table, Ristic, J., [7]. Considering the addressed modeling factors, the combined true replica-artificial mass simulation model was adopted as the most adequate. The total length and width of the model sub-structure amounted to 8.30m and 1.50m, respectively.

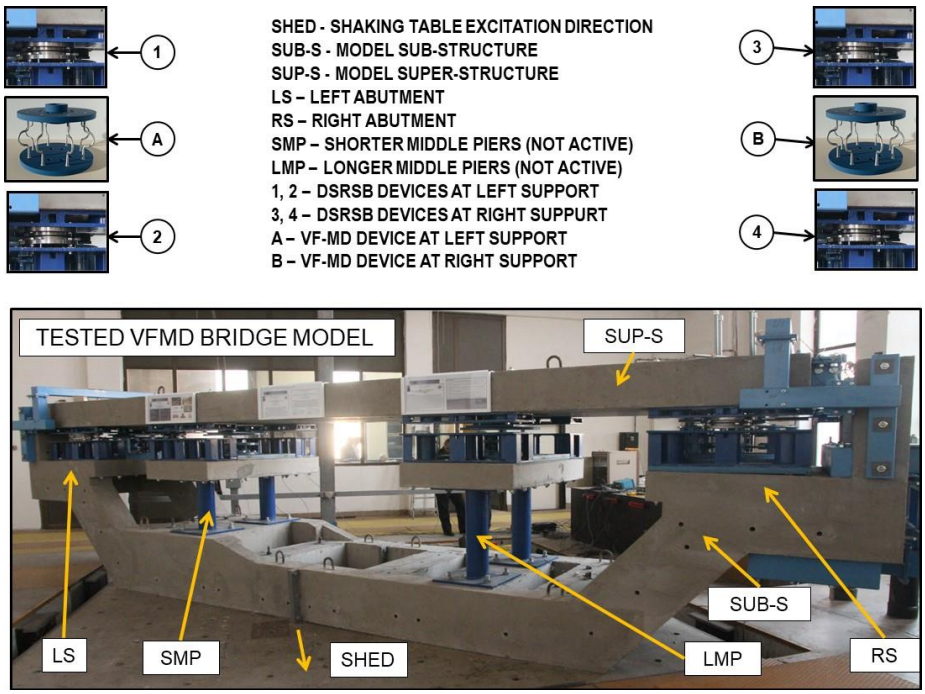


Figure 2. Constructed NVF bridge prototype model tested on the IZIIS seismic shaking table

The thickness of the model superstructure deck was conveniently increased to compensate for the additional superstructure load and to enable realistic simulation of the generated large inertia forces. In the presented tests, the mid-piers were not used and the tested model was transformed into a one-span structure. The existing steel components were manufactured of S355 steel class, while C25/30 concrete type was used for the construction of the concrete components.

c) Instrumentation of bridge model: The successfully used extensive instrumentation system of the model, Figure 3, was presented in details before by Ristic, J., [7]. It consisted of the adopted identical instrumentation devices, including: (1) Four LVDT transducers (four

linear variable differential transformers) for recording response time histories of relative displacements between the sub- and super- structure; (2) Four LP transducers (linear potentiometers) for recording absolute response displacements, assured by fixation of one of their ends to the referent points located beyond the shaking table and (3) Twelve acceleration sensors (ACC) to record the acceleration time history responses of the selected six characteristic model points in longitudinal and transverse direction, respectively.

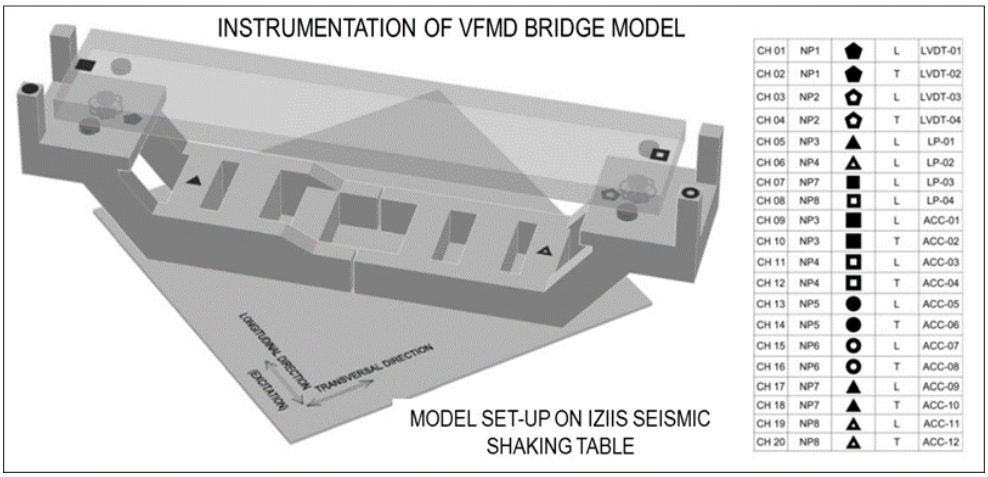


Figure 3. Instrumentation of the tested NVF bridge model: Acquisition channels and respective recording sensors

d) Sine-sweep testing of bridge model with isolation only: Seven repeated sine-sweep dynamic tests were initially conducted under low intensity sine-sweep dynamic inputs (0.02g to 0.05g) simulated by the shaking table. Generating different sine-sweep input signals with a wide range of frequencies (1 to 35Hz), a large volume of data was obtained. Using the recorded data, for the tested bridge model with mounted isolation only, the value of the fundamental period amounting to T_o=0.522s and damping amounting between 3.0 and 3.5%, were successfully defined.

e) Seismic testing of bridge model with isolation only: The basic, initial seismic test on the bridge model with installed isolation device only was conducted to directly assess the contribution of the created NVF energy dissipation devices implemented in the next study phase. In that respect, the initial test was realized under the simulated El Centro earthquake scaled to PGA = 0.81 g. From the conducted seismic test, a large unacceptable maximum relative displacement amounting to 42.34 mm was recorded. It was larger than the defined allowable displacement of 40.0 mm. However, in the case of the tested upgraded NVF bridge system presented in the next section, the maximum relative displacements were reduced to fully controlled values.

3.1. Testing of NVF bridge model under near-field earthquakes

The actual seismic response of the created NVF bridge system under earthquake excitations was controlled by the interactive effects of the nonlinear responses of the integrated seismic isolation and energy dissipation devices. To fully demonstrate the actual behaviour of the installed specific devices and the resulting global seismic response of the integral NVF bridge system, experimental seismic tests were conducted. The performed shaking table seismic tests provided a full evidence regarding the seismic performances of

the NVF bridge system at the global level. The detailed insight into the response characteristics of the seismic isolation and the NVF energy dissipation devices was also obtained from the conducted experimental study. The basic testing details and related observations from the original shaking table seismic tests are briefly summarized.

a) Simulated seismic input: Seismic testing of the NVF bridge model was performed under selected four different near-field earthquake records, characterized by representative frequency contents [7]. Following the relations from the similitude law, the original earthquake records were time compressed for a time factor of t_f = 1/3, calculated with the respective formula $t_f = 1 / (lr)^{0.5}$, where lr=9 and representing the originally considered geometrical scale of the bridge model. To obtain representative experimental results, high earthquake intensities were simulated by scaling of the respective records to high levels of peak ground accelerations amounting to PGA=0.75g for the El Centro (1940) earthquake record, PGA=0.73g for the Petrovac (Montenegro, 1979) earthquake record, PGA=0.77g for the Landers earthquake record and PGA=0.93g for the Northridge earthquake record. The ground-shaking records used in this study belong to the permanent seismic data base of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Ss. Cyril and Methodius University in Skopje. The existing seismic database for testing was created in the specific MTS shaking table operational format. Selection of ground shaking parameters should be carefully made considering the specific research objectives and the existing technical testing conditions.

Table 1. Peak relative sub-super structure displacements recorded by LVDT sensors during the original shaking-table tests on the NVF bridge model under simulated strong (compressed) near-source earthquakes

B1. SEISMIC TESTS SIMULATING COMPRESSED EL-CENTRO & PETROVAC EARTHQUAKE						
No.	O-T1: C-El-Centro, PGA=0.75G			O-T2: C-Petrovac, PGA=0.73G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
1	LVDT-01	-32.40	29.34	LVDT-01	-14.54	18.23
2	LVDT-02	-5.27	3.79	LVDT-02	-2.44	5.54
3	LVDT-03	-26.04	17.96	LVDT-03	-21.77	9.43
4	LVDT-04	-6.72	3.01	LVDT-04	-2.76	6.83
B2. SEISMIC TESTS SIMULATING COMPRESSED LANDERS & NORTHRIDGE EARTHQUAKE						
No.	O-T1: C-Landers, PGA=0.77G			O-T2: C-Nortrige, PGA=0.93G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
1	LVDT-01	-12.90	13.15	LVDT-01	-33.21	29.56
2	LVDT-02	-3.73	3.86	LVDT-02	-3.21	10.79
3	LVDT-03	-11.80	18.78	LVDT-03	-31.24	29.72
4	LVDT-04	-3.64	2.57	LVDT-04	-6.55	7.35

b) Data acquisition system: Due to the complexity of the conducted seismic tests, extensive experimental data files were recorded from each acquisition channel. Specifically, having an extensive set of 20 instrumented channels and some extra channels of sensors for controlling of the shaking table, along with the used highly refined data sampling rate, from each seismic test, about 5 million numerical values were recorded. The integral testing

process, involving sixteen shaking table tests, was very successfully completed. All sensors provided correct and complete experimental records. Following the systematic data processing (existence of about 80 million numerical data), representative results showing the system response were selected, processed and presented.

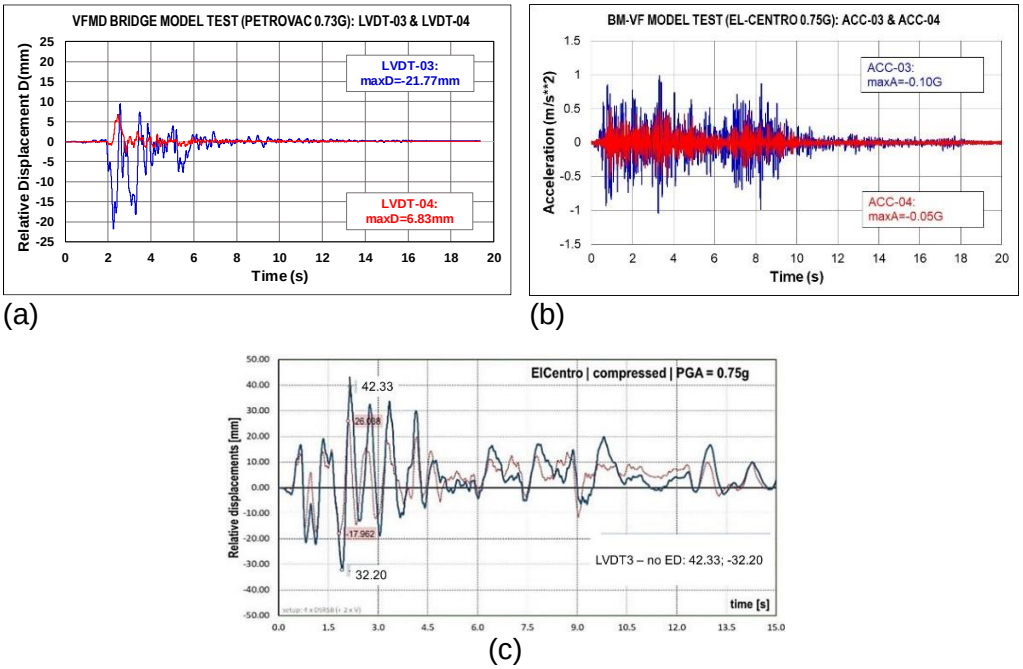


Figure 4. Recorded time-history responses of the NVF bridge model tested under simulated compressed strong Petrovac earthquake: (a) relative displacements and (b) acceleration responses of the superstructure recorded by ACC-03 & ACC-04. Recorded relative displacements of the NVF bridge with seismic isolators only (blue) under simulated compressed El-Centro earthquake (c).

c) Recorded relative displacements: The peak relative displacements, including positive and negative pulses, recorded during the seismic tests on the NVF bridge model under simulated four strong near-field earthquakes, are presented in Table 1. To graphically illustrate the recorded seismic responses of the tested NVF bridge model, Figure 4 shows the time history responses of relative displacements and accelerations of the characteristic measuring point 1, obtained during the test conducted under the simulated Petrovac earthquake. For the selected characteristic measuring point 1, Figure 4 (a) and Figure 4 (b), respectively show the recorded relative superstructure displacements and accelerations, in longitudinal (L) and transverse (T) direction, comparatively. Based on the results obtained from the experimental study, the following observations were summarized: The displacements recorded in L direction, representing the direction of the earthquake excitation, are dominant; (2) The displacements in T direction, normal to the earthquake excitation, are small and insignificant; (3) The maximum peak relative displacement amounting to Dmax = -32.40 mm was smaller than the allowable displacement of the seismic isolators amounting to Da = 40.0 mm, and (4) The new NVF bridge system is capable of advancing the seismic performances and providing a stable seismic response. With the recorded in all cases, the reduced relative displacements, Table 1, the advantages of the adopted NVF energy dissipation devices are clearly demonstrated.

d) Recorded accelerations: From the presented acceleration time-histories in L and T direction of the superstructure recording point 1, Figure 4 (right), it is evident that the recorded maximum accelerations are, in this case, significantly smaller than the input acceleration. The peak accelerations can be larger than the input acceleration in some cases, but they are not significantly amplified. Such response characteristics directly reflect the achieved advanced effects of the tested NVF bridge system.

e) Recorded absolute displacements: Considering the time-histories of absolute displacements recorded in L direction by the installed LP sensors on the sub- and super-structure segments of the tested NVF bridge model, a correct control of the seismic shaking table and successful accomplishment of the data recording process was confirmed in all realized testing cases.

3.2. Testing of NVF bridge model under far-field earthquakes

a) Testing objectives: The advanced seismic performances of the NVF bridge system subjected to strong near-field earthquakes are integrally demonstrated in section 3.1, based on the results obtained from the realized related seismic tests. Critical spectral amplitudes of the simulated earthquakes were avoided by the introduced DSRSB isolation system.

Table 2. Peak relative sub-super structure displacements recorded by LVDT sensors during the original shaking-table tests on the NVF bridge model conducted under simulated real (not compressed) earthquakes

B1. SEISMIC TESTS SIMULATING REAL EL-CENTRO & PETROVAC EARTHQUAKE						
No.	O-T1: R-El-Centro, PGA=0.52G			O-T2: R-Petrovac, PGA=0.29G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
3	LVDT-03	-29.86	19.80	LVDT-03	-35.60	32.83
4	LVDT-04	-3.70	2.354	LVDT-04	-10.07	7.44
B2. SEISMIC TESTS SIMULATING REAL LANDERS & NORTRIGE EARTHQUAKE						
No.	O-T1: R-Landers, PGA=0.27G			O-T2: R-Nortrige, PGA=0.25G		
	Channel	MaxD (-) (mm)	MaxD (+) (mm)	Channel	MaxD (-) (mm)	MaxD (+) (mm)
3	LVDT-03	-24.51	26.06	LVDT-03	-38.59	34.76
4	LVDT-04	-11.31	8.89	LVDT-04	-5.55	1.03

Incorporating the novel NVF energy dissipation devices, the damping of the created NVF system was significantly increased. However, having an enlarged vibration period of the first mode, the system became more sensitive to long period (far-field) earthquakes.

To fill this clearly evident investigation gap, the seismic response of the NVF bridge system exposed to long period earthquakes was also experimentally studied. Specifically, well targeted series of seismic tests with simulated far-field earthquakes were conducted.

b) Testing conditions: Analyzing the computed response spectra for the compressed and uncompressed earthquake records, a suitable and quite relevant testing scenario was defined. The used compressed earthquake records were relevant to simulate near-field earthquakes since they were derived following the test model similitude law. However, regarding the uncompressed real earthquake records, it was observed that the dominant part of their response spectra was distributed near the fundamental period of the assembled NVF

bridge system. Having in mind the significance of this observed property, the recorded uncompressed earthquake records were considered to represent a suitable and evidently relevant earthquake input option for realization of the planned extensive seismic testing of the NVF bridge system under simulated far-field earthquakes.

c) Testing results: From the realized integral seismic testing program, voluminous numerical data was obtained. However, as early as during the first seismic test, a highly intensified seismic response was observed. Therefore, the further seismic testing concept was accordingly modified. Specifically, the actual PGA value of any earthquake record was carefully adjusted to fully satisfy the dynamic shaking table payload and to properly assure the model safety in each conducted individual seismic test.

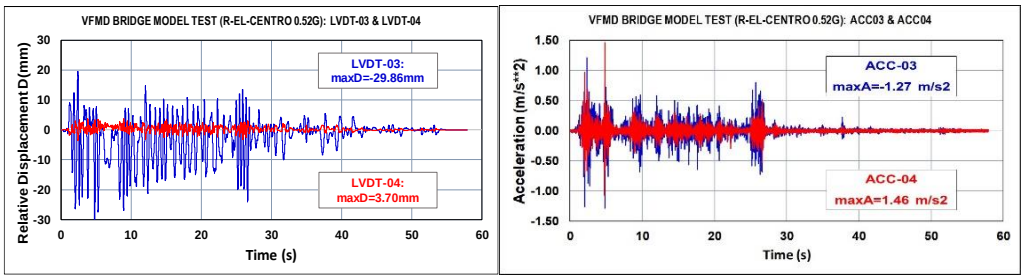


Figure 5. Superstructure relative displacements (left) and acceleration responses (right) recorded respectively by LVDT and ACC sensors during seismic test of NVF bridge model simulating real strong El-Centro earthquake

Table 2 shows the recorded peak relative sub- super- structure displacements during the original shaking table tests on the NVF bridge prototype model conducted by simulation of real (not compressed) long-period earthquake records. It was evident that the obtained maximum relative displacements were remarkably larger, even though the long-period earthquakes were simulated with lower PGA values. Respectively, the used earthquake records were accordingly scaled, El-Centro to PGA=0.52G, Petrovac to PGA=0.29G, Landers to PGA=0.27G and Northridge to PGA=0.25G. Fig. 5 respectively shows the time history response of the superstructure relative displacements recorded by LVDT-3 and LVDT-4 (left) and the time histories of acceleration responses recorded by ACC-03 & ACC-04 (right), during the NVF model test performed by simulation of the real strong El-Centro earthquake. With the presented tests realized by simulation of far-field earthquakes, the safety of the NVF system was also confirmed, because the PGA values became much lower due to their very significant attenuation with distance.

4. SUMMARY OF RESEARCH RESULTS

The capability of the NVF bridge system to protect bridge structures subjected to very strong near-field earthquakes is graphically demonstrated in Fig. 6. Having the installed novel NVF devices, the system provided suitable modification of the seismic response. In all test cases, the maximum recorded relative superstructure displacement was significantly reduced.

Suppressing the maximum relative displacements in all test cases below the allowable displacement of the isolation devices amounting to 40.0 mm, a stable, safe and reliable seismic response was confirmed. On the contrary, an unsafe seismic response was shown

in the comparative test of the bridge system having isolation only, since the maximum relative displacement became larger than the allowable displacement of the seismic isolation devices.

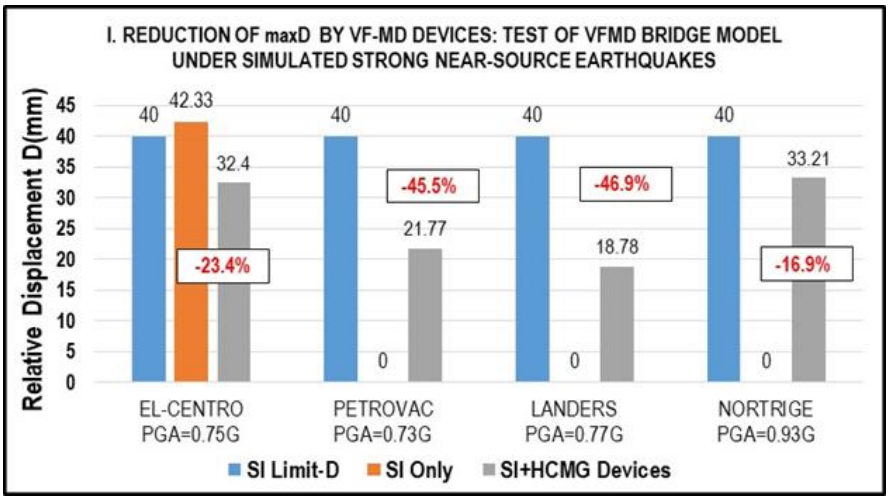


Figure 6. Confirmed reduction in maximum relative displacement by the installed NVF devices: Shaking-table tests of the NVF bridge model under simulated strong near-source earthquakes

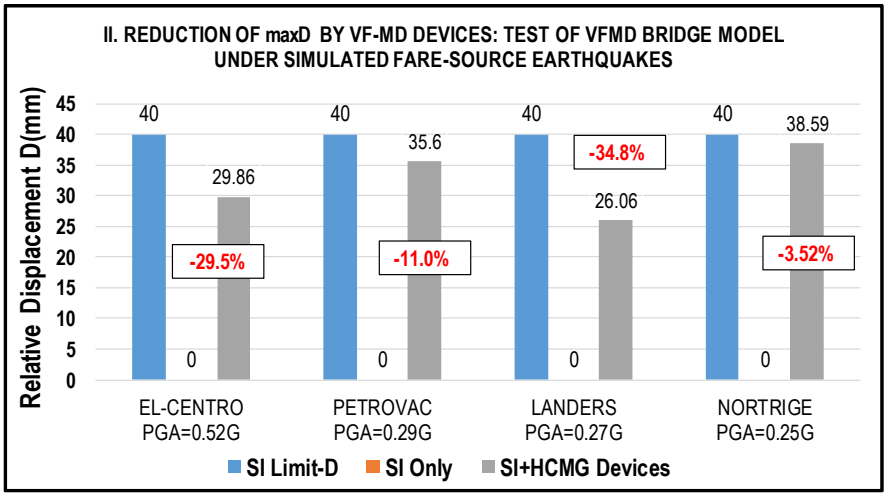


Figure 7. Confirmed reduction in maximum relative displacement by the installed NVF devices: Shaking-table tests of NVF bridge model under simulated far-source earthquakes

Similarly, the capability of the NVF bridge system to optimally protect bridge structures subjected to far-field (longer period) earthquakes is shown in Fig. 7. From the experimental test results, it is evident that the recorded maximum relative displacements are below the allowable displacement in all cases. The suitability of the NVF bridge system for seismic protection of bridges under far-field earthquakes is evident, specifically regarding the recorded rapid attenuation of the maximum ground accelerations.

5. CONCLUSIONS

Considering the derived and processed voluminous original experimental results, involving about 160 million numerical data recorded during the performed extensive shaking table seismic tests on the large–scale NVF bridge model, along with the observed unique supplementary results, the following conclusions were summarized:

1) It was experimentally confirmed that the created NVF energy dissipation device, involving a technically new option for increasing damping through uniform adaptable nonlinear response, provided advanced capability for energy dissipation and effective upgrading of isolated bridges exposed to near and far field earthquakes.
2) The required validity of the initial dynamic properties of the tested and modeled NVF bridge system was confirmed with the obtained very good correlation between the fundamental period defined experimentally with sine-sweep dynamic tests and the value calculated with the formulated analytical model.
3) The possible unsafe seismic response of the assembled bridge model with DSRSB isolation only was demonstrated with the conducted comparative seismic proof test. An unstable seismic response of the bridge with isolation only was obtained because the recorded maximum relative superstructure displacements were larger than the allowable displacement of the implemented seismic isolation devices.
4) For the seismic input characterizing strong near-field earthquakes, the NVF bridge system showed an advanced seismic protection capability. The stable and harmonized seismic response was confirmed with the conducted respective seismic shaking table tests. In all test cases, the maximum relative superstructure displacements remained significantly below the allowable displacement due to the efficient upgrading effects induced with the NVF energy dissipation devices.
5) Analogously, in the case of an earthquake input characterizing long-period or far-field earthquakes, the NVF bridge system again showed a satisfactory system seismic protection. Specifically, in all conducted seismic tests under simulated relatively high seismic intensity, the recorded maximum relative superstructure displacements remained below the allowable displacement. The upgrading effect of the NVF energy dissipation devices was experimentally confirmed.
6) The capability of the formulated new phenomenological nonlinear analytical model to realistically simulate the complex seismic response of the NVF bridge system under simulated near- and far-field earthquakes can be confirmed based on results obtained from the extensive experimental study. Specifically, in the future analytical studies, the required high correlation level can be established regarding the seismic responses predicted analytically and those recorded during the conducted the present original and representative seismic tests.
7) The experimentally validated NVF bridge system, involving adaptive NVF device for seismic response modification, can be successfully implemented in real practice for advanced seismic protection of bridges potentially exposed to strong near- and critical far-field earthquakes.

ACKNOWLEDGMENTS

The research was realized in the Institute of Earthquake Engineering and Engineering Seismology, “Ss Cyril & Methodius” University in Skopje, in the frames of the innovative NATO Science for Peace and Security Project: Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies (SFP: 983828), with participation of five countries: North Macedonia: Danilo Ristic, Leader & PPD-Director, Germany: Uwe Dorka, NPD-Director, Albania: Arian Lako, Bosnia & Herzegovina: Damir Zenunovic & Serbia: Radomir Folic. The extended support to the realization of the project is highly appreciated.

REFERENCES

[1] Yuan W., Feng R., & Dang X.: **Typical Earthquake Damage and Seismic Isolation Technology for Bridges Subjected to Near-Fault Ground Motions.** *International Conference on Engineering Simulation and Intelligent Control (ESAIC), 2018.* doi:10.1109/esaic.2018.00079.

[2] Kelly JM: **A Seismic Base Isolation: Review and Bibliography.** *Soil Dynamics and Earthquake Engineering,* 1986*,* 5(4): 202-216.

[3] Ristic Danilo: **Nonlinear Behavior and Stress-Strain Based Modeling of Reinforced Concrete Structures under Earthquake Induced Bending and Varying Axial Loads.** PhD Dissertation, School of Civil Engineering, Kyoto University, Kyoto, Japan, 1988.

[4] Ristic Danilo, Ristic Jelena: **New Integrated 2G3 Response Modification Method for Seismic Upgrading of New and Existing Bridges.** *15th World Conference on Earthquake Engineering, (WCEE)*, Lisbon, Portugal, 2012.

[5] Ristic Jelena, Misini Misini, Ristic Danilo, Guri Zijadin, Pllana Nebi: **Seismic Upgrading of Isolated Bridges with SF-ED Devices: Shaking Table Tests of Large-Scale Model.** *Građevinar,* 2017*, 70* (6): 463-485.

[6] Ristic Jelena: **Comparative Seismic Analysis of RC Bridge Structure Applying Macedonian Seismic Design Regulations and Eurocodes. MSc Thesis, Department for Theory of Structures.** “Ss. Cyril and Methodius” University, Skopje, Macedonia, 2011.

[7] Ristic Jelena: **Modern Technology for Seismic Protection of Bridge Structures Applying New System for Modification of Earthquake Response**. PhD Thesis, Institute of Earthquake Engineering and Engineering Seismology (IZIIS), “Ss. Cyril and Methodius” University, Skopje, Macedonia, 2016.

[8] Ristic Danilo, Dorka Uwe, Lako Arijan, Zenunovic Damir, Folic Radomir: **Seismic Upgrading of Bridges in South-East Europe by Innovative Technologies.** NATO SfP Project 983828, *Science for Peace and Security Programme*, Final Report, 2013.

doi.org/10.62683/SINARG2025.043

Research paper

PROTECTION OF THE ARCHITECTURAL HERITAGE OF VLASOTINCE – NEMANJINA STREET

Ana Momčilović Petronijević[1], Ivana Cvetković[2], Đorđe Stošić[3], Mirko Stanimirović[4]

Abstract

The potential of Vlasotince, a small town in southern Serbia, along with that of similar settlements, remains largely unrecognized and underutilized. Until recently, the town's significant architectural heritage had been almost entirely unexplored. However, in 2023 and 2024, comprehensive research was conducted on the architectural heritage of Vlasotince. As a result, the Institute for the Protection of Cultural Monuments in Niš, in collaboration with the Faculty of Civil Engineering and Architecture in Niš, published the Study on the Protection of the Architectural Heritage of Vlasotince – Stara Čarčija, as a potential basis for development. This study aims to highlight the role of architectural heritage as a foundation for the city's future growth. This paper presents a detailed analysis of the architectural heritage along Nemanjina Street in Vlasotince, with the objective of drawing attention to its cultural and historical significance. Furthermore, it explores potential models for the preservation and promotion of this heritage, emphasizing its importance in the broader context of sustainable urban development.

Key words: *architectural heritage, protection, presentation*

[1] Faculty of Civil Engineering and Architecture, University of Niš, Serbia, associate professor, ana.momcilovic.petronijevic@gaf.ni.ac.rs, https://orcid.org/0000-0001-7224-5590
[2] The Institute for Cultural Heritage Preservation Niš, ICHP Niš, senior conservator, architecture, Serbia, ivana.cvetkovic.ct@gmail.com
[3] The Institute for Cultural Heritage Preservation Niš, ICHP Niš, senior conservator documenter, Serbia, djordje.stosic@zzsknis.rs
[4] Faculty of Civil Engineering and Architecture, University of Niš, Serbia, associate professor, mirko.stanimirovic@gaf.ni.ac.rs, https://orcid.org/0000-0001-6201-5855

1. INTRODUCTION

Vlasotince, a small town in southern Serbia, shares the fate of most settlements of its type and size in the country. The built environment, particularly the architectural heritage as a potential driver of future development and a possible catalyst for positive socio-economic and societal change, is hardly ever considered. Unplanned urbanization and construction are slowly erasing valuable traces of the past embedded in the urban fabric.

In many cases, the architectural heritage of small towns remains unexplored and insufficiently examined. The trend of conducting heritage studies, an initial step toward drawing attention to architectural heritage and creating clear guidelines for its protection, has only gained momentum in recent years. The legal framework for protection was partially improved with the adoption of the Cultural Heritage Law in 2023 [1], as well as the National Architectural Strategy of the Republic of Serbia [2], which recognized architectural heritage as one of the most important categories of cultural heritage. Heritage protection studies have become a mandatory component of planning documents, thereby providing heritage protection with a more solid legal foundation.

The architectural heritage protection study of Vlasotince was developed during 2023 and 2024 through the collaboration between the Institute for Cultural Heritage Preservation Niš and the Faculty of Civil Engineering and Architecture at the University of Niš. This comprehensive analysis of the built environment, including the evaluation of individual buildings and entire ambient units, not only highlights the town's potential from the perspective of architectural heritage but also provides an overview of the degradation it has suffered, offers guidelines and protection measures, and aims to prevent further decline of the ambience.

One of the identified subunits with significant loss of architectural structures is Nemanjina Street in Vlasotince. Once a hub of social life and one of the most important traffic arteries, this street forms the urban heart of the town on the Vlasina River. However, due to recent interventions that are incompatible with the context of architectural heritage, Nemanjina Street is increasingly losing its architectural identity, transforming into a disjointed composition of buildings differing in volume, style, and materials.

Due to the pronounced degradation of its ambient values, this street is presented in the study as a representative example of the process of urban identity deterioration. The aim of this case presentation is to identify the types of degradation, propose measures for their mitigation, and define construction and design rules that would help preserve the character and identity of the space.

2. HISTORICAL BACKGROUND

Vlasotince is a small town located in the southeastern part of Serbia, in the area of the lower and middle basin of the Vlasina River. It lies at the crossroads of the Leskovac–Pirot and Leskovac–Crna Trava–Surdulica–Vranje routes. It is a relatively small municipality, where the farthest point from the center does not exceed 25 kilometers. The central point, the town of Vlasotince, is an urban settlement with the characteristics of a small city and serves as the municipal center. All 47 settlements within the municipality gravitate toward Vlasotince, as it hosts all the key institutions and services.

In historical records, Vlasotince was first mentioned in the 12th century, in the work The Life of St. Simeon, a biography of Stefan Nemanja, under the name Uska, referring to the area along the Vlasina River. During the period of Ottoman occupation, Vlasotince served as a refuge for exiled fugitives from across Serbia, which is why its population is largely considered to be of migrant origin. It appears in Ottoman records in 1516 under the name Vlasotinac, as a cultural and agricultural center. In the 16th century, it had around 600 inhabitants, and by the census of 1879, the population had grown to approximately 2,600. It was officially designated a town in 1878 [3].

After liberation from Ottoman rule, many young people from Vlasotince went abroad for education, especially to European countries, bringing back progressive ideas that contributed to the town's rapid development. This development was further accelerated by the growth of the textile industry, trade, crafts, brick-making, and viticulture.

The built environment of Vlasotince gradually formed at the end of the 18th and during the 19th century, reaching its peak development in the 20th century, when most of the buildings still standing today were constructed. In the 19th century, Vlasotince developed spontaneously as a road settlement. From the mid-19th century, it began to take the shape of an elongated linear agglomeration with a trade and crafts character [4], which can still be observed today. Toward the end of the 19th century, the čaršija (commercial core) continued to develop with elements of European architectural styles, and many representative buildings were constructed during this period, shaping the identity of the town as we know it today. A period of intense development occurred in the early 20th century, especially between the two world wars, when conditions were favorable for architectural and urban transformation, marked by significant building activity [5]. This era also introduced a greater diversity of styles. In addition to academicism, two completely different stylistic movements emerged: the Serbo-Byzantine (national style) and Art Nouveau (Secession) [6]. Family residential and commercial buildings constructed in the first decade of the 20th century are characterized by massiveness, symmetry, representativeness, and academic design [4].

3. RESEARCH ON ARCHITECTURAL HERITAGE

During 2023, the Institute for Cultural Heritage Preservation Niš conducted extensive research in the municipality of Vlasotince with the aim of assessing the condition of immovable cultural heritage. The survey focused primarily on officially protected cultural monuments, specifically the Church of the Holy Spirit and the Giga House, now home to the "Desanka Maksimović" Public Library. Additional analysis was carried out on the Old Municipality building (the so-called "Tower"), the memorial complex at the old cemetery, various other public buildings, as well as a large number of structures within the spatial unit of the Old Čaršija (market district). This area includes Dragoljub Petković Square, 12th Brigade and Dušanova Streets, Liberation Square, and the streets of Marko Orešković, AVNOJ, Ivo Lola Ribar, Nemanjina, Dimitrije Stojanović, Njegoševa, and Vuk Karadžić.

3.1. Methodology

Field reconnaissance, mapping, and on-site data collection have been carried out. In addition, technical and photographic documentation for around 100 buildings has been updated, and 3D photogrammetric models have been created for individual buildings as well

as entire urban ensembles. A comprehensive study of literature and archival material was undertaken, along with a review of previous construction interventions. In addition, the research involved historical-architectural, artistic, and urbanistic analysis of the building stock, as well as a comparative analysis of current conditions with historical photographs of individual structures and segments of the Old čaršija [4].

The architectural heritage of Vlasotince was identified and mapped, while numerous buildings were subject to architectural surveying and technical recording. All available archival and supplementary documentation was collected. A process of valorization was carried out, during which buildings were categorized within the spatial unit as follows:

I. Buildings of exceptional value
II. Buildings of value
III. Buildings that do not disrupt the ambient character
IV. Buildings without value
V. Buildings that are in discord with the environment
VI. Modernist buildings constructed after World War II

For each individual building, appropriate protection measures were proposed in accordance with its assigned category. All of these measures have been consolidated into the Study for the Protection of Immovable Cultural Heritage of Vlasotince. By recognizing and valorizing the spatial cultural-historical entity of the Old Čaršija, an opportunity has been created to improve the condition and appearance of the town while preserving its authentic values.

However, the research revealed that this ensemble is undergoing rapid degradation due to inappropriate construction interventions and interpolations that are incompatible with the character of the environment. Such changes are leading to a gradual loss of heritage value, disruption of the visual structure, and erosion of the town's identity. Degradation is present across nearly the entire area of the Old Čaršija, but it is most pronounced along Nemanjina Street, which once represented the urban and social axis of the town.

4. NEMANJINA STREET IN VLASOTINCE

Nemanjina Street represents one of the most significant sub-units within the urban fabric of Vlasotince. This area is formed by a series of mixed-use residential and commercial buildings, mostly housing, craft workshops and shops, characterized by prominent street fronts and deep, narrow plots. Residential spaces are most often located above the commercial and production areas, predominantly on the first floor, while some residential units are also situated within the inner courtyards.

Nemanjina Street occasionally takes on the role of a city promenade. During the evening hours, between 6 and 10 PM, it is closed to motor traffic and functions as a pedestrian zone. During this time, it becomes a tool for revitalizing and stimulating urban life, combining traditional forms of public space—such as the korzo, promenade, and bazaar—with contemporary modes of social interaction. This temporary functional shift contributes to preserving the street's identity and affirms its cultural and social value.

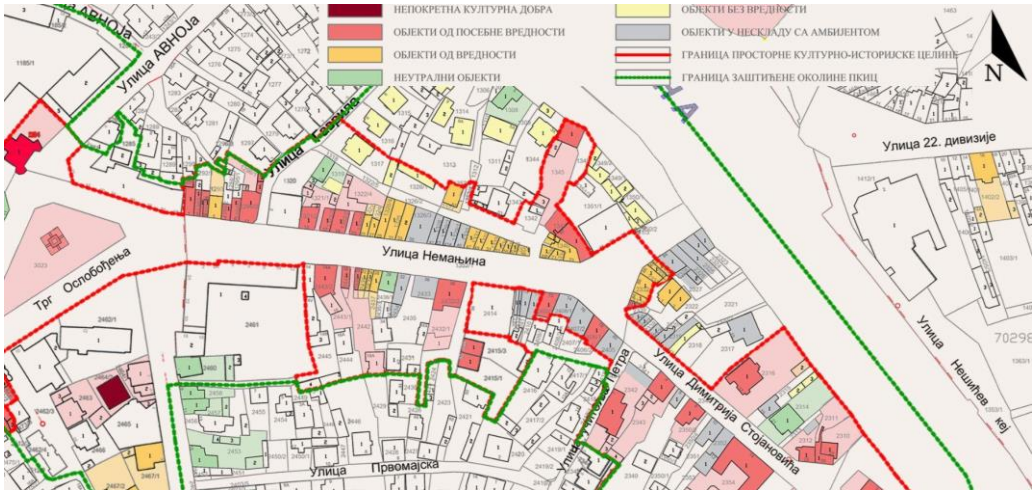


Figure 1. Part of the Old Bazaar in Vlasotince with Nemanjina Street highlighted, drawing by ICHP Niš

The **odd-numbered side** of Nemanjina Street today consists of a rather inharmonious sequence of buildings, due to uncoordinated building heights and diverse architectural styles resulting from different periods of construction. The sequence begins with two-story houses of fairly uniform appearance: the house of Sotir Valčić and the house of Vojislav Popović. This sequence is interrupted by the low, single-story shop of Blagoje Karuović. Next comes the two-story house of Krsta Bošković, one of the more prominent and valuable buildings in this section. After the intersection of Nemanjina Street with Gavrilo Princip Street, there is a three-story residential building whose height exceeds the ridge of the Bošković house, as well as that of the next, perhaps most representative building in the row—the house of Golub Aranđelović.



Figure 2. Odd-numbered side of Nemanjina Street, documentation by ICHP Niš

The insertion of the taller residential building between these two significant structures diminishes the architectural value of the entire composition. Next is the house of Ilija Krainčanić, currently under reconstruction and lacking a roof structure. Upon completion, the building is expected to regain its original appearance and reestablish harmony with the Aranđelović house.



Figure 3. Odd-numbered side of Nemanjina Street, documentation by ICHP Niš

This is followed by a row of shops, along with more recent single-story structures forming a marginal block. However, these newer buildings differ significantly in scale, height, and façade treatment from the established context. The row is interrupted by Krnjino alley (Krnjino sokače), which once featured notable examples of Ottoman-Balkan architecture, and leads to the Spaska House (Spaskina kuća), which, along with the Giga House, represents an exceptionally valuable example of traditional Ottoman-Balkan residential architecture. The house was built around 1880 by Stavra Spaska Krainčanić, a merchant and the first president of the Vlasotince municipality after liberation from the Ottomans. Taking advantage of the terrain, the shops on the odd side of Nemanjina Street have large wine cellars accessed via Krnjino alley, while the storefronts are entered directly from Nemanjina Street. Although the architecture of these shops has been altered and adapted to Western European models over time, the façades facing Krnjino alley still bear the imprint of Ottoman-Balkan design. Unfortunately, this part of the ensemble has undergone drastic changes in recent years.

Further down Nemanjina Street, there are several more shops and the two-story house of Vlajko Takić, whose height stands out in contrast to the surrounding one-story buildings. Its form may be related to that of the Bošković and Aranđelović houses.

Among the notable buildings on the odd side is the house of Krsta Bošković, built in 1925. It is a one-story corner building featuring classical architectural elements associated with

newer trends in architecture. The ground floor is characterized by exceptionally tall storefronts and pronounced pilasters with vertical fluting that continue to the upper floor and flank the corner section of the building. The corner is further emphasized by flat attic walls with inscriptions reading “House of Krsta Bošković” (Dom Krste Boškovića), as well as a semicircular pediment above the corner façade bearing the year of construction.



Figure 4. Façades of the Bošković and Aranđelović houses, drawings from ICHP Niš documentation

The house of Golub Aranđelović Belja is a one-story structure with a richly decorated façade. It features neo-Renaissance elements on the upper floor and classical details on the ground floor. With its dominant rusticated segmental archway at ground level, an iron-wrought balcony above, and an upper floor richly ornamented with stucco decoration, this house stands as the most striking feature of the street.



Figure 5. Ilija Krainčanić House, drawing and photo from ICHP Niš documentation

The house of Ilija Krainčanić is a tangible witness to the urban development of the old bazaar. Built in 1907 in the spirit of neoclassicism and academicism, it features distinct window decorations, prominent architraves above the openings, and articulated string and cornice moldings [4]. The structure is largely preserved in its original form.

The architectural heritage on the even-numbered (eastern) side of Nemanjina Street begins with the repurposed buildings that once housed the shops of Gavrilo Popović. These are followed by the two-story house of Uroš Valčić and several more recent, smaller-scale buildings. Next is a multi-story building constructed after the Second World War. Behind it stands the house of Đorđe Popović Krčimirac, a two-story building dating from the late 19th century. Unfortunately, adjacent to this valuable historical structure, a new building has been

erected that is entirely out of harmony with its surroundings—in terms of design, materials, and cornice height—significantly diminishing the overall character of the area.

A row of shops with gabled roofs characterizes the central part of this section and represents remnants of the former urban matrix, while the tavern of Ilija Krainčanić, located near the end of the row, is of architectural, historical, and social significance for the local community.



Figure 6. Even-numbered side of Nemanjina Street, documentation by ICHP Niš

One of the most representative buildings on this side of the street is the house of Đorđe Popović Krčimirac, with a basement, ground floor, and one upper floor. The ground floor is designed in the academicist style, featuring horizontal fluting and emphasized corners. The upper floor is adorned with rhythmically placed windows topped with triangular pediments and framed by narrow, fluted pilasters.

At the other extreme of this side of the street is perhaps the most egregious example of inappropriate construction in the entire town: a building on the site of the former “Crnatovac” tavern, originally built in the 19th century and used by the local waterworks company. This new building, adjacent to the Popović house, was constructed in direct contradiction to the guidelines provided by the Institute for the Protection of Cultural Monuments in Niš. At that time, since Nemanjina Street was not protected under the Law on Cultural Property, the heritage protection office was unable to intervene [4].



Figure 7. House of Đorđe Popović Krčimirac, current and original condition, documentation by ICHP Niš

4.1. State of Architectural Heritage

The greatest threat to the survival of built heritage is posed by humans themselves, due to economic and ideological motives, inappropriate interventions, vandalism, war, negligence, and other factors [7]. In the urban core of Vlasotince, significantly more buildings and ensembles could and should have been preserved than is currently the case. First due to wartime destruction, but even more so because of aggressive urban policy, many important structures — even entire neighborhoods — were demolished. These could today represent valuable cultural heritage. Urban planning up to now has largely neglected the existing urban matrix and heritage, while the construction of inappropriate architectural structures has further contributed to the city center's lack of spatial coherence.

When assessing the overall condition of Vlasotince's architectural heritage and the interventions that have endangered the preservation of its monumental value — both of individual buildings and of entire urban ensembles — it becomes evident that the current state of the čaršija (old town) is stylistically and morphologically distressing. Most buildings have lost much of their aesthetic value due to partial and often unprofessional façade interventions.

Based on the degree of degradation, several categories have been identified:

1. Façades preserved with almost no damage, aside from changes in color, dirt, graffiti, and biological degradation;
2. Façades preserved but disfigured by inappropriate partial interventions (advertising panels, air conditioning units, etc.);
3. Façades from which ornamental plaster elements have been partially removed;
4. Complete removal of ornamental plasterwork and its replacement with inadequate surface treatments;
5. Change in materiality and original appearance of portals, with dimensions retained;
6. Changes to the shape, material, size, and original appearance of openings;
7. Change of roofing material;
8. Additions or vertical extensions of buildings, i.e., change of dimensions in horizontal or vertical sense;

9. Complete replacement of buildings with new ones of similar scale but inappropriate architectural articulation;

10. Construction of new buildings with inappropriate scale, architectural expression, and materials.

An analysis of buildings on the odd-numbered side of Nemanjina Street, based on the above criteria, has identified the type of degradation present in each individual building.

Table 1. Types of Building Degradation on the Odd-Numbered Side of Nemanjina Street

Object number	1	3	5	7-11	11a	13-17	19-23	25	27-33	35-39	41-45	47-49
Object value	I	I	II	I	VI	I	I	II	II	V	V	II
Type of degradation	1, 5	1, 5, 7	1, 5, 7	1, 2, 6, 7	10	1, 5, 7	1, 2, 5	3, 5, 7	2,3, 46, 7	10	10	4, 6, 7
Object number	51	53-57	59	69	71	73	75					
Object value	II	II	II	II	II	II	I					
Type of degradation	4,6, 7	3,6, 7	3, 5, 7	3,5, 7	3, 5	3,6 7	2,6, 7					

Table 2. Types of Building Degradation on the Even-Numbered Side of Nemanjina Street

Object number	76	74	72	70	68	66	64-56	38	36	32	28-26	24-22	20-18	14 v
Object value	V	V	I	V	V	V	VI	I	III	V	V	II	I	I
Type of degradation	9	9	2, 6, 7	9	9	9	10	1, 6	10	3, 6	9	3, 6, 7	3, 6, 7, 9	4, 6, 7

4.2. Proposals for Improving the State of Heritage

In historic urban and rural areas, it is not enough to simply preserve buildings and physical structures. It is also necessary to identify what type of development is appropriate for such an environment. Any transformation within the urban core should occur gradually, ensuring the preservation of the essential characteristics of the place [8].

With the aim of deepening the understanding of potential development directions for this part of Vlasotince čaršija, a student architectural workshop titled “Preservation of Architectural Heritage: The Old Čaršija of Vlasotince” was conceived and implemented [9]. The workshop was organized with the aim of exploring ways to integrate the topic of cultural heritage protection and preservation into the master's study program at the Faculty of Civil Engineering and Architecture, University of Niš. As the field of heritage preservation in Serbia faces challenges due to a lack of specialized personnel, it is essential to involve the academic community in decision-making processes and in planning the future development of small towns [10]. Its goal was to introduce architecture students to the fundamental principles of conservation practice and the heritage values of Vlasotince, as well as to place them in the role of designers working within a protected urban ensemble.

Students received drawings of the current condition of the street fronts, a detailed assessment of the present state, and analyses of inappropriate interventions that have degraded the value of buildings and ensembles. They also received design guidelines developed by the Institute for Cultural Heritage Preservation, which served as a basis for further project development [9].

Through the proposed student solutions—based on prior analyses and consideration of the broader context rather than fragmentary designs for individual buildings—the potential for improving the condition of the area in question becomes evident.

Through detailed analysis, long-term planning, and the establishment of precise guidelines, it is possible to steer architectural development in harmony with cultural heritage. This would encourage the emergence of a positive architectural identity in towns and settlements.

The architectural heritage of Vlasotince is a key factor in preserving local identit, not only because of its aesthetic or historical value, but also as a symbol of endurance, the safeguarding of tradition, and local uniqueness. This heritage provides residents with a sense of belonging, collective identity, and pride. Through the study of historic buildings and the development of the urban environment, we can better understand how the people of Vlasotince once lived, how social and cultural customs were shaped, and what values they held.



Figure 8. Odd-numbered side of Nemanjina Street, proposal for improvement by Ilija Ilić, Teodora Dragojević, and Maša Milošević

It is therefore essential to restore a sense of responsibility and seriousness to spatial and urban planning in any settlement. It is unacceptable to continue allowing spontaneous and poorly considered urbanization, which leads to a neglect of overall quality of life, a decline in the quality of the built environment, and the degradation of the entire urban landscape.

5. CONCLUSION

Contemporary principles of cultural heritage preservation are based on the evolving relationship with the environment and the understanding that historical heritage is an essential component of a meaningful life for present and future generations [7]. Consequently, heritage becomes more accessible to people, whose active involvement in its preservation becomes a responsibility, as does their education about its value and the need for its safeguarding [11]. Since the 1980s, international expert communities have cautioned that conventional approaches to the management of historic urban areas yield insufficient outcomes unless spatial planning is conducted through an integrative and sustainable framework [12]. Nonetheless, numerous towns in our country, particularly smaller ones, have not yet been examined from this comprehensive perspective.

Conservation professionals in heritage protection encounter the challenge of evaluating architectural heritage—specifically, determining what is truly being preserved when only fragments of historic urban cores survive. The current situation is such that coherent historical ensembles are nearly non-existent. Over the previous decades, uncritical spatial interventions, piecemeal and illegal construction have disrupted the balance and devalued the heritage landscape. In practice, it is essential not only to preserve the surviving fragments—which, if lost, could lead to the irreversible and total loss of a city's identity—but also to plan for the regeneration and restoration of entire urban ensembles. Historic urban ambiances have been disrupted by post-war construction of high-rise buildings with inappropriate architectural expression, which has destroyed the existing harmony and scale. Furthermore, valuable buildings and entire settings have been disfigured by added elements and a fundamental disregard for the architectural characteristics of the built environment, while open spaces have been stripped of greenery and essential functions.

The protection of architectural heritage is currently in an unfavorable position due to widespread misunderstanding of the value of preservation, a lack of understanding of basic conservation principles, poorly defined procedures and legal frameworks, and an inadequately regulated system for supervising interventions on heritage buildings.

Nevertheless, all international charters emphasize the importance of an integrative approach to urban and spatial conservation in order to view historic towns from a holistic perspective [12]. Understanding and managing any historic urban environment requires recognizing that a city is not a static monument or a mere collection of buildings, but a living entity shaped, and continually reshaped, by dynamic economic, social, and cultural forces [13].

This generation of conservators is tasked not only with preserving individual buildings of monumental value and restoring them to a suitable condition, but also with developing comprehensive guidelines for the regeneration and revitalization of severely deteriorated urban areas. This includes addressing damage caused by past interventions. To achieve such remediation, it is not enough to focus on isolated buildings or groups of structures. Instead, it is essential to consider the specific urban layout and architectural characteristics of entire blocks and city sections [14]. It is essential to consistently conduct prior studies on the origin and functioning of the city in order to demonstrate that interventions and adaptations to contemporary needs will not compromise its values. Planning documents should define and recommend appropriate methods for the use of historic architectural complexes, ensuring that the original urban fabric remains intact. Rather than altering it, efforts should focus on the renewal of entire urban sections. The planning process must

establish optimal conditions for active participation of the local community, followed by the implementation of proposed interventions, designated uses and functions, and spatial development strategies [14].

In this regard, it is necessary to conduct detailed and comprehensive analyses and to develop the required documentation (studies, reports, design guidelines, etc.), which would then form the basis for further planning, defining land use, construction rules, and urban parameters.

Raising awareness of the importance of heritage preservation at all levels is essential in order to foster a favorable social climate for protecting and enhancing cultural heritage.

ACKNOWLEDGMENTS

The project is financially supported by the Ministry of Culture of the Republic of Serbia in 2023. During the same year, a memorandum of cooperation was signed between the Institute for the Protection of Cultural Monuments of Niš and the Faculty of Civil Engineering and Architecture at the University of Niš, with the aim of jointly working on the development of a Conservation Study for the Old Čaršija in Vlasotince, as well as the implementation of the student workshop 'Preservation of Architectural Heritage: The Old Bazaar (Čaršija) of Vlasotince.

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] http://www.parlament.gov.rs/upload/archive/files/lat/pdf/zakoni/2021/2145-21.%20-%20lat..pdf (accessed, april 2025)
[2] https://www.mgsi.gov.rs/cir/dokumenti/nacionalna-arhitektonska-strategija
[3] https://www.vlasotince.info/istorija/ (accessed, april 2025)
[4] Цветковић Ивана, Момчиловић Петронијевић Ана, Стошић Ђорђе, Станимировић Мирко: **Власотинце - студија заштите градитељског наслеђа, заштита старе чаршије**, Ниш, 81-83, 2024.
[5] Валчић Даница: **Градитељско наслеђе Власотинца**, Власина, Власотинце, 12, 2018.
[6] Đurđević Marina: **Pogled na najnovije graditeljsko nasleđejugoistočne Srbije do Prvog svetskog rata**. *Leskovački zbornik,* Leskovac, 61-68, 1995.
[7] Vučenović, Svetislav: **Urbana i arhitektonska konzervacija**, tom 1, Savet-Evrope, Beograd 2004, 79, 80.
[8] Јокилето, Јука: **Новији међународни трендови у заштити културног наслеђа**, Гласник Друштва Конзерватора Србије 25, 2001. 11-14.
[9] Stanimirović Mirko, Momčilović Petronijević Ana, Cvetković Ivana, Stošić Đorđe: **Arhitektonska radionice - očuvanje graditeljskog nasleđa: Stara čaršija Vlasotinca**, *Nauka+Praksa, br. 27/2024*, 76-85, 2024.
[10] Đukanović, Dubravka: **Education and Specialization of Conservators – the Perspective of the Profession and Heritage Conservation**, 50 Years /1972-2022/ of the Convention Concerning Concerning the Protection of World Cultural and Natural Heritage, 2023, 250-263.

[11] Јокилето, Јука: **Текући захтеви конзерваторског обучавања**, Гласник Друштва Конзерватора Србије 25, 2001. 14-16.
[12] Шекарић, Бранка: **Заштита урбаних просторних културно-историјских целина**, Гласник Друштва Конзерватора Србије 25, 2001. 29-33.
[13] RECOMMENDATION ON THE HISTORIC URBAN LANDSCAPE, Paris, 10 November 2011 https://whc.unesco.org/uploads/activities/documents/activity-638-98.pdf
[14] Чезари, Карло: **За план историјског градског језгра**, Гласник Друштва Конзерватора Србије 25, 2001. 25-29.

doi.org/10.62683/SINARG2025.044

Research paper

WIND FLOW MODELING IN EARLY URBAN DESIGN

Danka Kostadinović[1], Dragana Dimitrijević Jovanović[2], Vladan Jovanović[3]

Abstract

Buildings affect the wind flow pattern over an urban area. The wind has a significant effect on the comfort and safety of pedestrians, urban microclimate, and pollutant dispersion. It is important to include wind flow modeling in the early urban design to minimize wind safety issues and ensure pedestrian comfort. In this paper, numerical simulations based on Computational Fluid Dynamics (CFD) are performed to study the effect of four case study building layouts on the distribution of wind pressure, wind speed, and turbulence kinetic energy. The ANSYS software was used to simulate wind flow. Three-dimensional numerical simulation was employed, with the standard k-ε turbulence model. Simulation results show that urban space design with narrow passages between buildings leads to a significant increase in local wind speed and causes wind nuisance for pedestrians. When the wind is perpendicular to the buildings, the reverse flow zone behind buildings is much narrower compared to other cases. The corners of the buildings are the regions with high-speed flow due to the side vortices. Placing restaurant terraces, gardens, etc. close to these regions should be avoided due to safety issues and discomfort. Findings from this research can equip architects and urban planners with informed decision-making tools to create more comfortable urban environments.

Key words: *urban planning; urban design, wind flow, CFD, turbulence*

[1] Ph.D., Research Associate, University of Belgrade, Vinča Institute of Nuclear Sciences-National Institute of the Republic of Serbia, Serbia, dankak@vin.bg.ac.rs, 0000-0003-2890-4979
[2] Ph.D. student, Research Assistant, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, dragana.dimitrijevic@gaf.ni.ac.rs, 0000-0002-7914-5688
[3] Ph.D., student, Teaching Assistant, University of Niš, Faculty of Mechanical Engineering, Serbia, vladan.jovanovic@masfak.ni.ac.rs, 0009-0002-8564-9900

1. INTRODUCTION

Airflow depends on air pressure and temperature. Warm air rises, creating a low-pressure area while cool air sinks, creating a high-pressure zone. Airflow from zones of high pressure to low pressure creates winds. When it comes to buildings, the pressure distribution on the building envelope occurs due to the difference in the air density in the indoor and outdoor space caused by the temperature differences, the effect of the wind, and the ventilation system. Wind speed depends on many factors, such as relief, vegetation, and buildings. The roughness of the ground surface affects the airflow just above it due to the frictional drag. This surface friction slows the wind and changes the wind direction. This bottom layer, where friction changes the wind's speed and direction, is called the planetary boundary layer. Within the atmospheric boundary layer, with increasing height above the ground, the wind speed increases starting from zero (where frictional forces are maximum) to some constant value far from the ground. The thickness of the boundary layer depends on the shape and roughness of the ground surface. Over flat areas such as oceans and deserts, the height of the boundary layer can be less than 150 m, while over large cities with tall buildings, it can be 500 m. The impact of strong winds on structures can be very destructive. Therefore, it is necessary to determine the wind load on buildings to avoid safety issues on construction sites. The wind speed increases with the distance from the ground, so high-rise buildings are exposed to stronger wind. High-rise buildings change not only the wind direction but also change wind speed due to friction [1]. In urban areas, the wind speed is reduced by 25-30% compared to rural open areas. Although the mean wind speed is reduced, the gust wind speed in urban areas is significantly increased due to enhanced friction velocity and less atmospheric stability induced by urbanization [2].

Wind patterns becoming more erratic and turbulent due to extreme weather events related to climate change. The risks associated with strong winds are increased in urban areas, due to the abundance of objects. The change in wind speed influences pedestrian comfort near the building. Pedestrian comfort needs to be considered during buildings and urban design. To evaluate the wind conditions information is required on what acceptable or unacceptable conditions are. Table 1 shows the classification of wind speed and human body feeling based on [3]. A wind speed of 10 m/s at pedestrian level is considered to be uncomfortable with movements affected, while a wind speed from 1 m/s to 5 m/s is considered to be the most comfortable for humans [4]. The change in wind speed and direction in urban areas affects also the energy efficiency of buildings. The wind flow angle affects the natural ventilation and the building energy consumption [5].

Table 1. Wind speed and human body feeling

Wind Speed	Human Body Feeling
< 1	breezeless
1–5	comfortable
5–10	uncomfortable with movements
10–15	very uncomfortable with movement
15–20	intolerable
> 20	dangerous

Wind disruption can be reduced by designing buildings with shapes that decrease downdraught. In cases of existing buildings, the best approach is planting trees to slow down wind [6]. A physical modeling investigation for wind engineering is carried out in wind tunnels on a scale model under strictly controlled conditions. Wind tunnel testing is used to evaluate the wind effects on buildings and structures. Field measurements give realistic parameters, however, they require a lot of resources, time, and labor. In the model tests, the hydrodynamic similarity between the model and real scale object needs to be ensured [7]. Wind tunnel tests are complex, expensive, and time-consuming, instead numerical simulations are used based on Computational Fluid Dynamics (CFD). The process of wind flow modeling consists of several steps. First, the size of the computational domain, which provides a volume where the flow takes place, should be determined. Second, the domain should be discretized with a mesh of finite volumes, and then appropriate numerical approximations should be adopted. A set of non-linear partial differential equations defines the wind flow. The final step is the definition of criteria that will enable the completion of the iterative procedure to solve the set of equations.

In cities, the wind flow becomes complex when it interacts with buildings, creating various effects that are often a source of discomfort for users such as acceleration, vortices, downdrafts, etc. Wind flow around buildings depends on building density [8], roof shape and angle [9], while heights and layouts of buildings affect urban ventilation [10], [11]. Wind flow around building layouts is crucial to consider in early urban design to ensure good living conditions in urban environment. Understanding wind flow patterns around buildings is important for urban microclimate, diluting pollutants, and improving living conditions in urban areas. This paper explores the wind flow around four different layouts of buildings using CFD simulations. This research is based on the questions: What is the change in the pattern of pressure, velocity, and turbulence kinetic energy with the change in building's layout? Simulations of wind flow around buildings were performed in ANSYS software [12].

2. METHODS

The CFD simulations of wind flow over four different layouts of buildings were performed in ANSYS software (Student Version 18.1) which is based on the finite volume method [12]. A 3D rectangular computational domain, shown on example of one building (Figure 1a), was used for wind flow modeling. The 5H (H is the building height) distance from the inlet to buildings and 15H from the outlet to buildings was used based on the study [13]. These distances ensure the full development of turbulent flow. The downstream length of the domain is larger compared to the upstream length due to reestablishing a uniform flow of wind flow on the building leeward side. From the top of the building to the upper boundary of the domain, a distance of 5H was adopted to prevent the induced acceleration in this zone. A tetrahedral grid shown in Figure 1b) was used for the computational domain and model of building. To capture more details of the wind flow patterns the finer mesh was used around the buildings. Larger grid elements were applied to the domain far from the building to decrease computing time. It was considered that the convergence is ensured when the residual fell below the 10^{-4}.

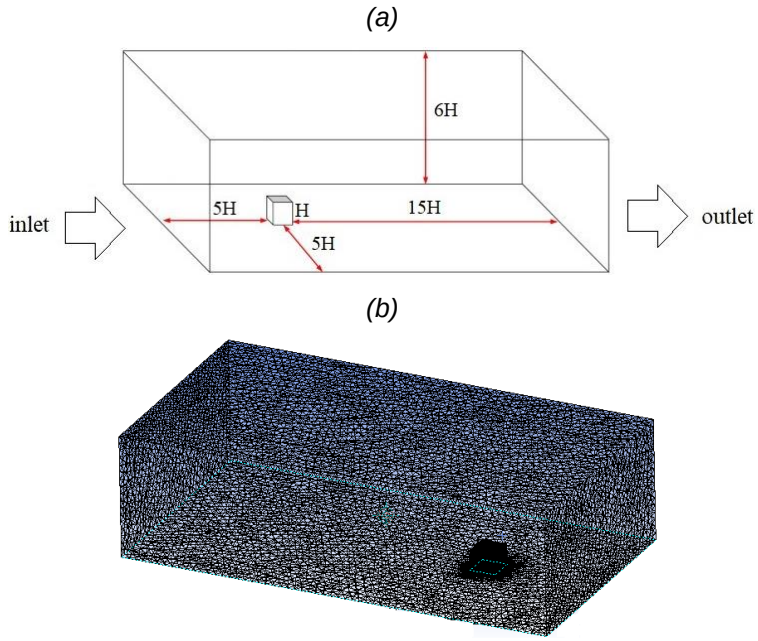


Figure 1. (a) Computational domain, (b) Grid used for the domain and buildings

Wind flow was represented by conservation of mass and momentum equations-RANS (Reynolds averaged Navier-Stokes).

$$\frac{\partial \bar{v}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j \frac{\partial \bar{v}_i}{\partial x_j}\right) = \rho \bar{F}_i - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\eta \frac{\partial \bar{v}_i}{\partial x_j} - \rho \overline{v_i' v_j'}\right) \tag{2}$$

It is challenging to model wind flow because there is no mathematical way to determine turbulence. Turbulence is estimated by different models to account for turbulence kinetic energy and dissipation of turbulent kinetic energy. The standard k-ε turbulence model was used to simulate the mean wind flow characteristics for turbulent flow. Two supplementary equations are used for the turbulent kinetic energy and rate of dissipation of turbulent kinetic energy. The SIMPLE algorithm was used as a relationship between velocity and pressure corrections.

$$\left(\frac{\partial k}{\partial t} + \bar{v}_j \frac{\partial k}{\partial x_j}\right) = P - \rho\varepsilon + \frac{\partial}{\partial x_j}\left(\left(\eta + \frac{\eta_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) \tag{3}$$

$$\rho\left(\frac{\partial \varepsilon}{\partial t} + \bar{v}_j \frac{\partial \varepsilon}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left(\left(\eta + \frac{\eta_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

The production term represents an energy transfer between the mean kinetic energy and the turbulent kinetic energy (Reynolds stress).

$$P = -\rho \overline{v_i' v_j'} \frac{\partial \bar{v}_i}{\partial x_j} \tag{5}$$

Five empirical constants appear in the equations have the following values in case of simulation of wind flow.

$$C_\eta = 0.09 \quad C_{\varepsilon 1} = 1.44 \quad C_{\varepsilon 2} = 1.92 \quad \sigma_k = 1 \quad \sigma_\varepsilon = 1.3 \tag{6}$$

For the simulation of the wind flow following boundary conditions was used:

- wind speed at the inlet of the domain,
- atmospheric pressure at the outlet of the domain.

At the inlet to the domain, a constant wind speed was set along the height, while atmospheric pressure was set at the outlet of domain. The no-slip condition is used walls of the buildings. The air temperature at the inlet and outlet of the domain was 26°C, while the intensity of turbulence was 5%.

3. RESULTS

Wind flow around the four different layouts of buildings was simulated:

- Case 1: Two rectangular buildings with dimensions of 70x25x40 m. The distance between the narrowest and widest part is 25 m and 95 m, respectively and the angle between buildings is 60°. The wind flow speed is 7 m/s.
- Case 2: Cube parallel buildings with dimensions 10x10x10 m. The distance between the buildings is 10 m. The wind flow speed is 8 m/s and it is perpendicular to the buildings.
- Case 3: Cube buildings with dimensions 10x10x10 m rotated 45° towards the wind flow. The distance between the buildings is 15 m. The wind flow speed is 7 m/s.
- Case 4: Rectangular buildings, with dimensions 10x20x10 m. The distance between the buildings is 20 m in the longitudinal direction and 50 m in the transverse direction. The wind flow speed is 10 m/s. The buildings are rotated 45° towards the wind flow.

The pressure contours around buildings in a horizontal plane are shown in Figure 2. The horizontal plane is positioned at half of the building's height. In all cases, the positive pressure is on the windward side of the building, while the negative pressure is on the leeward side of the buildings. Besides the leeward side, the negative pressure can be noticed on the top face and lateral sides of the buildings, due to flow separation. The rectangular buildings have a larger zone of negative pressure on the leeward side compared to cube buildings. In Case 1 (two rectangular buildings, diverging flow) there is a Venturi effect because the buildings are close together. The Venturi effect is especially expresses when wind passes between two high-rise buildings [14]. The flow in diverging passages is a superposition of the corner flow near the upstream outer corners of buildings. In the shortest distance between buildings, there is a pressure decrease due to an increase in velocity. Many researchers have found that the urban space design with long and narrow passages between buildings can lead to a significant increase in local wind speed and cause wind nuisance for pedestrians [15-16]. The low-pressure zone draws in the wind from the high-pressure zone, where the wind with high wind speed creates a natural flow. In Cases 2, 3, and 4, the pressure is highest on the winward sides of the first row of buildings, while the lowest pressure is on the leeward sides of the first row of buildings. In the case of nonsymmetric buildings and non-perpendicular wind flow (Case 1, 3, and 4) the underpressure zone on the leeward sides of buildings is wider compared to Case 2.

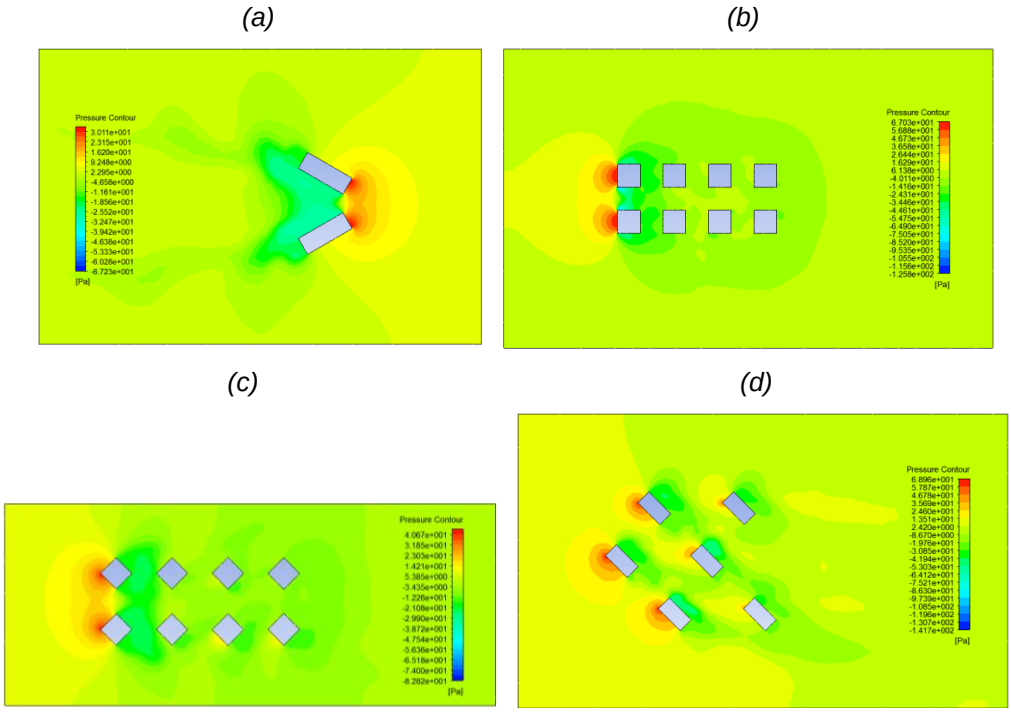


Figure 2. Pressure contours around buildings in horizontal plane: a) Case 1, b) Case 2, c) Case 3, d) Case 4

The velocity contours around buildings in a horizontal plane are shown in Figure 3. In all observed cases, the flow separation occurs at the lateral sides of the buildings where zones of increased wind speed can be observed (red area in Figure 3). The wind speed in this region can be reduced by: rounding corners of buildings, designing buildings with decreasing heights (pyramid buildings), or adding rows of trees to provide shelter at the pedestrian level. There is a large velocity gradient in these positions and underpressure zones. The corners of buildings are the zones with the most discomfort, due to the side vortices created from the difference in pressure between the windward and the leeward side. It is recommended to avoid placing gardens and restaurant terraces close to these areas. The wind flow patterns show more substantial disturbance on the leeward side than on the windward side. The velocity contours clearly show the existence of a turbulent zone on the leeward side. The wind reaches the undisturbed field far away from the building. The wider buildings disturb a longer and wider region on the windward and leeward sides of the buildings. In Case 1, at the ends of the lateral sides of the buildings, there is a separation of the wind flow and an increase in its speed (red area in Figure 3a). In Case 2 and Case 3, the wind flow separates at the lateral sides of the first row of buildings (red area in Figure 3a and b). The Venturi effect can be noticed in the Cases 2, 3, and 4. This effect is very unfavorable, due to the increase in the load on the buildings and the impact on pedestrians. Between the buildings in the so-called passage or urban canyon, there is a decrease in pressure and an increase in wind speed. In Case 1, wind speed is the highest at the beginning of the passage, where the distance between the buildings is the smallest. Further, as the passage widens, the flow velocity drops.

In Cases 2, 3 and 4, the wind speed is higher in the first row of buildings compared to the other rows. As the wind flows towards the lateral sides of buildings, the direction of the wind flow is no longer orthogonal to the wall of the building. Instead, it becomes parallel to the wall, so the pressure gradient increases towards the corners of the building. On the leeward side of buildings the wind currents cannot immediately "approach" due to the inertia of the air, and the current wave remains where it is separated from the walls. This is in agreement with the study [17], in which it was shown that the return flow is formed only at the first building in a series of buildings of equal height. A zone of turbulent flow is formed behind each building. When the wind is non perpendicular to the buildings (Case 3 and 4) the zone of reverse flow behind buildings is much wider compared to Case 2. This turbulence flow contributes to the feeling of discomfort on the leeward side of the buildings. In Case 4, a zone of reverse flow is also formed on the leeward side of the buildings, but in this case, it quickly calms down before the wind current reaches the next building in the row. The distance between the buildings is greater, so after passing the first buildings, the wind renews its profile.

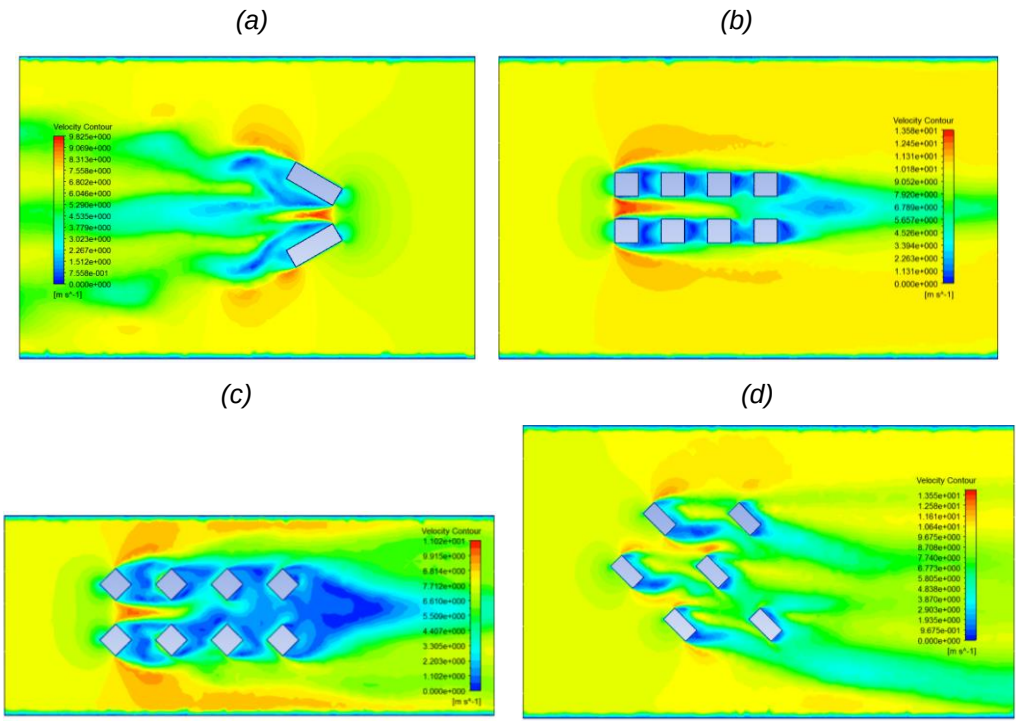


Figure 3. Velocity contours around buildings in horizontal plane: a) Case 1, b) Case 2, c) Case 3, d) Case 4

The velocity contours around buildings in the vertical plane are shown in Figure 4, while the velocity streamline around buildings is given in Figure 5. The vertical plane is positioned at half of the domain width. In Case 2, the flow separation zone and return flow is formed only on the top side of the first row of buildings. This is in agreement with the study [18], which showed that in the case of row of buildings with same or similar height the return flow are formed only above the first row of buildings. The air currents above the top of the second row of buildings descend slightly. Also, in this case, pedestrian areas are generally protected from high wind speeds. When it comes to rectangular buildings (Case 4), the air

current is attached to the roof. When the wind is not perpendicular to the buildings, the zone of reverse flow above the top of the first row of buildings is much smaller compared to other cases. In this case (Case 3), the zone of reverse flow on the leeward side of the last row of buildings is much longer compared to Case 2. The wind velocity around the winward edges and the lateral sides of the building increases with increasing building height. Figure 4 and Figure 5 show that at the top of the buildings and their lateral sides wind flow is detached from the surface and flow separation takes place. The separation bubbles are formed and characterized by reverse flows, low-velocity distributions, and high turbulence intensities. The lateral wind flows together with the flow over the top of the building causing the formation of 3D vortices on the leeward side of the buildings. In the Case 2 and 3, there are large pockets of turbulence between the two rows of buildings. These vortices negatively influence air quality because they trap vehicle emissions in street canyons.

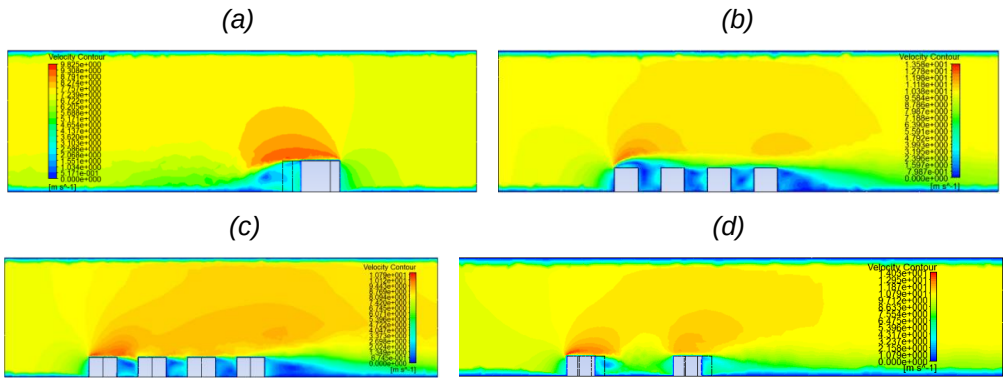


Figure 4. Velocity contours around buildings in vertical plane: a) Case 1, b) Case 2, c) Case 3, d) Case 4

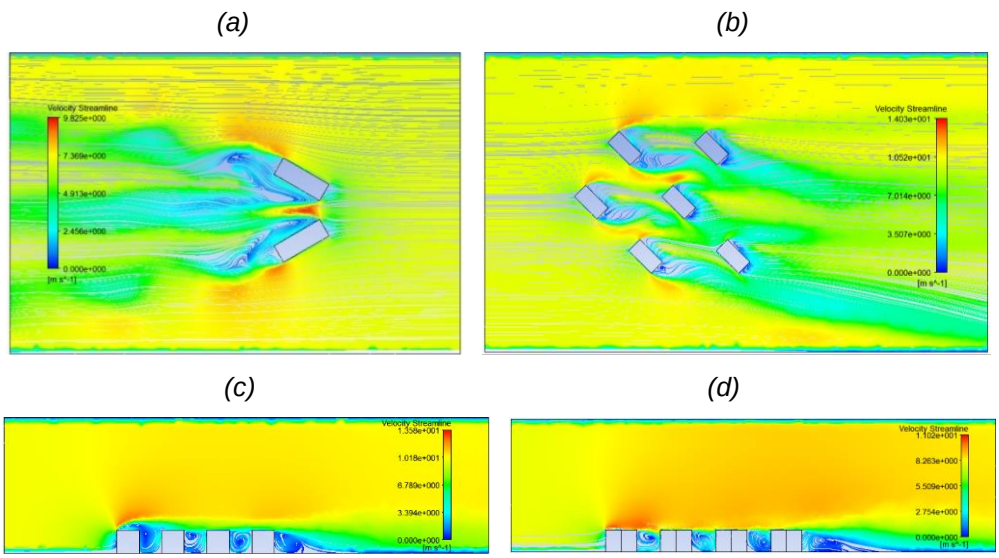


Figure 5. Velocity streamline around buildings: a) Case 1, b) Case 4, c) Case 2, d) Case 3

The distribution of turbulence kinetic energy around buildings in the horizontal plane is shown in Figure 6. It can be seen that in the row of buildings, the turbulence kinetic energy is highest on the sides of the first buildings in a row. Between buildings, the highest values

of kinetic energy of turbulence are on the windward side of the urban canyon. The turbulent kinetic energy is lowest in the inflow state. The turbulent kinetic energy increases when wind reaches the leeward side of the building because of the strong perturbations and a greater velocity gradient. The kinetic energy is transferred from large to smaller eddies. On the leeward side, with increased distance from the building, the turbulence kinetic energy decreases, due to dissipation. The turbulence dissipation rate is the velocity at which the mechanical energy of an isotropic small-scale vortex transforms into thermal energy, which greatly influences the diffusion process [19].

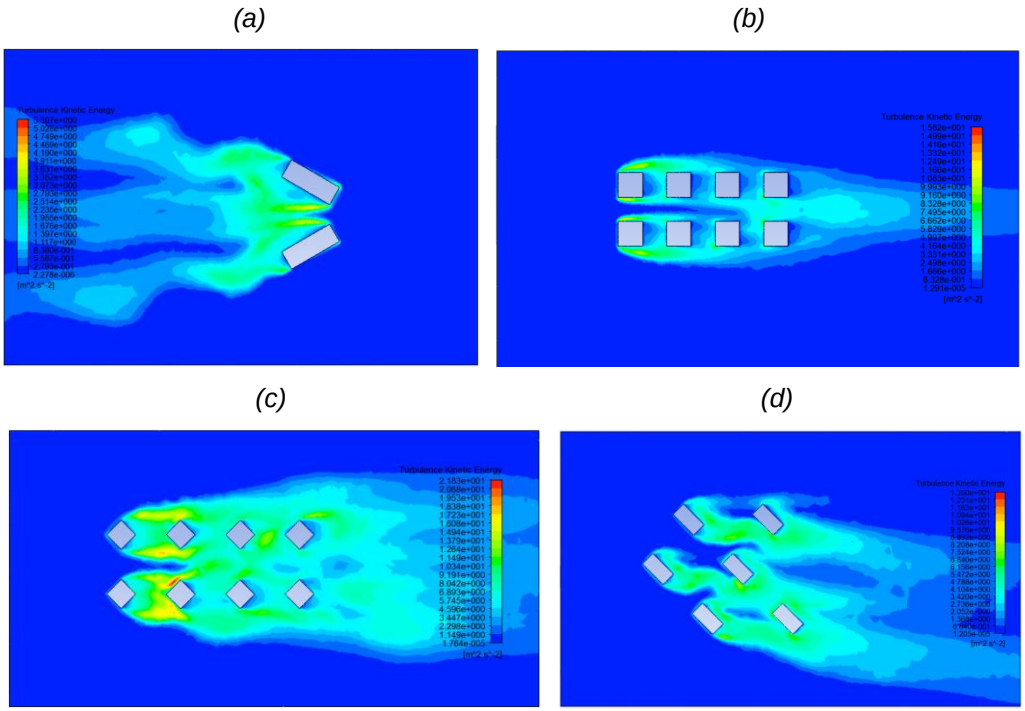


Figure 6. Distribution of turbulence kinetic energy around buildings: a) Case 1, b) Case 2, c) Case 3, d) Case 4

4. CONCLUSION

Wind conditions and wind flow patterns are strongly influenced by high-rise buildings and the urban environment around buildings because of the many flow situations arising from the interaction of wind with structures. It is essential to consider wind flow phenomena and integrate them early in the development of urban projects to achieve proper urban planning. Within such context, this paper investigates the influence of four different layouts of buildings on wind flow using Computational Fluid Dynamics (CFD) simulations. The ANSYS software was used to simulate wind flow around buildings. The distribution of wind pressure, velocity, and turbulence kinetic energy around buildings was analyzed. The simulation results show building layouts have a significant influence on the wind flow pattern. This paper can equip architects and urban planners with informed decision-making tools to create more comfortable urban environments. The main findings are as follows:

- pressure is positive on the windward side of the building, while negative on the leeward and lateral sides of the building,

- wind flow separation occurs at the corners of the buildings,
- zones of maximum wind speed are located on the lateral sides of buildings,
- narrow passages between buildings lead to a significant increase in local wind speed,
- when the wind is non-perpendicular to the buildings the zone of reverse flow behind buildings is much wider.

Understanding wind flow patterns allows urban and architectural designers to introduce a variety of wind mitigation measures early in the design process to improve the safety and comfort of pedestrians. This paper highlights the importance of wind flow modeling in early urban planning and architectural design. In future, the result of simulations needs to be validated with experimental data from wind tunnel tests. Future research also needs to explore the effect of inlet wind velocity which changes with the height of the domain.

ACKNOWLEDGMENTS

The research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03 136/2025-03/200017).

NOMENCLATURE

$\overline{v_i}$, $\overline{v_j}$ – Time-averaged velocity components, [m/s].

$\bar{F}_i$ – External forces, [kgm/s^2].

$\bar{p}$ – Time-averaged air presure, in [bar].

v_i', v_j' – Fluctuating part of velocity components, [m/s].

k – Turbulence kinetic energy, [m^2/s^2].

t – Time, [s].

$C_{\varepsilon 1}$ – Empirical constants.

$C_{\varepsilon 2}$ – Empirical constants.

ρ – Air density, in [kg/m^3].

η – Dynamic viscosity, [kg/ms].

ε – Turbulent dissipation rate, [m^{2}s^3].

η_t – Turbulent viscosity, [m^{2}s].

σ_k – Empirical constants.

σ_ε – Empirical constants.

REFERENCES

[1] Kostadinović Vranešević Kristina, Šarkić Glumac Anina: **Peak pressure on high-rise buildings roof: A dual approach through validated LES and wind tunnel experiments with uncertainty quantification**. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 250, 105784, 2024, https://doi.org/10.1016/j.jweia.2024.105784.

[2] Liu Gang, et al.: **Effect of urbanization on gust wind speed in summer over an urban area in Eastern China**. *Environmental Research Letters*, Vol. 18, no. 7, 074025, 2023, https://doi.org/10.1088/1748-9326/acddfa.

[3] Guo Weihong, Liu Xiao, Yuan Hu: **A case study on optimization of building design based on CFD simulation technology of wind environment**. *Procedia Engineering, Vol. 121, 225-231, 2015,* https://doi.org/10.1016/j.proeng.2015.08.1060.

[4] Hunt, J: **Fundamental studies of wind flow near buildings, Models and Systems in A rchitecture and Building**. *Published by Construction Press Ltd.*, Lunesdale House, Hornby, Lancaster, 1975.

[5] Huifen Zou, Fuhua Yang, Qian Zhang: **Research on the Impact of Wind Angles on the Residential Building Energy Consumption**. *Matematical Problems in Engineering,* 2014, https://doi.org/10.1155/2014/794650.

[6] Ren Xinyi, Zhang Guoyi, Chen Zhonggou, Zhu Junhao: **The Influence of Wind-Induced Response in Urban Trees on the Surrounding Flow Field**. *Atmosphere*, Vol. 14, No. 6, 1010, 2023, https://doi.org/10.3390/atmos14061010.

[7] Luo Tianxiao, Wu Guanxing, Zhang Pan, Zhang Hairui: **A new similarity criterion for wind tunnel testing of floating wind turbines achieving dynamic aerodynamic characteristics similarity**. *Energy Conversion and Management*, Vol. 301, No. 1, 118015, 2024, https://doi.org/10.1016/j.enconman.2023.118015.

[8] Buccolieri Riccardo, Sandberg Mats, Sabatino Di Silvana: **City breathability and its link to pollutant concentration distribution within urban-like geometries**. *Atmospheric Environment*, Vol. 44, No. 15, 1894-1903, 2010, https://doi.org/10.1016/j.atmosenv.2010.02.022.

[9] Kostadinović Vranešević Kristina, Vita Gulio, Bordas Stephane, Šarkić Glumac Anina: **Futhering knowledge on the flow pattern around high-rise buildings: LES investigation of the wind energy potential**. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 226, 105029, 2022, https://doi.org/10.1016/j.jweia.2022.105029.

[10] Hang Jian, Li Yuguo, Sandberg Mats, Buccolieri Riccardo, Sabatino Di Silvana: **The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas**. *Building Environment*, Vol. 56, 346-360, 2012, https://doi.org/10.1016/j.buildenv.2012.03.023.

[11] Chang Cheng-Hsin, Meroney N. Robert : **Concentration and flow distributions in urban street canyons: wind tunnel and computational data**. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 91, No. 9, 1141-1154, 2003, https://doi.org/10.1016/S0167-6105(03)00056-4.

[12] Ansys®, Fluent, ANSYS, Inc.

[13] Revuz Julia, Hargreaves David, Owen S. John: **On the domain size for the steady-state CFD modelling of a tall building**, *Wind and Structures*, Vol. 15, No. 4, 313-329, 2012, https://data.doi.or.kr/cite/10.12989/was.2012.15.4.313.

[14] Čeheľová Dagmara, Janák Milan, Bielek Boris: **The Impact of Relative Position of the High-Rise Buildings on the Wind Flow**, *Applied Mechanics*

and Materials, 820, 320-325, 2016, https://doi.org/10.4028/www.scientific.net/AMM.820.320.

[15] Li Biao, Luo Zhiwen, Sandberg Mats, Liu Jing: **Revisiting the 'Venturi effect' in passage ventilation between two non-parallel buildings**, *Building and Environment*, Vol. 94, No. 2, 714-722, 2015, https://doi.org/10.1016/j.buildenv.2015.10.023.

[16] Wiren B.: **A wind tunnel study of wind velocities in passages between and through buildings**. *Proceedings of the 4th International Conference on Wind Effects on Buildings and Structures*, (Heathrow), 1977, 465e475.

[17] Stathopoulos T., Storms R.: **Wind environmental conditions in passages between buildings,** *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 24, No. 1, 19-31, 1986, https://doi.org/10.1016/0167-6105(86)90070-X.

[18] Pourteimouri Paran, Campmans , Geert, Wijnberg Kathelije, Hulscher Suzanne: **A Numerical Study on the Impact of Building Dimensions on Airflow Patterns and Bed Morphology around Buildings at the Beach**, *Journal of Marine Science and Engineering*, Vol. 10, No. 1, 13, 2022, https://doi.org/10.3390/jmse10010013.

[19] Dong-Peng Guo, ,Peng Zhao, Ren-Tai Yao, Yun-Peng Li, Ji-Min Hu, Dan Fan: **Numerical and Wind Tunnel Simulation Studies of the Flow Field and Pollutant Diffusion around a Building under Neutral and Stable Atmospheric Stratifications**, *Journal of Applied Meteorology and Climatology*, Vol. 58, No. 11, 2405-2420, 2019, https://doi.org/10.1175/JAMC-D-19-0045.1.

doi.org/10.62683/SINARG2025.045

Research paper

ECOURBARCHITECTURAL HOUSES FROM PRINTED MATERIALS

Nikola Cekić[1]

Abstract

The rapid development of digital technologies of 3D printers and the introduction of construction robotised machines in the construction of houses, at the beginning of this century, brought a completely new conceptual strategy in the ecourbarchitectural design of functional residential-office, industrial, economic, tourist and other horizontal and vertical volumes. Incredible revolutionary urban planning changes have occurred in cultural-historical inherited artifactual and natural physical structures in space. Instead of the recent forty or more working hours for the traditional construction of one square meter of usable area in the building, when building materials and bricks were exchanged, today it takes only five minutes! With the introduction of robotic digital machines for printing walls and structural parts of buildings made of mud, concrete, plastic and long-specific materials, a new historical page of the future in the construction industry has been opened, when the amount of waste is zero and when the exact amount of required material is known in advance. An extremely high speed was achieved in the innovative construction of printed houses immediately ready for use. Examples from the world, in this work, show that buildings made of printed material provide users with absolute security since tests have confirmed their static resistance to earthquakes, winds and other disasters.

Key words: *3D printer, digital technologies, robotisation, eco-urban architecture, cultural and historical heritage*

[1] Academician, PhD., Full Eng. Architect. The Faculty of Civil Engineering and Architecture of the University of Niš, SERBIA - 18000 NIŠ, Aleksandra Medvedeva st. 14/111, email: ncekic@yahoo.com, ORCID 0000-0002-7607-3367

1. INTRODUCTION

Dramatic changes are visible not only in the high speed of construction, but also in the considerably reduced prices of usable built-up surface areas. In the world, digital-technical-technological 3D printers are being improved every day, with which even more effective buildings results can be achieved. Thus, in 2014, the Chinese company "WinSun New Materials" started using a huge 3D printer in the process of building houses, which allowed it to completely build as many as 10 houses in one day![2] This 3D printer, 6.6 meters high, 10 meters wide, and 150 meters long, used a material obtained from a mixture of cement and glass fibers for printing. It is predicted that in the future, old building materials will be used in order to raise recycling and environmental protection to a higher level. A very fast and cheap way of building buildings with a price lower than 1000 euros, from rice waste, local mud and straw, which is offered on the world market by many companies, among others WASP[3] from Italy, has an extremely promising character for the million people on the planet who live today in slums, suburbia and favelas.

2. EXAMPLES OF EXPLORED ECORURBARCHITECTURAL HOUSES MADE OF PRINTED MATERIAL



Figure 1. Bandiagara cliff in Mali. The land of the Dogons is a huge cultural landscape covering 400.000 ha and including 289 villages [1]

The Dogon are an ethnic group indigenous to the central highlands of Mali, West Africa, south of the Niger Bend, near the city of Bandiagara, and in Burkina Faso. The population is between 400,000 and 800,000 people. Since the twentieth century, there have been significant changes in the social organization, material culture and beliefs of the Dogon, in part because the Dogon country is one of Mali's main tourist attractions. The Dogon are best known in the world for their settlements and ground structures made of local indigenous materials [2], mud and wattle, wooden masks and sculptures. Colorful and harmoniously shaped houses made of mud could have been an inspiration for the design and construction of new cheap, more modern eco-architectural forms with 3D printers with a concept of space remodeling in poor neighborhoods.

[2] https://www.archdaily.com/497836/chinese-firm-3d-prints-10-homes-in-24-hours>
[3] https://www.3dwasp.com/en/3d-printed-house-gaia/



Figure 2. 3D-TECLA, first printed biomorphic mud cottage built in Ravenna, Italy [3]

Mario Cucinella, an Italian architect from Bologna, in collaboration with the company for 3D house printing - WASP [4], realized a pilot project in which he created a clay bioclimatic, low-carbon emission prototype house as a response to dramatic climate changes and the planetary housing crisis on the planet. The unusual physical structure of the "TECLA" house is designed with two interconnected solar domes through which natural light is introduced through the central skylight into the interior space. It was built from 350 layers of clay, 12 mm thick, of local origin from the nearby river bed, 150 km of extrusion and 60 m3 of natural materials. The size is 60m^2. The ecological house was built from organic, biomaterials in a time of 200 hours [4], while active printing with a homogeneous synthesized mixture of materials with 25% soil, 40% straw obtained from the rice stalks, 25% rice husk, 10% limestone and additives, mixed with a mixer took 72 hours. The designer says the challenge was to optimize "the thermal performance and living comfort of the building envelope". There is an opinion according to which this is the first derived 3D eco-architectural form in accordance with natural forms and biomorphic geometry. The house made of homogenized mud was built for only 1000 euros. WASP Company's ambitious goal is to print an attractive environmentally technologically sustainable village, which will be located in the Italian town of Massa Lombarda, Emilia Romagna, not far from Ravenna.



Figure 3. First 3D house printed with soil material, „Gaia“, 2018 [5]

The Italian company WASP-World's Advanced Saving Project produced a 3D infinite digitized printer with which a new model of an ecologically sustainable bioclimatic house was made in just ten days. 25% of the soil from the site (30% clay, 40% silt and 30% sand) was used as the main binder in the composition of the mixture, composed of 40% chopped rice straw, 25% rice husk and 10% hydraulic lime [6]. The resulting homogeneous mixed compound is made of natural waste materials, which originate from the rice production chain and which were used for the efficient, healthy bioclimatic construction of the new GAIA eco-sustainable house model. The foundation of the housing is continuously printed from concrete on site, with an extruder nozzle from the crane structure, while the 40 cm thick walls

[4] „World's Advanced Saving Project“. Italy’s pioneering specialists in 3D printing

are made by precisely stacking layers of combined mixed mud material with long plant fibers. In the central part, the walls are designed with digital precision and printed monolithically in the form of a braid. They considerably affect the static stability of the walls as well as the strength of the ecourbarchitectural structural assembly. The entire length of the hollowed-out fields of the wall, having 30m^2, have the function of solving vertical ventilation and thermoacoustic insulation of the house. The price of the materials used in the first house built of natural materials, for the wall structure, was €900.



Figure 4. Companies ICON and LAKE FLATO built a 3D prented house Zero in Austin, Texas, 2022 [7]

For the construction of the house Zero in the eastern part of Austin, Texas, 3D printing technology was used - the "Vulcan" construction system, from the American company ICON in cooperation with the Lake Flato architectural studio from San Antonio. 186m^2 of walls were constructed by printing in ten days, by mechanically applying layers of material according to a computer program. The ICON company says that: " House Zero is ground zero for the emergence of entirely new design languages and architectural vernaculars that will use robotic construction to deliver the things we need most from our housing: comfort, beauty, dignity, sustainability, attainability, and hope,". The walls of the house are made of "Lavacrete" 3d printed, the original ICON's proprietary material, similar to cement that does not transmit air and has excellent insulating thermoacoustic properties [8]. Apart from the new construction method, the soft curved surfaces of the exterior walls reinforced with steel sections are characteristic, while most of the interior walls are made of wood in order to make the interior space of the family house more attractive, comfortable and organically connected to the natural structures in the environment. The company ICON intends to continue working actively on improving and presenting the future of house construction with 3D printed material. They also plan to create a 3D printed community in Latin America, and with NASA to build structures on the moon.



Figure 5. First African 3D printed schools and dorimitories opened in Malawi [9]

As a result of the chronic lack of school infrastructure in Malawi, in the southeastern part of Africa, and thanks to the financial support of the Swiss manufacturer of construction materials, Lafarge Holcim, and the help of the development financial institution CDC Group

of the United Kingdom Government, the first school was built with innovative digital technology, 3D wall printing [10]. Malawi has a shortage of 36,000 classrooms and in the near future, due to a similar situation, the wave of this kind of construction will continue in Kenya and Zimbabwe. If the construction problems were to be solved in a traditional, conventional way, 70 years of work would be needed. With the 3D digital technology of printing buildings, the time is shortened by 7-8 times, and the investment costs are reduced multiple times. It took 18 hours to build the school building in Salima using digitized 3D printing technology. The "Vulcan" 3D printer, 4m high and 8m wide, was used for the realization, which is considered to be one of the best in the world. This 3D printer has the ability to lay 7 inches of homogeneously mixed concrete building material in one second.



Figure 6. Beckum, Germany, features the first 3D printed two-storey building, 2021 [11]

The first house in Germany was built using an automated digitized 3D printer, in Beckum, North Rhine-Westphalia, as part of the "Innovative Construction" funding program. The two-story family house contains about 160 m2 of living space, and was created in about 100 hours of printing with a 3D printer for concrete material from the company PERI, with a special nozzle that can cover a surface of one square meter in five minutes, concrete layers were applied, so that the masons and other workers were not needed. It is commissioned for use on 26th of July 2021. According to the state ministry, the first residential building in Germany was built as a pilot project and if the experience is positive and the printer's work is financially profitable, it will serve as a model, an example for the entire construction industry [12]. There are already buildings made with a 3D printer in the world. This house is a big challenge for ecourbarchitecture. In 2021, the 3D concrete house construction process received the cross-industrial "German Innovation Award."



Figure 7. BOD2 3D printer by COBOD company was used for the construction of building in Wallenhausen [13]

A three-story residential building in Wallenhausen, Bavaria, with five residential units and a usable area of 380m2, was built in just a few weeks after the unveiling of a two-story 3D-printed building in Beckum. A modular digitized BOD2 3D printer from the COBOD company,

measuring 12.50x20.00x7.50 meters, was used in the construction. The printer is flexible and can be expanded in all directions in a module of 2.50 meters to meet the requirements of all customers, and it took less than five minutes to cover a two-layer wall of 1m2. The company PERI used this printer to build the largest printed building in Wallenhausen, but also in Europe, at a maximum speed of 1m/sec or pouring 10 tons of concrete per hour. Only two workers participated in the work. It was completed in six weeks. Henrik Lund-Nielsen, founder and CEO of COBOD, commented: "We are incredibly excited to start seeing the fruits of the many automated 3D construction printers sold." Thomas Imbacher, head of innovation and marketing at PERI GmbH, said: "We are very confident that 3D construction printing will become more important in certain market segments in the coming years and that it has significant potential [14]. By printing the first residential building on site, we show that even large residential units can be printed with this new technology. When it comes to 3D construction printing, we are opening up additional areas of application on a whole new level."



a) *b)* *c)*

Figure 8. Examples of realized physical structures built by 3D printing technology:
a) World's first 3D printed steel bridge installed in Amsterdam, 2018 [15],
b) Phoenix - A New Reinforcement-Free 3D Printed Concrete Bridge - Lion France [16],
c) World's longest 3D-printed concrete bridge opens across canal in Shanghai [17]

In addition to printing buildings with 3D digital-robotized technology, the same is used for the realization of other physical structures in public space. Thus, the world's first stainless steel bridge, 12 meters long and weighing 4.5 tons, was cast with a robotic printer and placed across the canal in Amsterdam in 2018. The bridge was assembled in two parts, off-site, by welding. For six months, four digitized robots worked to pour the 1,100-meter-long layers (Figure: A). The Holcim company built the 3D-printed concrete bridge PHOENIX, for Lyon, France, designed with 10 tons of recycled material in collaboration with Zaha Hadid - Architects Computation and Design Group, Block Research Group at ETH Zurich and incremental 3D. The so-called circular construction, by integrating computer design and 3D printing, which facilitates a possible reduction of up to 50% in the use of materials without compromising performance was implemented. The bridge was designed on advanced "Ekocycle®" circular technology, relying only on compression, without reinforcement, using blocks that can be easily dismantled and recycled (Figure: B). On February 5th, 2019, the world's longest concrete-printed pedestrian bridge, 26.30 meters long and 3.60 meters wide, was opened in Shanghai over a canal in Shanghai's Baoshan District [18]. The arch bridge is built from 176 concrete units made using two 3D robotic printing systems. All components were printed within 450 hours (Figure: C).



Figure 9. NASA intends to build the astronaut habitats on the moon by 2040, using 3D printing [19]

NASA5 and ICON, an Austin, Texas-based construction company that uses a 3D printer to create low-rise buildings, have been planning to build a settlement on the moon by 2040. The plan calls for sending powerful robotic 3D printers that can build a housing unit in 48 hours and building materials to make lunar concrete composed of mineral fragments and dust from the moon's surface. Although it looks like a dream sequence, the NASA company is of the opinion that today is the key moment when the realization of the idea should be started. They believe in the possibility of successful realization of the ambitious plan for houses on the empty Moon, which would be used in the long term not only by astronauts but also by civilians. Work is being done to create new programs, functional machines and robotics for future space missions on the lunar surface that are still in the conceptual space exploration phase. There are obstacles in finding and forming localities for the construction of settlements [20]. The fine powder of moon dust is sharp and can cut like glass. It spreads easily and is toxic to inhale. In addition, the problem is that the temperatures are significantly higher than on Earth, and there is also harmful, adverse radiation.



a) *b)* *c)*

Figure 10. First 3D printed house in free scultputural form, by WATG company. Harbinger of future and advancement in the development of 3D printing technology of ecourbarchitectural structures is seen on newly designed eocurbarchitectonic sculptural forms formama [21]

WATG company, from Chicago, won the Freeform Home Design Challenge 2016 Design Award for the winning project "Curve Appeal" [22]. The Company says that this revolutionary solution should change the further development path in the construction of complex physical ecourbarchitectural forms (A). The 27-foot-tall archisculptural Phoenix House was built in Austin, Texas, using ICON's latest 3D digitized construction printer with which they think they will be building landing pads, roads, and NASA habitats on Mars in the near future (B). Architect Eduard Galkin, from Saint Petersburg, made a futuristic impressive project for an attractive one-story house with an archisculptural-biomorphic-organic form that would be realized with digital 3D printing technology (C).

[5] The National Aeronautics and Space Administration is an independent agency of the U.S.

3. CONCLUSIONS

A new advanced era of more effective technological, non-traditional processes of construction of buildings and application of modern materials has begun. In urban agglomerations, they contribute to a better and more sustainable life, save costs and enhance the time efficiency of construction, which favorably affects the opening of a new perspective in the field of social housing. Houses created with 3D printers offer many advantages. They are built much faster, in just a few weeks, in contrast to houses realized in the traditional way, where the works last several months and where the investment costs are noticeably increased. They are recyclable and energy efficient. With a small amount of energy to create synthetic material, reinforced with synthetic or plant long fibers, with straw and rice husk, with insulation and ventilation chambers in the wall envelope of the building, an excellent thermoacoustic protection of the interior space is achieved. The process of building a house begins by extruding homogenized material through a special extruding nozzle according to pre-made designs, layer by layer, so that the walls, partitions and structural parts of the building can be printed. The printer uses only the required amount of material mix for the constructions. The possibilities of architects, urban planners and planners have been increased resulting in freer and more creative thinking when designing physical structures, from the simplest to those with more complex spatial geometry. Same as the traditional construction, 3D printed houses meet all safety and quality standards. The construction of ecoarchitectural houses and settlements from printed materials with innovative 3D digitized-robotized technology has opened a new, revolutionary page of history in the construction industry. This short review shows great design-transformative and potential possibilities, with which, by redefining the way of thinking about construction, we can repair and make the existing world with an environmentally better concept.

REFERENCES

[1] https://www.amusingplanet.com/2018/07/the-dogon-villages-of-bandiagara.html (1.4.2025.)

[2] Bañón, C., Raspall, F. (October 2, 2020)., **3D Printing Architecture: Workflows, Applications, and Trends**, ISBN-10:9811583870, ISBN-13:978-9811583872. Publisher: Springer; 1st ed. 2021 edition

[3] https://www.gooood.cn/tecla-mario-cucinella-architects.htm (1.4.2025.)

[4] Brito, A. (February 17, 2024), **Blender 4.0: Precise Modeling for Architecture, Engineering, and 3D Printing**, ISBN-13:979-8877055728, ASIN: B0CVV198CB. Publisher: Independently published

[5] https://www.3dwasp.com/en/3d-printed-house-gaia/ (1.4.2025.)

[6] Burrows, R. (May 15, 2018)., **3D Thinking in Design and Architecture: From Antiquity to the Future**, ISBN-10:0500519544, ISBN-13:978-0500519547. Publisher: Thames & Hudson; Illustrated edition

[7] https://www.dezeen.com/2022/03/04/icon-lake-flato-3d-printed-house-zero-austin/ (1.4.2025.)

[8] Dethier, J. (March 3, 2020)., **The Art of Earth Architecture: Past, Present, Future**, ISBN-10:1616898895, ISBN-13:978-1616898892. Publisher: Princeton Architectural Press; Illustrated edition

[9] https://www.news24.com/news24/bi-archive/take-a-look-3d-printed-homes-and-schools-are-coming-to-africa-2020-12 (1.4.2025.)

[10] Grigoriadis, K., Lee, G. (May 21, 2024)., **3D Printing and Material Extrusion in Architecture: Construction and Design Manual**, ISBN-10:3869227508, ISBN-13:978-3869227504. Publisher: DOM Publishers
[11] https://www.baunetz.de/meldungen/Meldungen-Wohnhaus in Beckum von Mense-Korte ingenieure_architekten_7926836.html (1.4.2025.)
[12] Leach, N., Farahi, B. (December 18, 2017)., **3D-Printed Body Architecture (Architectural Design)**, ISBN-10:1119340187, ISBN-13:978-1119340188. Publisher: Wiley; 1st edition
[13] https://www.3d-grenzenlos.de/magazin/3d-objekte/3d-druck-von-mehrfamilienhaus-in-wellenhausen-27634093/#google_vignette (1.4.2025.)
[14] Minke, G. (January 31, 2022)., **Building with Earth: Design and Technology of a Sustainable Architecture**, ISBN-10:3035622531, ISBN-13:978-3035622539. Publisher: Birkhäuser; 4th rev. ed. Edition
[15] https://www.dezeen.com/2021/07/19/mx3d-3d-printed-bridge-stainless-steel-amsterdam/ (1.4.2025.)
[16] https://www.archdaily.com/1011966/phoenix-bridge-zaha-hadid-architects (1.4.2025.)
[17] https://www.dezeen.com/2019/02/05/worlds-longest-3d-printed-concrete-bridge-shanghai/ (1.4.2025.)
[18] Rangel, B. Ana Sofia, G., Lino, J., Santana L. (January 2, 2023), **3D Printing for Construction with Alternative Materials (Digital Innovations in Architecture, Engineering and Construction)**, ISBN-10:3031093186, ISBN-13:978-3031093180. Publisher: Springer; 1st ed.
[19] https://www.ponoko.com/blog/wp-content/uploads/2012/02/1-nasaposter2011-15highres-768x768.jpg (1.4.2025.)
[20] Sanjayan, J. G., Nazari, A., Nematollahi, B. (March 5, 2019)., **3D Concrete Printing Technology: Construction and Building Applications**, ISBN-10:0128154810, ISBN-13:978-0128154816. Publisher: Butterworth-Heinemann; 1st edition
[21] https://www.archdaily.com/887821/the-worlds-first-freeform-3d-printed-house-enters-development-phase (1.4.2025.)
[22] Rael R., San Fratello V., **Printing Architecture: Innovative Recipes for 3D Printing**, ISBN-10:1616896965, ISBN-13:978-1616896966. Publisher: Princeton Architectural Press, May 1, 2018

doi.org/10.62683/SINARG2025.046

Research paper

ERASING MEMORY: THE DESTRUCTION OF GENERALŠTAB AND THE LOSS OF ARCHITECTURAL IDENTITY

Luka Radosavljević[1], Katarina Radosavljević[2]

Abstract

The ongoing destruction of the Generalštab complex in Belgrade, designed by Nikola Dobrović, represents a critical loss to modernist architecture, urban identity, and collective memory. Built between 1955 and 1965, the complex is a masterpiece of Yugoslav modernism, integrating symbolic topography, tectonic expression, and spatial dynamism, as well as technological advancements. Its partial destruction during the 1999 NATO bombings and subsequent neglect led to its present deteriorating state, underscoring the vulnerability of architectural and cultural heritage in the face of political and economic pressures. This paper investigates the architectural, historical, and cultural ramifications of the Generalštab's disappearance. Using a multidisciplinary methodology that integrates archival research, spatial analysis, and comparative studies of modernist heritage preservation, the research explores how the building's erasure alters the perception of urban continuity and reconfigures historical discourse. The findings suggest that the loss extends beyond the physical structure: it fractures the city's architectural fabric, diminishes opportunities for historical reflection, and weakens the dialogue between present and past through the erosion of urban identity. By contextualizing these outcomes within global paradigms of adaptive reuse and contested heritage, this analysis underscores the importance of preserving architectural narratives as constitutive elements of collective memory. It emphasizes the need for a critical reimagining of heritage preservation strategies, proposing a nuanced and proactive approach that recognizes modernist landmarks as both cultural repositories and agents of urban continuity in shaping future landscapes.

Key words: *generalštab, adaptive reuse, heritage, memory, modernism*

[1] Mr, architect, StudioAfter, Serbia, njafrfu@gmail.com, ORCID N/A
[2] Mrs, architect, StudioAfter, Serbia, k8dojcev@gmail.com, ORCID N/A

1. INTRODUCTION

The remains of the Generalštab complex—once home tothe Ministry of Defense and the former Yugoslav General Staff—stand as a solemn reminder of the 1999 NATO bombing in the heart of Belgrade. Designed by modernist architect Nikola Dobrović and completed in the 1960s, the Generalštab marked a pinnacle of Serbian and Yugoslav modernist architecture. With its bold architectural language and monumental scale it becamea distinctive element of Belgrade's skyline, embodying the post-war modernization of both the city and the state.

The complex suffered extensive damage during the 1999 conflict, and has stood in partial ruin for over two decades, suspended between calls for preservation and redevelopment pressures. In the early 2024 the Serbian government approved a preliminary 99-year lease with an investment consortium—led by a US corporation—aiming to transform the site into a luxury hotel and residential complex. This proposal reignited a wave of professional dissent: Europa Nostra, ICOMOS Serbia, Baza- Spatial Praxis Platform, and a broad coalition of Serbian architects warned that the project threatens to efface a seminal artefact of Yugoslav modernism from Belgrade's architectural palimpsest, all while bypassing international heritage procedures..

The destruction and the possible erasure of the Generalštab has precipitated far-reaching architectural, spatial, and cultural consequences. These consequences extend beyond the loss of a single building – they touch on collective memory, urban identity, and the ideological narratives that shape how post-conflict societies deal with their heritage.



Figure 1. Generalštab (Army Headquarters), before 1999., City Assembly of Belgrade.

2. METHODOLOGICAL FRAMEWORK: INTERDISCIPLINARY APPROACHES TO ARCHITECTURAL LOSS AND URBAN MEMORY

2.1. Research Philosophy and Approach

The research on the Generalštab complex requires a framework that addresses on only its materiality, but also its symbolic and cultural resonance. Architecture is not only considered as a physical construct, but as a site of memory, identity, and ideological tension. A critically reflective, interdisciplinary approach was adopted, drawing from architectural history, memory studies, heritage conservation theory, and urban studies. To support this approach, a wide range of sources was utilized, including academic literature, archival documents, visual media, and official reports, enabling a multifaceted understanding of the complex's historical trajectory, present condition, and possible futures.

The choice of an interdisciplinary methodology stems from the recognition that no single disciplinary perspective can fully capture the architectural, spatial, and cultural layers involved. Through the integration of empirical investigation and theoretical reflection, the research aims to illuminate not just the apparent outcomes of destruction but also the tacit transformations in collective memory, urban continuity, and public discourse.

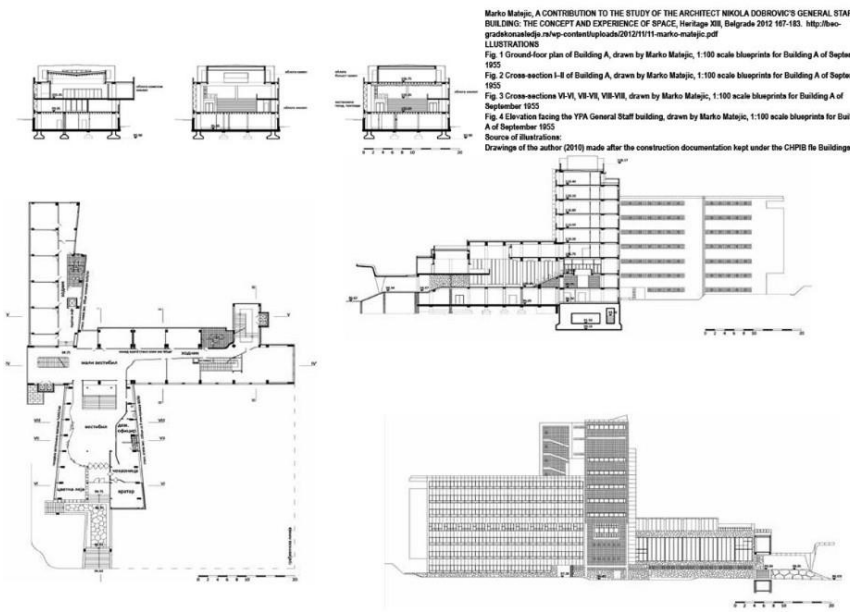


Figure 2. Technical drawings according to 1955. documentation, Docomomo Srbija

2.2. Methodological design

The research is structured as a qualitative case study, positioning the Generalštab complex as a focal point for analyzing broader patterns in the treatment of modernist heritage within post-conflict urban contexts. The case study approach was selected to enable depth of analysis, welcoming the complexity and contextual particularity of the Generalštab's circumstance, more than flattening it to generalized trends.

A composite methodology was employed, combining archival research, site observation, discourse and literature analysis, and international case study comparison. Each metod contributes to a deeper understanding of both the material damage and the evolving cultural significance of the site.

2.3. Sources and Data collection

2.3.1. Archival research

Primary sources—including original blueprints, architectural drawings, construction photographs, official reports, and writings by Nikola Dobrović—were extensively examined. These materials were crucial for reconstructing the building's original intent, symbolic structure, and urban significance. Secondary sources, such as Kovačević's 2001 monograph and Docomomo's 2003 documentation [1] , provided further insight into the project's tectonic, spatial, and technological ambitions.

2.3.2. Field observation and Spatial Analysis

Site visits were conducted to document the current condition of the complex and its urban surroundings. These empirical observations recorded the existing material state, cycles of degradation, spatial (dis)continuity or disconnection from the urban context, and uncontrolled public uses in the area. A comparison of historical maps and maps of the contemporary period assisted in gaining an understanding of how the site evolved in the overall urban evolution of Belgrade. This grounded the research in the tangible realities of the ruin.

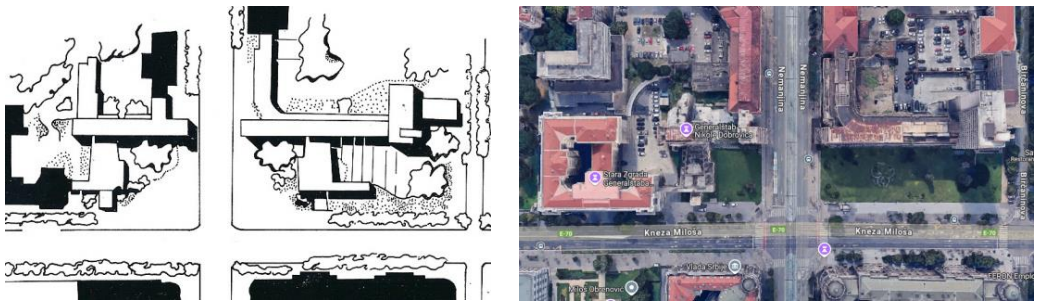


Figure 3. Comparative analysis of maps, Google Images

2.3.3. Literature Review and Theoretical Engagement/Discourse Analysis

A thematic literature review engaged foundational and contemporary works on collective memory (Halbwachs [2], Assmann [3]), difficult heritage (Macdonald [4], Bădescu [5]), heritage value theory, and urban continuity. Studies on the Generalštab complex itself (Kovačević [6], Weiss [7]) were analyzed to understand its architectural reception. These concepts framed the Generalštab's ruin functions not merely as physical residue, but as a mnemonic device, a site of cultural negotiation, and a node in urban symbolic networks. As Bădescu puts it, these ruins serve as "*mnemonic objects*" that embody the trauma of the 1999 bombings, preserving public consciousness through their material presence.

Additionally, media reports, public petitions, policy documents, and professional commentaries spanning two decades were systematically reviewed. This corpus enabled an analysis of shifting societal attitudes and highlighted recurring tensions between calls for memorialization, commercial redevelopment, and adaptive reuse.

2.3.4. Comparative Case Study Analysis

Selected international cases were examined to situate the Generalštab within an international framework of contentious modernist heritage management. The Palast der Republik in Berlin, the Hiroshima Peace Memorial Dome [8], and the adaptive reuse of the Stiftung Exilmuseum Berlin [9] were used as comparative benchmarks. These cases provided important lessons for framing and understanding the political, ethical, and design challenges involved in decision-making regarding the future of modernist buildings impacted by conflict.

2.3. Analytical Strategies and Considerations

The analysis followed a thematic logic, identifying patterns, contradictions, and shifting narratives. Archival findings were cross-referenced with field data to assess disparities between intended meaning and contemporary perception. Discourse and spatial analyses were integrated to explore the link between form and symbolism , while comparative cases served as mirrors for critical reflection.

Given the traumatic history of the site, the research was conducted with ethical sensitivity. Topics of memory politics, cultural loss, and wartime destruction were handled with care to avoid bias or spectacle. Whenever possible, the views of affected communities, architects, planners, and heritage advocates were prioritized. Rather than simplifying collective memory, the project sought to acknowledge its complexity—honoring the symbolic, emotional, and cultural dimensions embedded in the ruin.

3. RESULT: IMPACTS OF THE GENERALŠTAB'S DESTRUCTION



Figure 4. Generalštab complex before the bombing, Bojan Kovačević

3.1. Architectural Consequences

The destruction of the Generalštab complex constitutes a profound architectural loss for the modernist heritage of Belgrade and the country as a whole. As the only realized building by Nikola Dobrović in the city—and widely regarded as his magnum opus—the complex encapsulated a post-war vision of Yugoslavia that merged tectonic dynamism with symbolic

topography. Completed in 1963 on the remnants of wartime devastation, its twin interlocking wings—divided by a widening central void—were interpreted as an abstraction of the Sutjeska canyon or as a spatial metaphor of Bergsonian movement and continuity. Although Dobrović never explicitly endorsed these interpretations, their symbolic resonance persists.

Architecturally, the Generalštab represents a unique synthesis of modernity and tradition. Composed of two asymmetrically oriented wings (Building A and Building B) the complex evoked both tectonic force and symbolic memory. Reaching up to 20m in height, the reinforced concrete structure was covered with red granite and white marble, sourced from Kosjerić and Brač respectfully —materials that created a stark and evocative contrast on the façade. Its sculptural voids, exposed concrete façades, and layered composition, exemplified Belgrade's post-war architectural renaissance. Some critics perceived this stylistic approach as "*anachronistic*" as compared to the 1960s modernism, which only amplified the building's timeless character.

This synthesis was halted by the bombing in 1999: the balance of solid volumes and voids was brutally broken, volumes and spatial arrangements were destroyed. Its southern wing collapsed, and the remaining structures have since been degraded through exposure to the elements. Intricate details of craft, material expression, and internal flow have been lost.



Figure 5. Generalštab in 2012., 13 years after the bombing, Bojan Kovačević

Today, the Generalštab embodies what might be described as an "architecture of ruin"—a spatial condition in which material decay, structural incompleteness, and historical memory fuse into a new architectural entity. Neither a functioning building nor a designated memorial, the site occupies a liminal space between presence and absence, past and potential. Its broken masses, stripped layers, and suspended decay disclose violent processes of erosion, time, and force, making of the site a living palimpsest of devastation and endurance. As such, the ruin challenges conventional heritage frameworks and demands a more nuanced engagement than simple restoration or symbolic preservation.

The destruction also initiated a lasting debate between proponents of reconstruction and those who prefer maintaining the ruin as an authentic war relic. While architects and critics such as Mihajlo Mitrović and Bojan Kovačević called for its complete restoration as an exhibition of cultural resilience, others dismissed the modernist aesthetic as dated, thus

allowing the site to crumble. Caught between these opposing views, the Generalštab has assumed a suspended identity—neither erased nor maintained. As a "spomenik pamćenju" (monument of memory), a tangible witness to collective trauma, and a contested object in Belgrade's ongoing urban narrative, the building has acquired new meanings within this suspended tension.

3.2. Spatial and Urban Consequences



Figure 6. The site of Generalštab in 2024., www.blic.rs

The demolition of the Generalštab complex deeply disrupted central Belgrade's spatial logic and urban continuity. Strategically positioned on Nemanjina Street, one of the city's most prominent civic axes, the complex previously served as a powerful institutional anchor in the administrative district. Its monumental façade and volumetric arrangement contributed to the rhythm and cohesion of the urban streetscape, reinforcing post-war ideals of authority, order, and progress.

In its ruined state, however, the Generalštab constitutes a spatial void and urban rupture. The damaged structure, now fenced off for safety, interrupts pedestrian movement and disrupts public space functionality. Beyond its physical footprint, the site represents a psychological scar—an unresolved trauma etched into the city's collective spatial memory, one which tears the built environment and architectural heritage of the place.

Unlike other post-war cities that have incorporated ruins into memorial parks or civic landscapes, the Generalštab remains fenced and empty, preserving an aura of voidness in the city center.

It is both a landmark and a symbol of violence. For many residents, the site evokes a complicated blend of mourning, defiance, and frustration; for younger generations, it is a commonplace feature of the environment, subtly influencing urban awareness. The physical displacement of governmental functions has also disrupted the long-standing symbolic alignment between Nemanjina Street and the Ministry of Defense, weakening the site's institutional identity.

This spatial discontinuity extends to the narrative level. The removal—or non-removal of the Generalštab not only fractures the morphological and spatial characteristics of the site but also resultes in drastic changes in cultural identity and collective memory, redefining the site as a contentious place of trauma, memory, and symbolic negotiation in the changing urban narrative on the urban and national level.

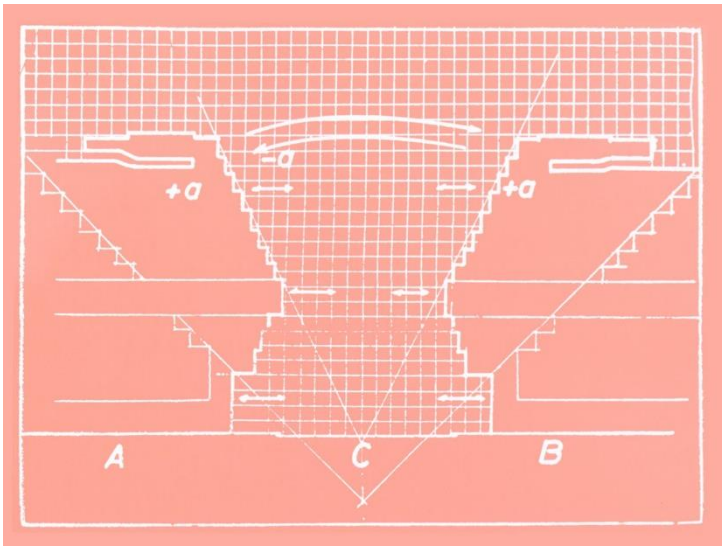


Figure 7. Dobrovic's Bergsonian drawing for the Army Headquarters, Cabinet Magazine

3.3. Cultural and Memory Consequences

The cultural impact of the Generalštab's destruction extends far beyond architectural loss—it pierces deeply into questions of identity, memory, and national narrative. The complex has become a locus of contested meaning, with divergent interpretations across social, political, and generational lines.

However, some segments of the public and political establishment hold a more ambivalent or even disdainful view of the Generalštab. In Serbia's complex memory landscape, modernist architecture—especially that of the Yugoslav socialist era—is often marginalized as either less beautiful or ideologically problematic. Therefore, the Generalštab holds a difficult place in the national narrative as a representation of Tito-era aspirations, caught between adoration and disavowal. This ideological ambivalence has led to a long-term deadlock over the site's future; neither complete restoration nor complete demolition have been agreed upon politically or culturally.

Public discourse surrounding the site oscillates between two paradigms: *memorialization* and *erasure*. Advocates for preservation argue for stabilizing the structure as a war memorial, akin to the preservation of the Hiroshima Peace Memorial Dome, as a material testimony to the trauma of the 1999 bombings. Stabilizing the structure as a war memorial would embed a narrative of resilience and loss into the city's urban fabric, offering future generations a tangible connection to a contested history. In contrast, proponents of redevelopment envision the removal of the ruin as a pathway to healing and economic revitalization. Some proposals even sought to overwrite the site's memory with monuments from more distant, pre-socialist epochs, reflecting a desire to anchor national identity in older, less politically fraught heritage. This drive toward erasure, while framed as practical

urban development, risks a form of collective amnesia—substituting reconciliation with forgetting in the public realm.

The two opposing paradigms of memorialization and erasure are frequently discussed in public discussions about the Generalštab. In a similar vein to the preservation of the Hiroshima Peace Memorial Dome, preservationists also see the building as a site for moral contemplation—a physical reminder of the pain caused by the bombings in 1999. Memorializing the building as a war memorial would provide future generations with a physical reference to a contested history, while inscribing a history of grief and resilience into Belgrade's cityscape. However, redevelopment proponents rebut that the demolition of the deteriorating structures will resurrect the city's economy. Perhaps, the most viable solution to the current *status quo* is somewhere in the middle of this spectrum.



Figure 8. The Hiroshima Peace Memorial, https://whc.unesco.org/en/list/775

Yet the Generalštab also embodies the potential for reinterpretation. As a *spatial palimpsest*, it contains overlapping layers of ideology, trauma, and historical narrative—each partially erased but still legible. Like medieval manuscripts that were written and re-written over scraped pages, the building invites a multiplicity of meanings: a scar of violence, a remnant of lost utopia, a symbol of endurance.

Its ruinous incompleteness enhances this interpretive openness. Far from being a limitation, the unfinished state allows future generations to project new significance onto its surfaces. This dynamic potential positions the Generalštab as not just a relic of the past, but a platform for a more complex and inclusive cultural memory.

3.3.1. Spatial Palimpsest: The Layering of Memory and Absence

A dense, multi-layered architectural narrative is created by the intersection of layers of history, material void, and collective memory at the Generalštab complex, which can be

considered as a spatial palimpsest. The fragmented condition of the Generalštab bears the imprint of multiple temporal and ideological layers—much like a medieval manuscript that has been erased and overwritten, yet still retains traces of its earlier text. Despite its fractured and at times contradictory form, one can still discern the building's early modernist ambitions, the scars of wartime destruction, decades of abandonment, and the ongoing debate over its cultural significance.

As a spatial artifact, the ruin is difficult to understand. As a silent witness to collective mourning, a scar of violence, a remnant of a deposed political regime, or a symbol of tenacity, it invites a variety of interpretations, many of which are contradictory. Its narrative flexibility is fueled by its material incompleteness, in order for future generations to impose new meanings on its worn surfaces. The Generalštab is a case of the phenomenon by which architecture moves beyond its inherent function to be incorporated into the work of cultural memory.

This palimpsestic state questions traditional heritage processes aimed at either complete restoration or replacement. It instead demands a developed process that recognizes the superimposed accumulation of history within material forms. To preserve the ruin—or to modify it with restrained judgment—would be to sustain the visible tensions between making and decay, aspiration and vulnerability, and remembering and forgetting. Thus, the Generalštab presents an opportunity to become involved with architectural heritage not simply as a form of static preservation, but as a dynamic, ongoing arena of memorialization.

3.4. Adaptive Reuse Precedent: Stiftung Exilmuseum Berlin

A particularly relevant example of reimagining contested heritage through adaptive reuse—one that parallels the case of the Generalštab—is Berlin's Anhalter Bahnhof. Severely damaged during World War II by Allied bombings, the structure was largely dismantled in the post-war period, leaving only its monumental entrance façade. For decades, the site remained an incomplete void within Berlin's urban fabric, serving as a fragmented testament to destruction and historical discontinuity.

Current plans call for incorporating the ruin into the Exilmuseum Berlin, a new cultural organization that will be located behind the remaining façade, rather than completely destroying or rebuilding it. The museum, which was designed by Dorte Mandrup Arkitekter [6], is devoted to chronicling the history of exile, with a particular emphasis on those who escaped Nazi Germany. This story is closely linked to the station's history because many people used it as a departure point during the 1930s. Instead of hiding the ruin's remains, the building's design highlights and maintains the façade as a tangible witness, using the new structure to produce a spatial tension between reconstruction and absence.

This approach has several characteristics which could resonate with the Generalštab. First, it identifies the ruins not merely as remnants to be preserved, but instead as a generative component in building a new urban mythology. The physical incompleteness of the Anhalter Bahnhof is consciously incorporated into the museum experience, guiding spatial movement and informing collective memory. Second, it demonstrates a highly evolved integration of historical heritage and modern functionality—situating the ruin as a place and also as an active partner in an innovative public program. The project neither idealizes the historical context nor deletes it, but uses history in the daily life of the city fabric.

For the Generalštab, this precedent in history argues for the feasibility of keeping damaged architectural fragments in a hybrid typology—a thing that invokes loss but accommodates eventual use. In the way that the ruin of the Anhalter Bahnhof prefigures the experience of exile, the fractured forms of the Generalštab could accommodate a program that addresses the narratives regarding war, resilience, and architectural heritage within the post-Yugoslav environment. In this kind of case, adaptive reuse transcends mere utility and is a cultural endeavor that enables architecture to hold memory while giving new meaning to a building that could otherwise languish in limbo.



Figure 9. Stiftung Exilmuseum Berlin, https://www.dortemandrup.dk/work/stiftung-exilmuseum-berlin

4. DISCUSSION: CONTESTED HERITAGE

4.1. Contested Heritage and the Architectural Ethics of Intervention

The Generalštab complex exemplifies the challenges of engaging with contested modernist heritage in a post-conflict society. Its ruin is not merely the result of wartime destruction, but an active site of cultural negotiation—shifting between symbol, scar, and speculative real estate. Its unresolved condition reflects deeper tensions within Serbia's collective memory and post-socialist identity, shaped as much by ideological discord as by architectural decay.

As a case of *difficult heritage*, the Generalštab challenges dominant narratives and evokes discomfort. Unlike traditional monuments that affirm national cohesion, it invites discomfort and conflicting interpretations—particularly regarding Yugoslav modernism and the trauma of the 1999 NATO bombings. Its fragmentary state resists conventional typologies, becoming a dynamic participant in Belgrade's evolving urban and commemorative landscape.

International precedents such as Berlin's Anhalter Bahnhof [10] — soon to house the Exilmuseum—offer models for spatializing trauma without effacing it. By embedding new civic functions within historic remnants, these projects reframe ruins as witnesses and vessels of memory. A similar approach in Belgrade could position the Generalštab as both cultural artifact and civic resource, bridging past and future. Yet current redevelopment proposals—including private luxury investment—highlight the risks of erasure through commercialization. The site has become a flashpoint for debates over neoliberal urbanism, revealing the urgent need for heritage impact assessments, public consultation, and ethically grounded design competitions.

Adaptive reuse, as used in this study, offers a proactive way—not as a compromise gesture, but as a responsible design ethic. It circumvents the reconstruction-versus-erasure state, and recharacterizes architecture as a space of negotiation: balancing permanence with change, loss with renewal, and memory with utility. By the reinforcement of the existing buildings, incorporating commemorative and community-oriented functions, and emphasizing the storytelling potential of the ruins, Belgrade could be able to develop a model for ethically and spatially accountable reutilization of disputed cultural heritage.

The Generalštab thereby exceeds the status of mere remainder of a failed modernist utopia; it is a spatial inquiry relevant to contemporary debate. How can cities metabolize trauma? Who has the authority to shape architectural memory? And what kinds of futures can be envisioned from unresolved pasts? The answer lies not in erasure, but in the challenging and imaginative process of designing to incorporate and negotiate the existing ruin.

4.2. Memory, Reconstruction, and Urban Continuity



Figure 10. Student led protest in front of Generalštab, 2025. www.bbc.com

Despite its partial destruction, the Generalštab remains a symbolic presence in Belgrade—a fractured landmark that embodies suspended memory and interrupted spatial logic. Once a prominent institutional anchor along Nemanjina Street, its current dilapidated state marks not just a physical gap, but a symbolic pause in the city's architectural and civic dialogue.

Reconstruction is not a neutral act from the point of view of memory studies; it dictates what will be remembered, what will be legitimized, and what will be left behind. The Generalštab's present limbo—neither preserved, obliterated, nor repurposed—leaves it hanging between forgetting and commemoration, disrupting both historical legibility and spatial coherence.

Reconstruction, when thoughtfully undertaken, should not seek to replicate a lost past, but instead to embed memory within contemporary spatial practice. Stabilizing the existing structure and introducing new, meaningful functions provides a constructive alternative to both nostalgic imitation and complete erasure. Rather than simply restoring absent forms or suppressing painful histories, this approach inscribes memory into space—aligning with evolving conservation principles that prioritize cultural meaning over the reproduction of physical material.

To serve both memory and the city, any intervention at the site must be participatory, context-sensitive, and symbolically attuned. The future of the Generalštab is not only an architectural problem, but a civic one [11]. It challenges Belgrade to consider how architecture can facilitate remembrance without denying rupture, and how cities can mend the spatial scars of war while embracing plural historical narratives [12].

4.3. Adaptive Reuse as a Method for Conserving and Reimagining

Adaptive reuse provides a robust and contextually nuanced alternative, one that resists the either/or of demolition or complete reconstruction. As a design strategy and philosophical position, adaptive reuse allows buildings of cultural and historical significance to continue to be meaningful—not by returning them to a fixed past, but by projecting them into the present. For sites like the Generalštab, which occupy a conflicted position between trauma, memory, and architectural heritage, adaptive reuse can serve as a redemptive gesture without erasing historical rupture.

Rather than proposing nostalgic reconstruction or allowing ongoing decay, adaptive reuse allows the ruin to be an agency in the formulation of new spatial stories. In the context of the Generalštab, this may include stabilizing the existing structures, restoring functional interiors, and introducing new architectural elements that engage in both visual and symbolic dialogue with Dobrović's initial design. Importantly, this is not done to "complete" the building or cover its deficiencies; rather, it renders the history of destruction comprehensible while providing contemporary public function.

As a method of conservation, adaptive reuse recontextualizes preservation not as the preservation of stasis but as a negotiated process of transformation. It acknowledges the different layers of identity of a site—from its modernist origin and wartime devastation to its long-term abandonment and contemporary controversy. In doing so, it follows progressive heritage practice, including the Nara Document on Authenticity (1994) [13], in promoting interpretations of heritage value led by cultural and contextual factors. Adaptive reuse allows for the preservation of both the architectural and symbolic significance of the Generalštab and to reintegrate the site into Belgrade's urban fabric.

Additionally, the idea of reuse offers possibilities for inventive programmatic development. A hybrid civic-cultural complex can incorporate commemorative elements—exhibitions on 20th-century modernism and the bombings of 1999, for instance—within dynamic public utilities: cultural centers, community centers, archival centers, or even

shared workspaces. Such a multilateral approach would ensure that memory is not only a stagnant monument but is alive through daily spatial interaction.

At a strategic level, adaptive reuse is essential to building urban resilience. In an urban context like Belgrade, where there is a constantly growing need for central space, the redevelopment of a historic but underutilized site responds to both symbolic and spatial needs. It is a model for reconciling heritage and development—not by denying the site's importance, but by reaffirming its position as a site of collective memory. In this framework, the Generalštab becomes not just a ruin to preserve or a parcel to develop, but a public architecture of reflection and renewal.

5. CONCLUSION

The destruction of Nikola Dobrović's Generalštab complex fundamentally marks a rupture in the architectural, spatial, and cultural continuity of Belgrade and Serbia. It transcends the erasure of a modernist icon and symbolizes the nation’s inability to face its past and define its future. In terms of architecture, the ruin represents a gap in Serbia's modernist legacy; in terms of space, it creates a wound in the urban fabric of the city; and in terms of culture, it serves as a mirror of disputed memories and ideological conflicts over which historical periods should be remembered or ignored.

The Generalštab embodies the complexities of post-conflict heritage: it is at once a physical remnant, a political symbol, and a site of cultural trauma. Public responses—ranging from reverence to rejection—attest to the contested nature of its legacy and to the ongoing negotiation between remembrance and erasure. This study believes that *adaptive reuse*, if approached with care and sensitivity, offers a constructive path forward. Rather than erasing the ruin or restoring it nostalgically, adaptive reuse allows it to evolve—transforming it into a site of active reflection and contemporary relevance.

A central element of the Generalštab's uncertain future regards recent plans for the privatization and redevelopment of the site for commercial purposes, in particular including proposals linked with luxury hotel projects. Such developments threaten the fragile relationship between the site's architectural value, memorial value, and collective memory that it sustains. Privatization in the absence of a heritage-sensitive policy thus endangers not just the physical remnants of Dobrović's vision but also forecloses on a public, critically engaged re-reading of the site. By allowing a site so steeped in the city's trauma and modernist heritage to be commodified, Belgrade stands to lose not just a building, but the dissolution of its own historical consciousness.

Ultimately, the decision regarding the Generalštab will set a precedent for how Serbia confronts its architectural and political past. Through participatory processes, reflective design, and courageous architectural thinking, the site has the potential to become more than a ruin—it can serve as a model for how cities metabolize difficult history and foster inclusive urban memory. Even in its brokenness, the Generalštab offers an opportunity to shape a more thoughtful and resilient future.

REFERENCES

[1] Nacionalna radna grupa Srbija: **Minimalni dokumentacioni dosije 2003.** (DEF-RS-011-b-0001). *Docomomo_Srbija*, Beograd, 2003.

[2] Halbwachs Maurice: **On Collective Memory**. *University of Chicago Press*, Chicago, 1992.

[3] Assmann Jan: **Cultural Memory and Early Civilization: Writing, Remembrance, and Political Imagination**. *Cambridge University Press*, Cambridge, 2011.

[4] Macdonald Sharon: **Difficult Heritage: Negotiating the Nazi Past in Nuremberg and Beyond**. *Routledge*, London, 2009.

[5] Gruia Bădescu: **Making Sense of Ruins: Architectural Reconstruction and Collective Memory in Belgrade.** *Nationalities Papers,* 2019.

[6] Bojan Kovačević: **Arhitektura zgrade Generalštaba.** *NIC Vojska,* Beograd, 2001.

[7] Srđan Jovanović Weiss: **NATO as architectural critic, destruction and classification.** *Cabinet Magazine, Issue 1 / Invented Languages,* New York 2000.-2001.

[8] **Hiroshima Peace Memorial** (Genbaku Dome): https://whc.unesco.org/en/list/775 (accessed 3.4.2025.)

[9] **Stiftung Exilmuseum Berlin** – Dorte Mandrup Arkitekter: https://www.dortemandrup.dk/work/stiftung-exilmuseum-berlin (accessed 27.4.2025.)

[10] **Anhalter Bahnhof – Historical Overview**: https://www.berlin.de/landesdenkmalamt/denkmal/denkmalverzeichnis/ (accessed 27.4.2025.)

[11] **Studentski protest za Generalštab** https://www.bbc.com/serbian/articles/clyrjj3zpmlo/lat (accessed 17. 06. 2025.)

[12] **Zgrada Generalštaba i Ministarstva odbrane više nisu kulturno dobro** https://www.blic.rs/vesti/drustvo/generalstab-i-zgrada-ministarstva-odbrane-vise-nisu-kulturno-dobro-izbrisane-iz/xvrkv1n (accessed 18. 06. 2025.)

[13] **The Nara Document on Authenticity** (1994): https://www.icomos.org/charters/nara-e.pdf (accessed 1.4.2025.)

doi.org/10.62683/SINARG2025.047

Research paper

LIFE CYCLE ASSESSMENT OF NOVEL MATERIALS FOR LOW-CARBON CONCRETE PRODUCTION

Hesam Afsoosbiria[1], Hamed Afsoosbiria[2,3], Agnieszka Machowska[4]

Abstract

Concrete is a fundamental material in construction, but its production, particularly the manufacturing of cement as a binding agent, is a significant source of CO_2 emissions, contributing to global climate change. With the continued demand for concrete in infrastructure development, there is an urgent need to identify and implement sustainable, low-carbon alternatives. This study addresses this challenge by evaluating the environmental performance of conventional and emerging low-carbon materials used in concrete production. Using the Life Cycle Assessment (LCA) methodology, we conducted a comparative analysis of multiple concrete mixtures, focusing on their embodied carbon and overall environmental impact. Our findings highlight the potential of novel materials to reduce the carbon footprint of concrete while maintaining structural integrity. This research provides critical insights into the sustainability of low-carbon concrete and offers actionable recommendations for the construction industry to transition toward more environmentally friendly practices.

Key words: *Concrete, Cement, Substantially, Life Cycle Assessment, Environmental Impact.*

[1] MSc. Eng. Hesam Afsoosbiria, Doctoral study, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: hesam.afsoosbiria.dokt@pw.edu.pl, Poland, ORCID: 0000-0002-9408-6073.

[2] MSc. Eng. Hamed Afsoosbiria, Doctoral study, VSB-TU Ostrava, Faculty of Civil Engineering, e-mail: hamed.afsoosbiria@vsb.cz, Czech Republic, ORCID: 0000-0002-7210-6379.

[3] Faculty of Civil Engineering, Warsaw University of Technology, 00-637 Warsaw, Poland; hamed.afsoosbiria.stud@pw.edu.pl, Poland, ORCID: 0000-0002-7210-6379.

[4] DSc, PhD. Eng. Agnieszka Machowska, university professor, Warsaw University of Technology, Faculty of Environmental Engineering, e-mail: agnieszka.machowska@pw.edu.pl, Poland, ORCID: 0000-0002-3573-6822.

1. INTRODUCTION

Concrete is one of the most broadly utilized building materials globally, playing a critical role in constructing roads, buildings, bridges, and various other infrastructures. On average, around one ton of concrete is produced annually for every person on the planet. Given its widespread use, it is essential to accurately assess the environmental impact of this material [1]. Reducing the use of cement and natural aggregates in concrete production is an effective way to mitigate this impact. Incorporating supplementary cementitious materials (SCMs) as partial replacements for cement could significantly lower the overall CO_2 footprint of the final concrete product. However, the environmental implications of concrete extend beyond cement alone, as aggregates also play a critical role in both resource consumption and waste generation within the construction sector [2,3]. On one hand, aggregates constitute about three-quarters of concrete by volume, making concrete a significant consumer of natural resources. When concrete is demolished after its service life or due to deterioration, it becomes inert waste, often occupying substantial space in landfills [4]. Meanwhile, the massive consumption of aggregates and concrete in construction inevitably results in the generation of waste, specifically Construction and Demolition (C&D) waste. Globally, the total production of C&D waste exceeds three billion tons annually [5]. Greenhouse gas (GHG) emissions occur not only during the manufacturing stage but also throughout the construction process, including construction, operations, maintenance, and the final renovation or demolition stage [6]. The built environment accounts for over 37% of global energy-related CO_2 emissions. In 2021, operational CO_2 emissions from the buildings sector increased by 5% compared to 2020, exceeding the 2019 peak by 2%. Furthermore, construction materials, which currently contribute 9% of total energy-related CO2 emissions, are expected to see their impact double by 2060 [7]. To address climate change and global warming, efforts to reduce carbon emissions are being pursued globally [8]. Growing global environmental awareness and increasing demand for eco-friendly materials are driving the sector toward a sustainability-focused approach. As a result, the industry is gradually adopting materials with lower embodied energy and reduced environmental impact, as well as those better suited to local climate conditions [9]. Reducing CO_2 emissions from cement and concrete production is crucial in advancing climate goals. Decarbonizing these materials could lower carbon intensity and significantly reduce the construction sector's ecological footprint [10]. The integration of alternative materials supports the conservation of natural resources and minimizes waste disposal by incorporating urban and industrial waste into concrete, according to the principles of the circular economy. The environmental benefits of using recycled materials in common building elements are typically assessed through a Life Cycle Assessment (LCA), evaluating primary embodied energy and greenhouse gas emissions based on a “cradle-to-gate” approach [11]. Life-cycle analysis (LCA) involves collecting and assessing the inputs, outputs, and potential environmental impacts of a product system throughout its entire life cycle. This methodology enables the quantification of environmental loads and helps identify key processes that significantly contribute to the overall impact. As a result, LCA serves as a crucial tool in the design and development of materials, products, and systems [12]. In this context, LCA has been widely applied in various studies to investigate the environmental impact of manufacturing construction and building materials, such as cement-based materials [13, 14, 15, 16]. This research aims to assess the sustainability of concrete incorporating pozzolanic materials and to quantify the carbon footprints of several concrete mixes made with alternative materials.

2. DEFINITIONS AND FRAMEWORKS OF LIFE CYCLE ASSESSMENT (LCA)

Sustainability is typically investigated using Life Cycle Assessment (LCA), a key environmental management tool that evaluates the impacts and resource demands of a product or service. By quantifying material and energy consumption, along with waste emissions throughout its lifespan, LCA provides a comprehensive analysis of environmental effects. Although its primary focus is on environmental aspects, its life cycle approach and methodology could be adapted to assess economic and social impacts as well [17]. According to ISO standards, LCA involves four key steps: defining the goal and scope, developing the Life Cycle Inventory, examining environmental impacts, and interpreting the results [18, 19, 20, 21]. The life cycle assessment framework is shown in Figure 1.

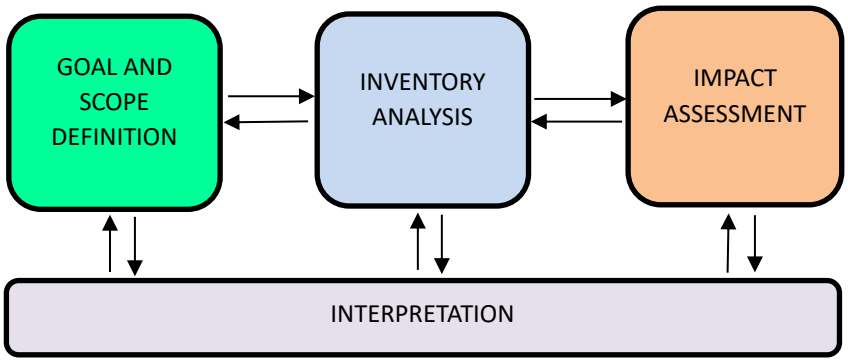


Figure 1. Life cycle assessment Framework [22, 23]

This initial phase involves identifying the assessment's purpose, the intended audience, and the specific questions to be addressed. It also includes defining the system boundaries, which establish what is included in the assessment, such as materials, processes, and transportation, and what is excluded [24]. According to ISO 14044, the system boundary defines which methods are included in the LCA and must align with the study's goal. Like other products, the LCA system boundary for buildings could follow a cradle-to-grave, cradle-to-gate (for building product analysis), or gate-to-gate (for construction process analysis) approach. Typically, the cradle-to-grave approach is used, covering the entire lifecycle from the pre-use phase to the End-of-Life (EOL) phase. The system boundary should also specify spatial and temporal limits, serving as both a research constraint and a benchmark for future studies [25]. In the scope definition, the function and functional unit (e.g., liter, m^2, m^3), system boundaries, data quality requirements, system comparisons, and considerations for critical analyses should be carefully considered and clearly described [26]. This study aims to conduct a cradle-to-gate LCA to evaluate the environmental implications of producing concrete using recycled material and then compare them with reference concrete.

In the Inventory Analysis (LCI) phase, data is gathered on the inputs and outputs of the system under study. This involves quantifying energy consumption, raw material usage, air, water, and soil emissions, and waste generation. Given its data-intensive nature, inventory analysis often requires specialized databases and software tools to systematically compile, manage, and analyze relevant information [24]. The effectiveness of a Life Cycle Assessment

(LCA) considerably depends on the accuracy and completeness of its Life Cycle Inventory (LCI), which gathers data on mass and energy inputs and outputs across all life-cycle stages. Without a reliable and thorough LCI, the LCA's value could be compromised by uncertainties in the subsequent Life Cycle Impact Assessment (LCIA) or by gaps in the environmental impact categories assessed. In short, robust and trustworthy LCAs for concrete production are grounded in well-developed and comprehensive LCIs [27]. The third phase involves evaluating the potential environmental impacts associated with the inputs and outputs identified during the inventory analysis [24]. In this phase, the results from the inventory analysis are investigated to determine their potential environmental impacts. As with the inventory phase, the choice of assessment method and impact categories is guided by the Goal and Scope definition. Most LCA practitioners typically rely on established and published assessment methodologies rather than developing new ones from scratch [28]. The final stage of a Life Cycle Assessment (LCA) involves interpreting the results, where the impact assessment outcomes are analyzed for their robustness and sensitivity to input data. Conclusions are then drawn in alignment with the LCA's original goals and objectives. This stage also includes data validation, which is carried out by comparing findings with existing literature and performing sensitivity analyses to assess the reliability of non-local databases [28].

3. CARBON FOOTPRINT CALCULATION AND REDUCTION FOR CONCRETE MIXES

Concrete is the most widely produced material in the world and has a significant role in the construction industry. However, the environmental impact of traditional concrete production, particularly in terms of carbon emissions and the depletion of natural resources, is a serious concern [29]. Sustainable construction is increasingly being supported by a broader selection of materials considered suitable for use in concrete. This opens up opportunities to incorporate new materials into concrete mix designs. The use of these secondary materials could significantly reduce environmental impacts by lowering energy consumption in cement production, decreasing landfill use, and minimizing the emission of combustion gases [30]. There is also limited potential for reducing CO2 emissions without a greater use of secondary cementitious materials (SCMs) such as FA/GGBS. In addition, Current clinker replacement levels in the UK are just over 13%, with a target of reaching 30% replacement by 2050 [30]. Figure 2 presents the life cycle assessment for concrete from cradle to gate, including three phases and considering measures to mitigate the carbon footprint. The first phase is the extraction and processing of raw materials used in construction, such as cement or concrete. In this stage, important materials include sand, gravel, supplementary cementitious materials (SCMs) like fly ash, rice husk ash (RHA), or slag. These materials are generally obtained from quarries, mines, or industrial by-products. The environmental impact at this stage, particularly regarding CO_2 emissions, is primarily linked to the energy consumed during the mining and processing of these materials. Extraction materials require processes such as drilling, blasting, and crushing, all of which consume diesel and electricity. Moreover, the screening and washing of aggregates such as sand and gravel contribute significantly to energy demand. Even the production or collection of SCMs like fly ash, a by-product of coal combustion, involves emissions from the drying process or transport from power plants. Therefore, in the first stage, the selection and quantity

of raw materials directly impact the carbon footprint of the final product. Utilizing locally sourced materials, recycled aggregates, or low-carbon alternatives could significantly reduce emissions during this phase. The second phase involves the movement of raw materials from their extraction sites to the manufacturing facility. This stage primarily contributes to CO_2 emissions through the use of fossil fuel-powered vehicles, such as diesel trucks, which are commonly used to transport heavy construction materials. The environmental impact of this phase is influenced by factors such as distance traveled, mode of transport, fuel type, and load efficiency. In Life Cycle Assessment (LCA) for construction products, it is necessary to accurately capture these details to quantify the overall carbon footprint and environmental impact of the product system. The third phase encompasses all processes that transform raw materials into the final construction product at the factory. It consists of activities such as mixing, processing, casting, and curing concrete, as well as any energy or water used during production. This phase is often one of the most energy-intensive phases of the life cycle, especially for materials like cement, which produce high CO_2 emissions due to both fuel combustion and chemical processes, such as calcination. The concrete mix design is essential as it defines the proportions and types of materials (cement, aggregates, water, admixtures, and SCMs) used to create concrete. Optimizing the concrete mix design by reducing cement content, incorporating supplementary cementitious materials (SCMs), or using effective admixtures could significantly decrease the carbon footprint and resource intensity during the manufacturing stage.

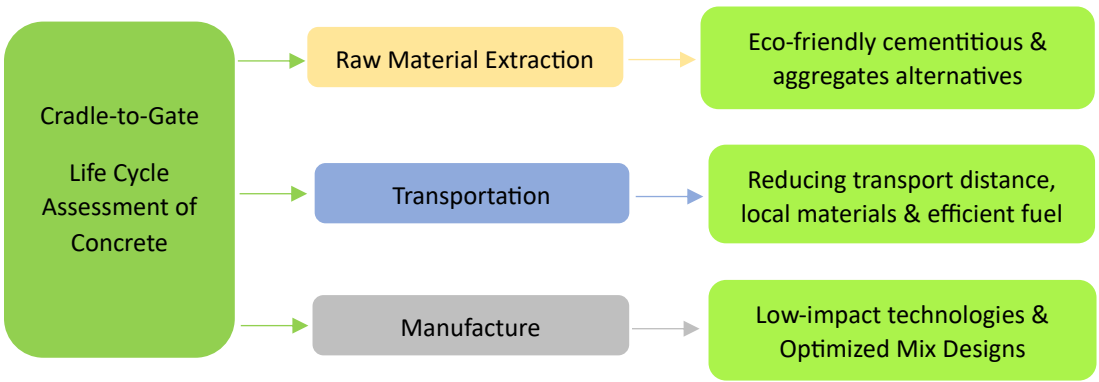


Figure 2. Product Phases (Cradle-to-Gate) of Life Cycle Assessment of Concrete with Potentially Carbon Footprint Mitigation Measures [Author].

To calculate the carbon impact of a concrete mixture, it is necessary to initially determine the quantity of each material used in the mix design. Subsequently, for each constituent, it is necessary to select an appropriate Embodied Carbon ($kgCO_2e/kg$), which accurately reflects its environmental impact. Figure 3 shows CO_2 emissions for the raw materials used in this study.

Each material's quantity must then be multiplied by its corresponding carbon factor to determine the individual carbon impact. Ultimately, the total carbon footprint of the concrete mixture could be obtained by summing the carbon impacts of all constituents [31].

Carbon impact of a concrete mix = ∑ Quantity of each constituent (kg/m^3) × carbon emission factor for constituent (kgCO_2e/kg) (1)

The reduction in carbon emissions between mixes could be calculated by comparing them to a baseline concrete. The calculation of the reduction is as follows [31].

$$\text{Carbon reduction (\%)} = [1 - (\frac{\text{Carbon impact of reduced carbon mix}}{Carbon\ impact\ of\ baseline\ mix})] \times 100 \quad (2)$$

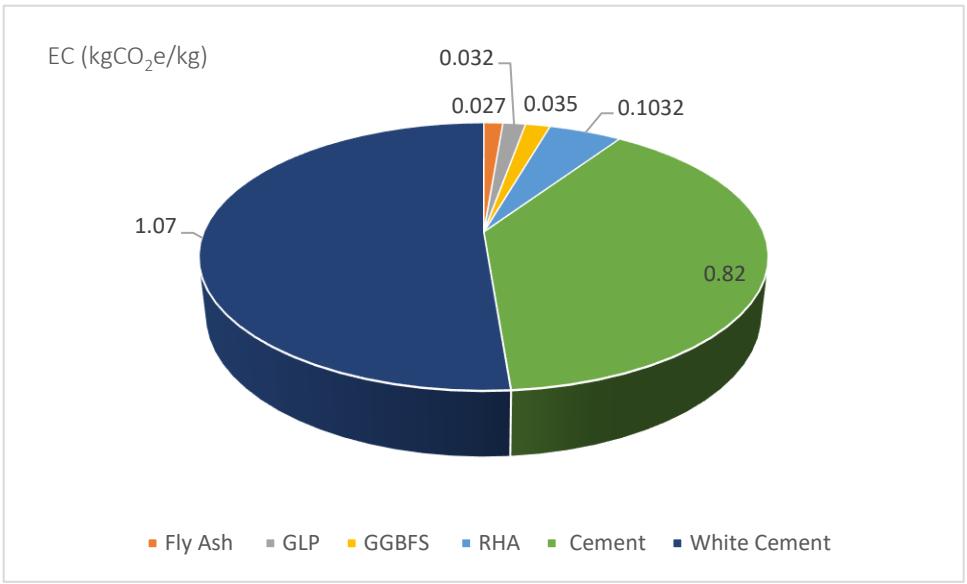


Figure 3. Embodied Carbon (kgCO_2e/kg) of various binder materials based on Table 1. Sources: created based on [32, 33, 34, 35]

4. EVALUATING THE ENVIRONMENTAL IMPACT OF VARIOUS CONCRETE MIXTURES INCORPORATING ALTERNATIVE MATERIALS

Comparisons of the environmental impact of different concrete mixes have been carried out by considering the major parameters as quantities of raw materials required to produce 1 m^3 of concrete. Table 1 provides the raw material quantities required for 1 m^3 of each concrete mix. It presents five different concrete mix designs, each incorporating various combinations of binder and aggregate materials to explore alternative and sustainable compositions. Sample 1 is a conventional mix using only ordinary Portland cement (OPC), while Sample 2 entirely replaces OPC with a blend of fly ash and GGBFS, highlighting a low-carbon approach. Sample 3 combines a reduced amount of OPC with a high proportion of GGBFS, aiming for sustainability. Sample 4 introduces rice husk ash (RHA) as a partial cement replacement, promoting pozzolanic activity. Finally, Sample 5 uses white cement with ground limestone powder. Although white cement has a higher energy demand and carbon intensity than OPC, the inclusion of limestone powder helps mitigate some of the

environmental impact. All mixes maintain comparable aggregate and water content to ensure consistency in performance testing.

Table 1. Dosage of concrete components for 1 m^3 of concrete. Sources: created based on [36,37,38,39]

Mixture	Cement (kg)	White Cement (kg)	Fly Ash (kg)	GGBFS (kg)	RHA (kg)	Ground Limestone Powder (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Water (kg)
Sample 1	360	0	0	0	0	0	1027	775	180
Sample 2	0	0	150	150	0	0	1365	585	150
Sample 3	90	0	0	270	0	0	1027	775	180
Sample 4	280	0	0	0	70	0	1023	837	140
Sample 5	0	407.9	0	0	0	102.0	1029.7	745.8	158.1

For the concrete mix design presented in Table 1, the CO_2 emission has been calculated according to Formula 1 to assess the environmental impact. For the calculation of CO_2 emission, the basic values of each raw material have been considered in various studies.

Table 2. CO_2 Emission by Raw Materials for 1m^3 of concrete Sources: created based on [32,33,34,35]

Material's	EC ($kgCO_2e/kg$)	Actual CO_2 Emission from 1 m^3 concrete				
		Sample1 (baseline mix)	Sample 2	Sample 3	Sample 4	Sample 5
Cement	0.82	295.2	0	73.8	229.6	0
White Cement	1.07	0	0	0	0	436.45
Fly Ash	0.027	0	4.05	0	0	0
GGBFS	0.035	0	5.25	9.45	0	0
RHA	0.1032	0	0	0	7.2	0
GLP	0.032	0	0	0	0	3.26
Coarse Aggregate	0.0408	41.9	55.7	41.9	41.7	42.01
Fine Aggregate	0.0139	10.77	8.13	10.8	11.6	10.36
Total Carbon impact of different mixes (kgCO2e/m3)		347.87	73.13	135.95	290.1	492.08

Table 2 displays the CO_2 emissions per cubic meter of concrete for five distinct mix designs, based on individual raw materials' emission coefficients (EC). Sample 1, which consists of a baseline mix utilizing 360 kg of Ordinary Portland Cement (OPC), results in an emission of 347.87 kg CO_2 equivalent per cubic meter ($kgCO_2e/m^3$). Cement is the primary contributor to these emissions, accounting for the majority at 295.2 $kgCO_2e$. Sample 2, which replaces cement entirely with fly ash and GGBFS, demonstrates a remarkable reduction in emissions, reaching just 73.13 $kgCO_2e/m^3$. This makes it an excellent choice for environmentally conscious construction, highlighting its potential as a sustainable alternative. Sample 3, combining 90 kg of OPC and 270 kg of GGBFS, results in emissions of 135.95 $kgCO_2e/m^3$. This level is still below the baseline, indicating a positive step toward reducing overall emissions. Sample 4, which includes rice husk ash (RHA) as a partial replacement, shows a total emissions level of 290.1 $kgCO_2e/m^3$. It's important to note that RHA replaced 20% of the cement by weight, significantly contributing to the reduction of CO_2 emissions. Sample 5 recorded the highest emissions at 492.08 $kgCO_2e/m^3$, primarily due to the use of white cement, which alone contributed 436.45 $kgCO_2e$. While the inclusion of ground limestone powder, which has a low CO_2 emission factor of 0.032 kg CO_2/kg, helps decrease overall CO_2 emissions, the use of white cement, which has a higher emission coefficient compared to ordinary Portland cement (OPC), ultimately results in a significantly larger carbon footprint. This highlights the importance of material selection in minimizing the environmental impact of concrete production. Figure 4. Shows Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various concrete mixes.

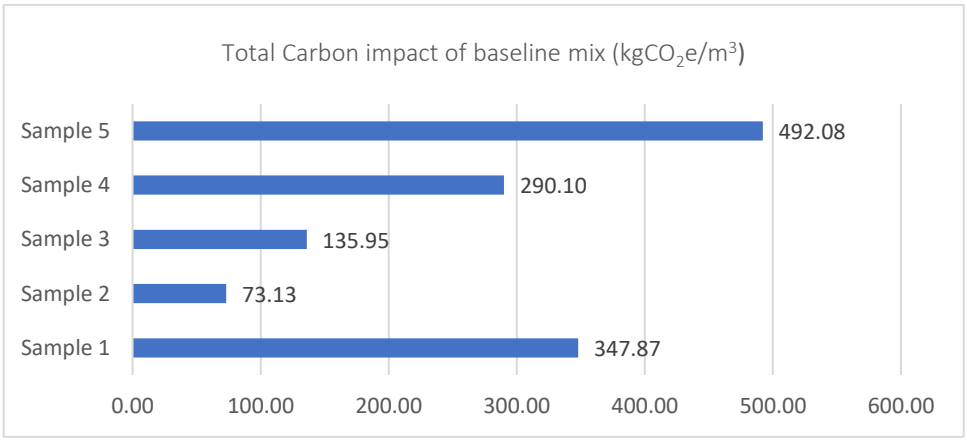


Figure 4. Cradle-to-Gate (A1–A3) Life Cycle Assessment (LCA) approach for comparative analysis of the environmental impacts of various concrete mixes.

Figure 5 illustrates the carbon reduction percentages of various concrete samples relative to a baseline concrete (Sample 1). The baseline exhibits a 0% carbon reduction, serving as the reference point. Sample 2 demonstrates the highest carbon reduction at 78.97%, followed by Sample 3 with a decrease of 60.91%, and Sample 4 with a modest reduction of 16.6%. These samples are indicated with green bars, signifying positive environmental performance. In contrast, Sample 5 exhibits a carbon increase of 41.45% compared to the baseline, as depicted by the red bar, indicating a detrimental impact on carbon emissions. The accompanying table below the chart provides a clear numerical summary of these results. Overall, the figure emphasizes the variability in carbon performance across different

concrete formulations, highlighting the serious importance of material selection for sustainable construction.

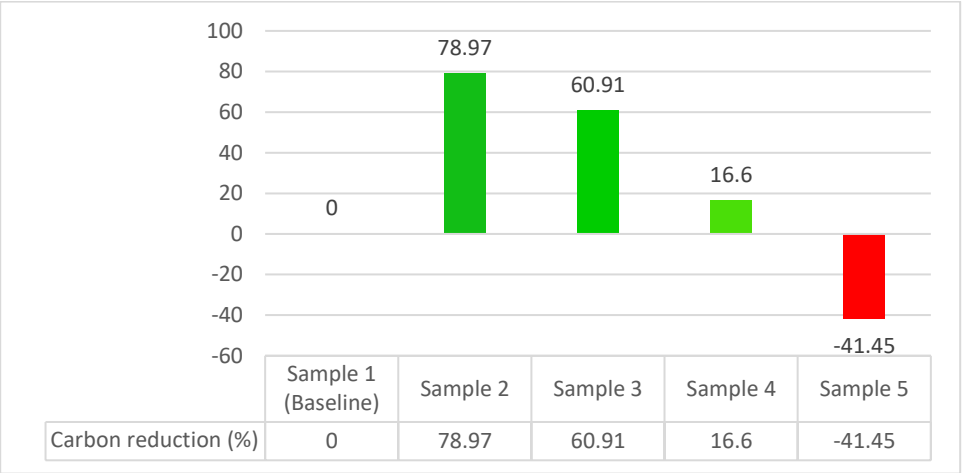


Figure 5. Carbon reduction compared to baseline concrete

5. CONCLUSIONS

In summary, low-carbon concrete is essential for improving sustainable construction and environmental responsibility by reducing carbon emissions and improving resource efficiency. This study highlights the cradle-to-gate embodied carbon emissions of concrete mixtures designed with various binders such as Cement, White Cement, Fly Ash, GGBFS, RHA, GLP, and compares them with each other, showing the way forward in reducing the environmental impact of concrete production to combat climate change. Significant variations in carbon emissions are directly associated with the choice of raw materials in concrete mixtures. The findings from the carbon reduction analysis and CO_2 emission data demonstrate the substantial influence of raw material selection on the environmental performance of concrete. Samples incorporating supplementary cementitious materials, such as ground granulated blast furnace slag (GGBFS), fly ash, and rice husk ash (RHA), exhibited significant reductions in carbon emissions compared to the baseline concrete mix. Specifically, Sample 2 achieved the highest carbon reduction of 78.97%, with the lowest total carbon footprint of 73.13 $kgCO_2e/m^3$, highlighting the effectiveness of using industrial by-products in sustainable concrete design. Sample 4 achieved only a modest reduction (16.6%), mainly because of the limited substitution and the introduction of RHA, while maintaining a moderate total emission level (290.1 $kgCO_2e/m^3$). Conversely, Sample 5, which utilized white cement with a high embodied carbon value (1.07 $kgCO_2e/kg$), led to a 41.45% increase in emissions, reaching a total of 492.08 $kgCO_2e/m^3$. Although ground limestone powder was combined into Sample 5, contributing a relatively low embodied carbon value (0.032 $kgCO_2e/kg$), its positive environmental effect was minimal due to the enormous carbon impact of the high white cement content. Overall, these results emphasize that replacing ordinary Portland cement with suitable alternative binders is significant in dramatically decreasing the carbon footprint of concrete. Careful and balanced selection of materials is essential for advancing the development of low-carbon and environmentally sustainable concrete formulations.

REFERENCES

[1] Van den Heede, P., & De Belie, N.: **Environmental Impact and Life Cycle Assessment (LCA) of Traditional and 'Green' Concretes: Literature Review and Theoretical Calculations**. *Cement and Concrete Composites*, 34(4), 431–442, 2012, https://doi.org/10.1016/j.cemconcomp.2012.01.004.

[2] Limbachiya, M., Meddah, M. S., & Ouchagour, Y.: **Use of recycled concrete aggregate in fly-ash concrete**. *Construction and Building Materials*, 27(1), 439–449, 2012, https://doi.org/10.1016/j.conbuildmat.2011.07.023.

[3] Colomer Mendoza, F. J., Altabella, J. E., & Gallardo Izquierdo, A.: **Application of inert wastes in the construction, operation and closure of landfills: Calculation tool**. *Waste Management*, 59, 276–285, 2017, https://doi.org/10.1016/j.wasman.2016.10.041.

[4] Jiménez, C., Barra, M., Josa, A., & Valls, S.: **LCA of Recycled and Conventional Concretes Designed Using the Equivalent Mortar Volume and Classic Methods**. *Construction and Building Materials*, 84, 245–252, 2015, https://doi.org/10.1016/j.conbuildmat.2015.03.051.

[5] Ali Akhtar, Ajit K. Sarmah, **Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective**, *Journal of Cleaner Production*, Volume 186, 2018, Pages 262-281, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.03.085.

[6] Kaewunruen, S., Sresakoolchai, J., & Zhou, Z.: **Sustainability-Based Lifecycle Management for Bridge Infrastructure Using 6D BIM**. *Sustainability*, 12(6), 2436, 2020, https://doi.org/10.3390/su12062436.

[7] Arenas, N.F., & Shafique, M.: **Reducing Embodied Carbon Emissions of Buildings – A Key Consideration to Meet the Net Zero Target**. *Sustainable Futures*, 7, 100166, 2024, https://doi.org/10.1016/j.sftr.2024.100166.

[8] Gu, L., Zhou, Y., Mei, T., Zhou, G., & Xu, L.: **Carbon Footprint Analysis of Bamboo Scrimber Flooring—Implications for Carbon Sequestration of Bamboo Forests and Its Products**. *Forests*, 10(1), 51, 2019, https://doi.org/10.3390/f10010051.

[9] Fernandes, J., Peixoto, M., Mateus, R., & Gervásio, H.: **Life Cycle Analysis of Environmental Impacts of Earthen Materials in the Portuguese Context: Rammed Earth and Compressed Earth Blocks**. *Journal of Cleaner Production*, 241, 118286, 2019, https://doi.org/10.1016/j.jclepro.2019.118286.

[10] Barbhuiya, S., Kanavaris, F., Das, B.B., & Idrees, M.: **Decarbonising Cement and Concrete Production: Strategies, Challenges and Pathways for Sustainable Development**. *Journal of Building Engineering*, 86, 108861, 2024, https://doi.org/10.1016/j.jobe.2024.108861.

[11] Collivignarelli, M.C., Cillari, G., Ricciardi, P., Carnevale Miino, M., Torretta, V., Rada, E.C., & Abbà, A.: **The Production of Sustainable Concrete with the Use of Alternative Aggregates: A Review**. *Sustainability*, 12(19), 7903, 2020, https://doi.org/10.3390/su12197903.

[12] Agrela, F., Rosales, M., López Alonso, M., Ordóñez, J., & Cuenca-Moyano, G.M.: **Life-Cycle Assessment and Environmental Costs of Cement-Based Materials Manufactured with Mixed Recycled Aggregate and Biomass Ash**. *Materials*, 17(17), 4357, 2024, https://doi.org/10.3390/ma17174357.

[13] Manjunatha, M., Preethi, S., Malingaraya, H.G., Mounika, K.N., Niveditha, K.N., & Ravi: **Life Cycle Assessment (LCA) of Concrete Prepared with Sustainable Cement-Based Materials**. *Materials Today*: Proceedings, 47(13), 3637–3644, 2021, https://doi.org/10.1016/j.matpr.2021.01.248.

[14] Althoey, F., Ansari, W.S., Sufian, M., & Deifalla, A.F.: **Advancements in Low-Carbon Concrete as a Construction Material for the Sustainable Built Environment**. *Developments in the Built Environment*, 16, 100284, 2023, https://doi.org/10.1016/j.dibe.2023.100284.

[15] Al-Gheethi, A.A., Memon, Z.A., Balasbaneh, A.T., Al-Kutti, W.A., Mokhtar, N., Othman, N., Juki, M.I., Noman, E.A., & Algaifi, H.A.: **Critical Analysis for Life Cycle Assessment of Bio-Cementitious Materials Production and Sustainable Solutions**. *Sustainability*, 14(3), 1920, 2022, https://doi.org/10.3390/su14031920.

[16] Chairani, R., Adinda, A.R., Fillipi, D., Jatmoko, M., & Suryawan, I.W.K.: **Environmental Impact Analysis in the Cement Industry with Life Cycle Assessment Approach**. *JTERA (Jurnal Teknologi Rekayasa)*, 2021, https://api.semanticscholar.org/CorpusID:237380063.

[17] Xing, W., Tam, V.W.Y., Le, K.N., Hao, J.L., & Wang, J.: **Life Cycle Assessment of Recycled Aggregate Concrete on Its Environmental Impacts: A Critical Review**. *Construction and Building Materials*, 317, 125950, 2022, https://doi.org/10.1016/j.conbuildmat.2021.125950.

[18] Pillai, R.G., Gettu, R., Santhanam, M., Rengaraju, S., Dhandapani, Y., Rathnarajan, S., & Basavaraj, A.S.: **Service Life and Life Cycle Assessment of Reinforced Concrete Systems with Limestone Calcined Clay Cement (LC3)**. *Cement and Concrete Research*, 118, 111–119, 2019, https://doi.org/10.1016/j.cemconres.2018.11.019.

[19] Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., & Pennington, D.W.: **Life Cycle Assessment: Part 1: Framework, Goal and Scope Definition, Inventory Analysis, and Applications**. *Environment International*, 30(5), 701–720, 2004, https://doi.org/10.1016/j.envint.2003.11.005.

[20] Curran, M.A.: **Life Cycle Assessment: A Review of the Methodology and Its Application to Sustainability**. *Current Opinion in Chemical Engineering*, 2(3), 273–277, 2013, https://doi.org/10.1016/j.coche.2013.02.002.

[21] Gaurav, G., Singh, A.B., Mistry, S., Gupta, S., Dangayach, G.S., & Meena, M.L.: **Recent Progress of Scientific Research on Life Cycle Assessment**. *Materials Today: Proceedings*, 47(11), 3161–3170, 2021, https://doi.org/10.1016/j.matpr.2021.06.208.

[22] Yang, Y.: **A Unified Framework of Life Cycle Assessment. International Journal of Life Cycle Assessment**, 24, 620–626, 2019, https://doi.org/10.1007/s11367-019-01595-w.

[23] Akintayo, B.D., Babatunde, O.M., & Olanrewaju, O.A.: **Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach**. *Sustainability*, 16(2), 484, 2024, https://doi.org/10.3390/su16020484.

[24] Paknahad, C., Tohidi, M., & Bahadori-Jahromi, A.: **Improving the Sustainability of Reinforced Concrete Structures through the Adoption of Eco-Friendly Flooring Systems**. *Sustainability*, 17(7), 2915, 2025, https://doi.org/10.3390/su17072915.

[25] **ISO, ISO 14044 environmental management- Life cycle assessment- Requirements and guidelines**. *International Organization for Standardization*, Geneva, Switzerland, 2006.

[26] Vieira, D.R., Calmon, J.L., & Coelho, F.Z.: **Life Cycle Assessment (LCA) Applied to the Manufacturing of Common and Ecological Concrete: A Review**. *Construction and Building Materials*, 124, 656–666, 2016, https://doi.org/10.1016/j.conbuildmat.2016.07.125.

[27] Gursel, A.P., Masanet, E., Horvath, A., & Stadel, A.: **Life-Cycle Inventory Analysis of Concrete Production: A Critical Review**. *Cement and Concrete Composites*, 51, 38–48, 2014, https://doi.org/10.1016/j.cemconcomp.2014.03.005.

[28] Abd Rashid, A.F., & Yusoff, S.: **A Review of Life Cycle Assessment Method for Building Industry**. *Renewable and Sustainable Energy Reviews*, 45, 244–248, 2015, https://doi.org/10.1016/j.rser.2015.01.043.

[29] Ismail, L., Abdel Razik, M., Ateya, E., et al.: **Optimizing Sustainable Concrete Mixes with Recycled Aggregate and Portland Slag Cement for Reducing Environmental Impact**. *Discovery Materials*, 4, 68, 2024, https://doi.org/10.1007/s43939-024-00136-z.

[30] Tait, M.W., & Cheung, W.M.: **A Comparative Cradle-to-Gate Life Cycle Assessment of Three Concrete Mix Designs**. *International Journal of Life Cycle Assessment*, 21, 847–860, 2016, https://doi.org/10.1007/s11367-016-1045-5.

[31] Department of Climate Change, Energy, the Environment and Water (DCCEEW): **How to Calculate Embodied Carbon of a Concrete Mix**: *Fact Sheet*. Rev 01 May 2024, New South Wales: Department of Climate Change, Energy, the Environment and Water. 2024.

[32] Patil, S., Joshi, D., Menon, R., & Wadhwa, L.K.: **Environmental Impact Assessment of Fly Ash and GGBS Based Geopolymer Concrete in Road Construction**. *E3S Web of Conferences*, 405, 03021, 2023, https://doi.org/10.1051/e3sconf/202340503021.

[33] Ozturk, E., Ince, C., Derogar, S., & Ball, R.: **Factors Affecting the CO_2 Emissions, Cost Efficiency and Eco-Strength Efficiency of Concrete Containing Rice Husk Ash: A Database Study**. *Construction and Building Materials*, 326, 126905, 2022, https://doi.org/10.1016/j.conbuildmat.2022.126905.

[34] Jungclaus, M.A., Williams, S.L., Arehart, J.H., & Srubar, W.V.: **Whole-Life Carbon Emissions of Concrete Mixtures Considering Maximum CO_2 Sequestration via Carbonation**. *Resources, Conservation and Recycling*, 206, 107605, 2024, https://doi.org/10.1016/j.resconrec.2024.107605.

[35] Hammond, G. P., and C. I. Jones.: **Embodied energy and carbon in construction materials**. *Proc. Instn Civil. Engrs: Energy*, 2008, in press

[36] Huo, Y., Huang, J., Han, X., Sun, H., Liu, T., Zhou, J., & Yang, Y.: **Mass GGBFS Concrete Mixed with Recycled Aggregates as Alkali-Active Substances: Workability, Temperature History and Strength**. *Materials*, 16(16), 5632, 2023, https://doi.org/10.3390/ma16165632.

[37] Machowska, A.: **The Properties of Mass Concrete with CFBC Fly Ash-Slag Binder**. *Archives of Civil Engineering*, 66(4), 471–484, 2020, https://doi.org/10.24425/ace.2020.135232.

[38] Afsoosbiria, H., & Afsoosbiria, H.: **Mechanical Properties and Durability Assessment of Sustainable Green Concrete Incorporated with Rice Husk Ash as Partial Replacement of Cement**. *Transactions of VSB - Technical University of Ostrava, Civil Engineering Series*, 24(1), 2024.

[39] Xia, J., Cao, C., Jiang, Z., Ren, Q., Zhang, Y., Wang, J., & Leng, F.: **Design and Preparation of White High-Strength Concrete with Ground Limestone Powder by Means of Response Surface Methodology**. *Materials*, 15(9), 3359, 2022, https://doi.org/10.3390/ma15093359.

doi.org/10.62683/SINARG2025.049

Research paper

MULTI-FAMILY HOUSING IN SKOPJE DURING THE PERIOD OF MODERNISM FROM 1945 – 1980.

Nataša Matić[1]

Abstract

In the post-war period, Skopje became a modern and functional city, divided into zones for basic functions, with a large number of built multi-family residential buildings under the influence of the world Modern movement. However, this period of construction was interrupted by the catastrophic floods in 1962, followed by an earthquake in 1963. The city was rebuilt in the spirit of Modernism and the world's architectural avant-garde of the time. The focus of this research is on the functional and design characteristics of multi-family residential buildings built in the later period of Skopje Modernism. These events created two periods of intensified construction of Skopje – first one could be marked as development between two wars, from 1945 to 1963, and the second one is reconstruction of the city after earthquake – which created first detailed modernization of Skopje. The primary goal of this research is the analysis of the physical and functional aspects of these facilities and the assessment of how well they fit into the established criteria model. The results of this assessment can then be used to inform future design decisions and better understand the relationship between typology and design.

Key words: *Multi-family housing, Modern architecture, Analysis, Function, Typology*

[1] M.Sc., PhD Candidate, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, nmatic.arch@gmail.com, ORCID N/A

1. INTRODUCTION

The architectural transformation of Skopje in the decades following the Second World War represents a pivotal chapter in the city's urban and cultural development. The immediate post-war period marked the beginning of intensive construction efforts aimed at rebuilding and modernizing the urban fabric. However, it was the devastating floods in 1962, followed by earthquake of 1963 that catalyzed a more comprehensive and large-scale reconstruction, positioning Skopje as a focal point of architectural and urban experimentation within the broader context of socialist Yugoslavia. This period of renewal not only shaped the city's physical landscape but also reflected the ideological, social, and cultural currents of its time.

This dissertation aims to explore and critically assess the architectural legacy of multi-family residential buildings constructed in Skopje during the post-war modernist era, with particular emphasis on the period between 1945 and 1980. Special attention is given to developments following the 1963 earthquake, which introduced a new scale and urgency to residential construction. The study will identify and valorize characteristic residential typologies, offering a detailed classification and typological analysis. Furthermore, it will investigate the architectural form, structural systems, and spatial organization of selected buildings, situating them within the broader theoretical discourse on late modernism and urban planning in socialist contexts [1]. The architectural phenomena under study will be examined not only as physical structures but as cultural and historical artifacts that embody the socio-political narratives of their time. Through a combination of archival research, field analysis, and case study methodology, representative examples will be critically evaluated to uncover the values and intentions embedded in their design and construction.

A notable illustration of Skopje's authentic architectural identity across two key historical phases can be observed within the central urban area through two distinct examples of collective residential housing. The first, commonly referred to as the "Aegean Buildings," was constructed in the early 1950s, while the second, the "City Wall" residential and commercial complex, emerged decade later during the post-earthquake reconstruction era. These two architectural entities will serve as case studies, each representing a typological model corresponding to their respective periods of development. In addition to the in-depth examination of these selected buildings, a detailed systematization of their architectural components and elements will be conducted, contributing to the objective and comprehensive analysis of the research subject.

2. MULTI-FAMILY RESIDENTIAL BUILDINGS IN THE FRAMEWORK OF THE CENTRAL CITY CORE

Integral to the reshaping of the city center was the introduction of multi-family residential complexes that embodied these modernist ideals. Notable among these were the City Wall and the Aegean Buildings, two large-scale residential interventions strategically located within the heart of Skopje (Figure 1). These complexes were not conceived as isolated housing units, but were integrated into a broader urban composition, framing major boulevards and defining the spatial character of the new city core. The City Wall complex formed a modern reinterpretation of a traditional defensive perimeter, while the Aegean Buildings articulated dense residential corridors along the reconstructed grid, both contributing to the consolidation of the urban structure.

By combining residential functions with public spaces, commercial uses, and pedestrian connectivity, these projects exemplified a holistic approach to urban living. Multi-family residential architecture thus played a pivotal role in both the physical reconstruction and the symbolic modernization of Skopje, establishing a resilient, functional, and socially cohesive urban core.

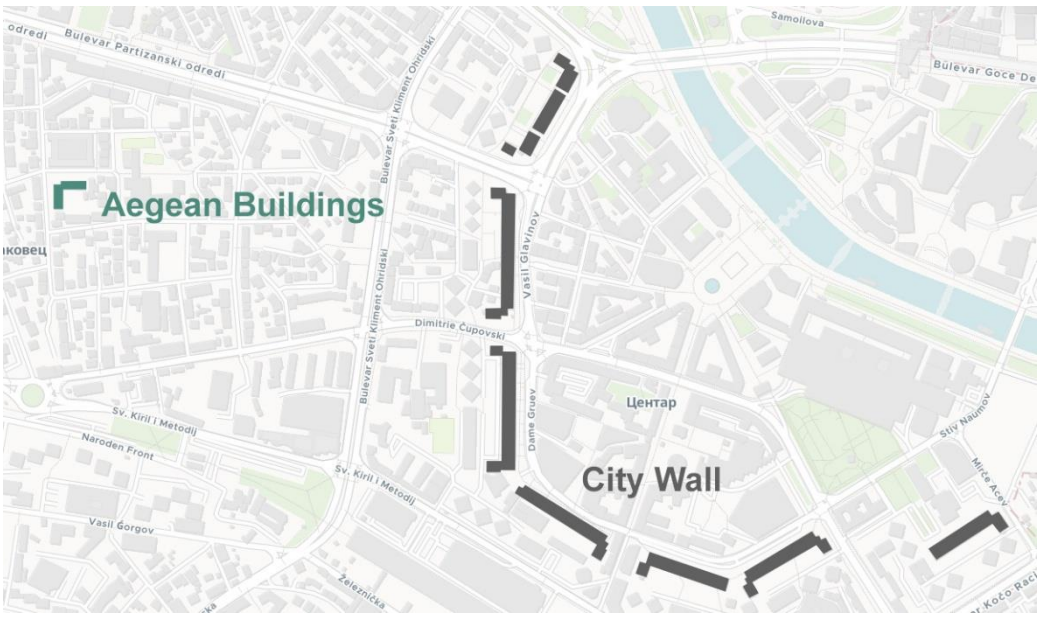


Figure 1. Schematic representation of the selected buildings in the city center (Source: author)

3. CASE STUDIES

3.1. Case study 1 – „Aegean Buildings“, a collective housing on the Borka Taleski street in Skopje

In the period immediately following the conclusion of the Second World War, Skopje—as well as the broader region of Macedonia—witnessed a significant surge in the construction of collective residential housing. Characteristic of this early post-war phase was the emergence of grouped low-rise buildings, typically limited to a maximum of four stories, marking the initial steps in the organized development of multi-family housing. The new collective housing projects were largely influenced by functionalist and rationalist approaches, prioritizing economy of space, structural efficiency, and standardized forms. These developments were frequently situated within newly planned urban neighborhoods, where attention was given to communal green spaces and proximity to essential infrastructure, in accordance with the principles of the Athens Charter.

During the 1950s, architectural design began to shift from purely utilitarian forms toward a more refined expression of modernist aesthetics. Architects in Skopje, while still operating under centralized planning frameworks, gradually introduced localized elements into their designs, contributing to a nascent architectural identity that combined international modernism with regional specificity.

3.1.1. Architectural-Urban Structure

The Aegean Buildings, completed in 1951, represent a significant example of post-war residential architecture in Skopje. According to resident accounts, the complex was initially intended to house refugees displaced by the Greek Civil War (1946–1949). Despite their architectural significance, architect responsible for designing the Aegean Buildings remains unidentified in available records. The architectural composition consists of two elongated volumes arranged orthogonally, with a slight misalignment at their intersection, resulting in a softened transition rather than a rigid angular junction.

The buildings are set back approximately six meters from the property boundary, establishing a spatial buffer that enhances the sense of privacy and separation from the surrounding urban environment. This semi-public zone, further enriched with planted greenery, contributes to the creation of a calm and secluded atmosphere (Figure 2). Each volume measures approximately 10 meters in width and 35 meters in length, and contains two separate access points, each serving four residential units. In total, the complex comprises 16 units. Despite its central location within the urban fabric of Skopje, the overall low density and strategic orientation of the buildings foster a distinct sense of domestic tranquility and spatial intimacy.

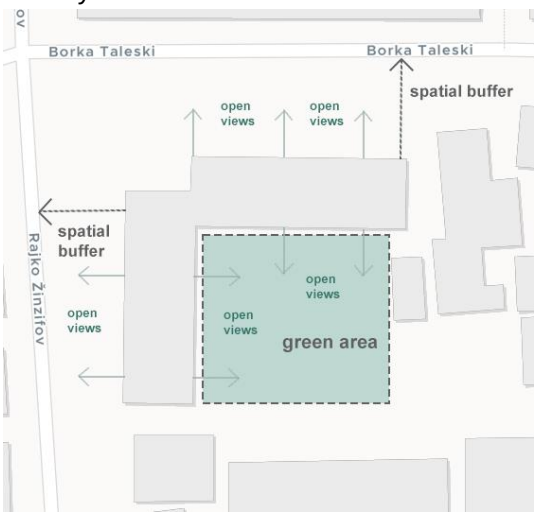


Figure 2. Schematic representation of architectural - urban structure (Source: author)

3.1.2. Detail

Architectural detailing in the Aegean Buildings reflects the principles of mid-20th-century modernism, with a strong emphasis on clarity of function and material honesty. A defining visual and functional feature is the treatment of the entrances and stairwells, which are punctuated by prefabricated circular openings—an element that recurs in the design of the original wooden entrance doors (Figure 3). This motif not only offers aesthetic value but also contributes to the modulation of light and ventilation within the common areas.

The preservation of these original architectural elements throughout the building is particularly noteworthy, given the passage of time and ongoing use. The front façade is distinguished by continuous terraces and prominent stairwells, which span the length of the residential units, aligning with the location of principal living spaces [2]. The exterior is finished with a natural cement plaster, providing a neutral and robust surface, while the recessed

sections of the façade are rendered in a light yellow tone, introducing visual contrast and enhancing the overall lightness of the elevation.

The roof is constructed using a traditional pitched solution, enabling the integration of attic spaces for each unit. These are typically used for additional storage, further optimizing the functionality of the spatial layout.

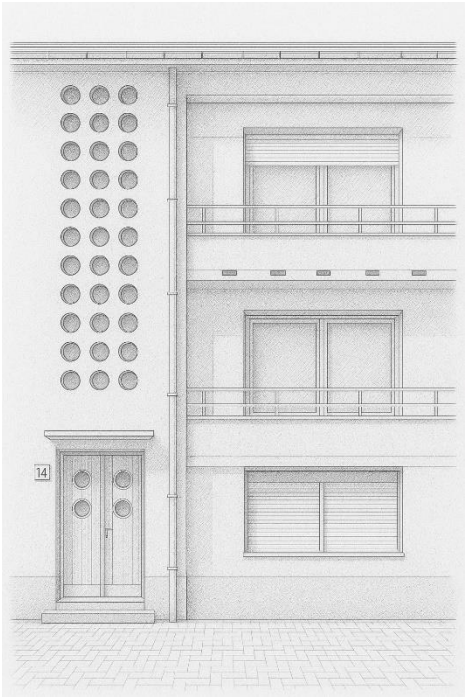


Figure 3. Part of north façade of residential building - facing the Borka Taleski street (Source: author)

3.1.3. Functional organization

The design approach of the Aegean Buildings is grounded in the principles of functionalism, characteristic of the architectural trends of the 1950s. Rooted in the belief that architectural form should be primarily guided by practical utility, functionalism emerged as a critical response to both pre-war eclecticism and the decorative excesses of earlier styles. During this era, functionality was not only a technical concern but also a moral imperative, aligning closely with the Modernist ethos of rationality, simplicity, and honesty in material expression. This means that every component of the building serves a clearly defined purpose, reflecting a commitment to utility and spatial efficiency. The internal configuration of the residential units follows a rational and efficient layout [3].

Each apartment includes a semi-subterranean basement, which is elevated slightly above ground level to accommodate windows that allow for natural light penetration. This design strategy facilitates a raised ground floor, enhancing the living conditions in terms of light and air quality.

Residential units are functionally organized, with service spaces—such as bathrooms, separate toilets, and kitchens (including pantries)—located towards the rear of the units. This zoning strategy delineates private and utility areas from the primary living zones situated at the front, which benefit from direct access to the terraces. The inclusion of attic spaces further

contributes to the practical functionality of the units, offering supplementary storage without disrupting the spatial logic of the living areas (Figure 4).

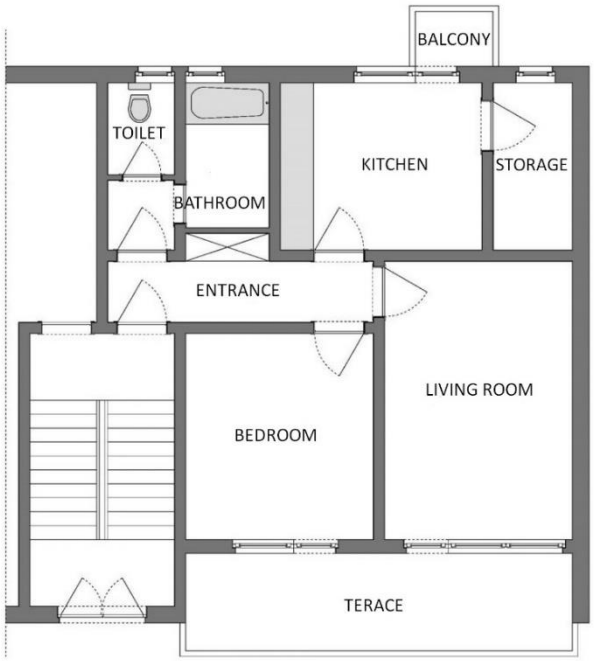


Figure 4. Characteristic layout of living space (Source: author)

Owing to the relatively shallow depth of the building tract, the apartments benefit from dual orientation, extending along both the north–south and east–west axes. A notable architectural feature is the deliberate minimization of corridor spaces, with circulation areas limited primarily to the entrance zone. This design approach reflects an emphasis on spatial efficiency and a commitment to maximizing the usable floor area.

3.2. Case study 2 – "City Wall", residential and building complex that encircles the city center in Skopje

The reconstruction efforts gained a new dimension following the 1963 earthquake, which devastated large parts of the city. This event not only accelerated urban renewal but also provided opportunities for international collaboration, most notably through the United Nations-supported master plan led by the Japanese architect Kenzo Tange. In the wake of this disaster, Skopje became a testing ground for advanced architectural experimentation and urban planning, further solidifying its role in shaping late modernist architecture in the region. One of best examples for that is residential complex called City Wall, built in the 1966-1968 period by group of authors. Authors of horizontal blocks are Nikola Bogachev, Slavko Đurić, Ljubinka Malenkova, Aleksandar Serafimovski, Simeon Simoski and Vera Kosevska, author of type B tower blocks is Aleksandar Smilevski and authors of type M tower blocks are Aleksandar Serafimovski, Vasilka Ladinska, Dimitar Dimitrov, Rosanda Minčeva and Slavko Đurić.

3.2.1. Architectural-Urban Structure

As a fundamental component of the city center, the proposed composition strategically emphasizes and encircles the urban core, with the positioning of buildings situated on the eastern bank of the Vardar River. The urban perimeter is delineated by a modern reinterpretation of a ring-wall system, composed of interconnected block structures (P+6, height 24 meters) and vertical tower elements (P+12, height 45 meters) (Figures 5 and 6).

The intervention within the City Wall area aimed to reconfigure the fragmented urban fabric by integrating the temporal layers of the city center and enhancing the visual and physical qualities of the zone where two distinct urban matrices intersect [4]. The spatial strategy involved the careful placement of towers and blocks, which introduced formal diversity while simultaneously reinforcing the cohesion of the urban structure (Figure 5). The towers were systematically organized into clusters of two or three and positioned along streets intersecting the linear formation of blocks adjacent to the inner ring-road, creating a rhythmic and dynamic urban edge.

The dual-structured arrangement predominantly faces the inner ring-road, with the principal entrances of residential and commercial spaces oriented accordingly. The inner portion of the composition remains largely pedestrianized, ensuring a contrast between the vehicular outer boundary and the tranquil, community-focused inner spaces.

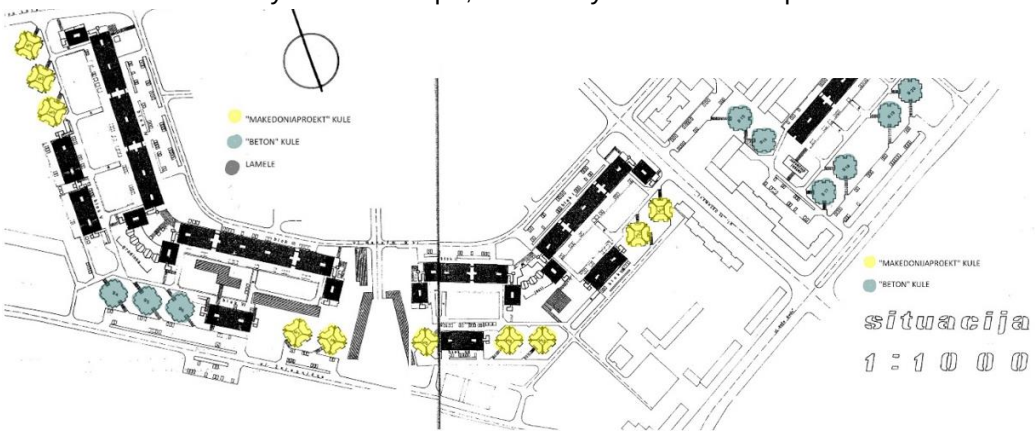


Figure 5. Ground floor situation and position of the complex with context (Source: Master plan for Skopje, 1965, edited by author)

A network of pedestrian passages connects these zones, often tracing the alignments of the historic street grid and facilitating a smooth transition from public to semi-public spaces within the residential ensemble.

While the use of two distinct building types introduced architectural variety, the primary rationale for the inclusion of towers was to improve cross-ventilation within the dense urban environment. By breaking the massing of the blocks and facilitating airflow, the towers significantly contributed to the environmental comfort of the area [5].

3.2.2. Detail

The architectural expression of the City Wall residential complex is characterized by a restrained yet dynamic treatment of the façade, which reflects the modernist principles underlying the overall urban concept. The use of modular elements and rhythmic fenestration

patterns reinforces the compositional clarity of the building volumes while introducing a sense of human scale across the expansive urban perimeter [6].

The façade articulation is deliberately minimalistic, employing horizontal and vertical divisions that accentuate the linearity of the blocks and the verticality of the towers. Balconies, window groupings, and subtle reliefs in the surface treatment contribute to a carefully modulated play of light and shadow, enhancing the visual depth of the elevations without resorting to excessive ornamentation (Figure 6).



Figure 6. 3D model of City wall tower (Source: collective MEELEM, made in Revit)

Materiality plays a crucial role in defining the architectural character of the complex. Prefabricated concrete panels, exposed aggregate surfaces, and smooth plaster finishes were utilized to ensure both durability and a consistent aesthetic language across the ensemble. The materials were selected not only for their functional robustness but also for their ability to age gracefully within the urban environment.

Architectural detailing emphasizes functionality and clarity, with particular attention given to the integration of entrances, stairwells, and communal terraces into the overall façade composition. These elements are often expressed through slight volumetric shifts or subtle textural changes, allowing the differentiation of public and private zones within the architectural whole.

Overall, the façade treatment of the City Wall complex encapsulates the ideals of modernist urbanism, seeking to balance aesthetic restraint, environmental responsiveness, and social functionality within a cohesive architectural language.

3.2.3. Functional organization

The architectural articulation of the residential buildings incorporates a variety of apartment types, designed to address diverse user needs.

Each residential block and tower is provisioned with a set of auxiliary spaces intended to enhance community life. These include a multipurpose room for house council meetings and children's activities, a two-room apartment designated for the housemaster, a workshop equipped with storage facilities, rooms dedicated to the storage of bicycles and strollers, and shared drying rooms located at intermediate floor levels (mezzanines).

The typical floor plan of the City Wall Tower demonstrates a highly rationalized and efficient functional organization, characteristic of the late modernist approach to residential architecture. The plan is organized around a central vertical circulation core, consisting of stairwells and elevators, ensuring clear and equitable access to all apartment units. This central core serves as a communal node, minimizing corridor lengths and thereby optimizing usable residential space.

Each typical floor accommodates four residential units, systematically arranged around the core to ensure maximum efficiency in layout and ease of orientation. The apartments are designed with a clear division between the day and night zones. Upon entry, residents are welcomed into an anteroom (1), which serves as a transitional buffer between public circulation and private living spaces. This is followed by access to the living room (2), typically adjacent to a kitchen (3) and dining area (5), promoting functional adjacency and facilitating domestic routines.

Private areas are carefully sequestered from public zones. The apartments contain both a children's bedroom (7) and a parental bedroom (8), always located along the periphery of the floor plan to maximize natural lighting and ventilation. Supporting spaces such as the bathroom (9), WC (10), and storage rooms (4) are strategically positioned close to bedrooms and circulation paths, reinforcing spatial logic and convenience.

Generous balconies (12) are incorporated into each unit, enhancing the living quality by providing private outdoor spaces while also contributing to the climatic performance of the apartments through shading and ventilation. The presence of integrated storage solutions such as wardrobes (11) further enhances the functional utility of the apartments, minimizing clutter and promoting efficient use of space (Figure 7) [7].

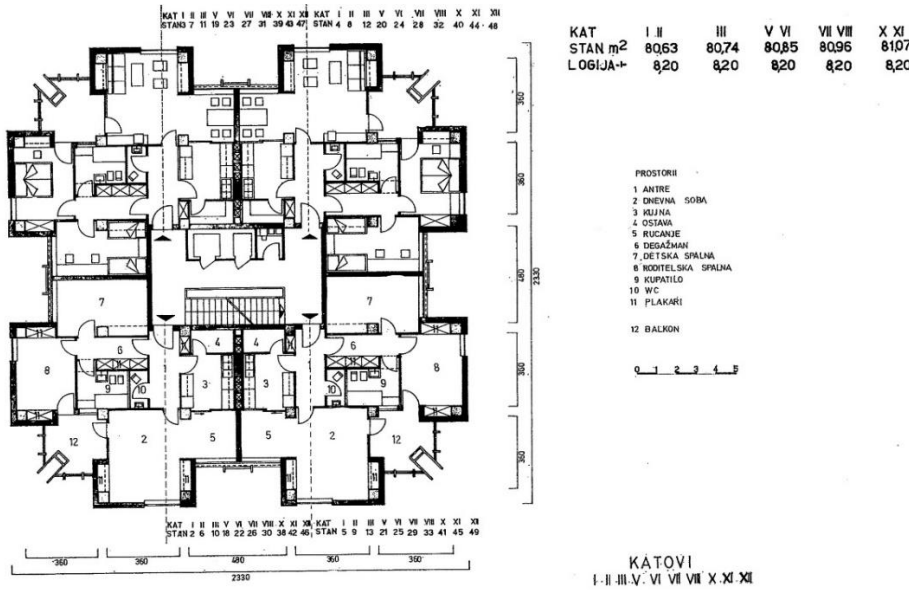


Figure 7. Typical floor plan of City Wall Tower (Source: Master plan for Skopje, 1965)

A notable feature of the organization is the symmetrical layout, which ensures that all units have similar levels of access to natural light and views. The structural grid of 360 cm modular spans further supports a rational and adaptable interior division, enabling flexibility in apartment typologies and future adaptability.

In summary, the typical floor plan of the City Wall Tower reflects a disciplined and human-centered functional organization. It effectively balances efficiency, comfort, and flexibility, aligning with the broader urbanistic and architectural goals of the City Wall complex, which sought to create modern, healthy living environments within a dense urban context [8].

3.3. Comparative analysis of two case studies

The following comparative analysis explores the similarities and differences between these two approaches, highlighting their architectural, functional, and urbanistic implications within the evolving context of Skopje's development.

Category	Aegean Buildings (1951)	City Wall Complex (1966–1968)
Historical Context	Post-WWII housing for Greek Civil War refugees; early socialist Yugoslavia	Post-1963 earthquake reconstruction; UN-led modernist urban renewal
Architectural Style	Early Modernism with functionalist and rationalist influences; human-scale design	Mature Modernism; large-scale, experimental urban planning with modular and prefabricated construction
Urban Structure	Two low-rise buildings (P+2), orthogonally arranged; soft transition zones; domestic scale	Complex of mid-rise blocks and high-rise towers forming a "city wall" ring around the center; dynamic rhythm, monumental scale
Density & Scale	Low-density, small-scale, 16 residential units; community intimacy	High-density, mixed-use; designed for thousands of residents with commercial and public amenities
Site Integration	Set back from street, greenery buffers; blends into neighborhood; semi-private outdoor space	Urban intervention forming a visual and physical boundary around city center; pedestrian networks and visual corridors integrated
Detailing	Simple, modest details (circular openings, natural cement finish); pitched roofs; attic storage	Façade modulation through balconies, fenestration, and reliefs; flat roofs; use of prefabricated panels; vertical and horizontal articulation
Material Expression	Honest use of materials; plaster, wood, cement; minimalistic but warm	Brutalist tones with modular concrete, exposed aggregate; more industrial and durable finishes for high-traffic urban living
Functional Layout	Efficient small units; dual orientation; raised ground floors; zoned day/night areas; minimized circulation space	Centralized cores in towers; symmetrical plans; generous balconies; clear zoning; integrated storage and communal spaces
Community Aspects	Informal community formed through spatial intimacy; no formal shared amenities	Designed with explicit communal infrastructure (meeting rooms, playrooms, shared storage, drying rooms, etc.)
Ventilation & Light	Dual-orientation apartments; shallow building depth for natural light and ventilation	Strategic massing of towers for cross-ventilation; light-optimized layouts with broad balconies and open views
Adaptability	Some flexibility with attic storage and minimal corridors	Modular structural grid (360 cm spans) allows flexibility in apartment typologies

4. CONCLUSION

The transformation of Skopje's urban and architectural landscape in the post-war period represents a profound narrative of resilience, modernization, and identity formation. Through the study of multi-family residential buildings, notably the Aegean Buildings and the City Wall complex, this paper has demonstrated how architecture served both functional and symbolic roles in Skopje's reconstruction and growth. The early post-war developments embodied a pragmatic adaptation of modernist principles, emphasizing efficiency, simplicity, and community, while the post-earthquake interventions introduced more ambitious urbanistic and architectural innovations, shaped by international collaboration and avant-garde thinking [9]. The detailed analysis of their urban structures, material articulation, and functional organization reveals not only the evolving aesthetic and technical aspirations of their time but also the broader socio-political imperatives driving Skopje's modernization. Ultimately, the residential architecture of Skopje's modernist era stands not merely as a functional response to post-war and post-disaster reconstruction but as a vital cultural and historical legacy that encapsulates the city's ideological, social, and spatial transformations during a period of profound upheaval [10]. These architectural interventions—ranging from the restrained functionalism of the Aegean Buildings to the ambitious, systematized urbanism of the City Wall complex—embody the shifting priorities of a society navigating between pragmatism and utopian ambition. As such, they offer critical lessons for contemporary architectural discourse, particularly in the realms of urban resilience, sustainable housing, and context-sensitive design. The capacity of these projects to respond simultaneously to emergency housing needs, collective identity formation, and long-term urban coherence highlights their relevance in addressing today's complex challenges of climate adaptation, densification, and social equity. In this regard, Skopje's modernist housing legacy provides not only a historical reference but a methodological and ethical framework for reimagining future modes of inhabitation in cities undergoing rapid transformation.

REFERENCES

[1] Petrović Marjan: **Design and functional characteristics of the multi-family housing architecture in the period of mature and late modern architecture of Niš – case studies**. *Facta Universitatis, Series: Architecture and Civil Engineering*, Vol. 18, No 2, pp. 177-193. 2020, https://doi.org/10.2298/FUACE200927013P .

[2] Keković Aleksandar, Petrović Marjan: Formative characteristics of Moderne Style in Niš. Facta Universitatis, Series: Architecture and Civil Engineering, Vol. 6, No 1, pp. 55-64. 2008.

[3] Keković Aleksandar: **Stambena arhitektura Niša u pokretu Moderna između dva svetska rata**. *Građevinsko-arhitektonski fakultet, Univerzitet u Nišu*, Niš, 2009.

[4] Marina Ognen, Penčić Divna: **Urban transformation of Skopje, Fragmented city – Legacy of history**. Skopje, 2004.

[5] Korobar Vlatko, Siljanoska Jasmina: **The Skopje City Wall Housing Complex.** *Docomomo Journal* No 68, pp. 90–97. 2023, https://doi.org/10.52200/docomomo.68.09 .

[6] Backović Vera: **Grad, arhitektura, društvo**. *Čigoja štampa*, Beograd, 2020.

[7] https://marh.mk/wp-content/uploads/2017/05/1_Gradski-zid-Skopje.pdf (25.04.2025)

[8] Alfirević Đorđe, Simonović Alfirević Sanja: **The "Socialist Apartment" in Yugoslavia: Paradigm or Tendency?**. *Spatium*, No. 40, pp.8-17, 2018, DOI: https://doi.org/10.2298/SPAT1840008A .
[9] Kenneth Frampton: **Modern Architecture: A critical history**. *Thames & Hudson*, 1992.
[10] Senior Derek, United Nations Development Programme: **Skopje Resurgent: The Story of a United Nations Special Fund Town Planning Project.** *Uited Nations,* New York, 1970.

doi.org/10.62683/SINARG2025.052

Review paper

POSSIBILITY OF APPLICATION OF ASH, SLAG AND FLOOD GYPSUM AS COMBUSTION PRODUCTS FROM THE KOSTOLAC THERMAL POWER PLANT IN CONSTRUCTION

Dragan Milošević[1], Tanja Miladinović[2]

Abstract

The use of ash, slag and waste gypsum resulting from the flue gas desulfurization process as a combustion by-product from thermal power plants is becoming increasingly relevant in the context of sustainable waste management and reducing negative environmental impacts. The use of ash, slag and waste gypsum resulting from the flue gas desulfurization process as a combustion by-product from thermal power plants is becoming increasingly relevant in the context of sustainable waste management and reducing negative environmental impacts. In order to mitigate negative effects and improve efficiency in the construction industry and other sectors, these materials can be used in various ways. Using these products reduces the amount of waste, while at the same time reducing the need for the use of natural resources. This contributes to sustainable development, although it is necessary to carefully determine the quality of combustion by-products from thermal power plants due to the possible negative impact on the long-term stability of buildings. The fact that depositing these materials requires not only space but also significant financial resources is very important. Above all, the use of fly ash, slag and spent gypsum in the construction industry can contribute to the reduction of carbon dioxide emissions (CO_2)

Key words: *Ash, Slag, FGD gypsum, Carbon-dioxide*

[1] B.Sc. in Mining Engineering, expert advisor, Serbian, Serbia, dragan.milosevic@ribeograd.ac.rs, ORCID 0000-0003-3714-1950

[2] B.Sc. in Geology, researcher assistant, Serbian, Serbia, tanja.miladinovic@ribeograd.ac.rs, ORCID 0000-0002-1174-5599

1. INTRODUCTION

Electricity production in thermal power plants of Electric Power Company of Serbia is based on the use of lignite (about 70%). This process generates large amounts of ash and slag, which, despite having useful value, are disposed of in ash landfills within power plants. Ash, slag and, in recent years, FGD gypsum are most often disposed of in landfills located in the immediate vicinity of thermal power plants [1]. Thermal power plants in Serbia consume 35 to 40 million tons of coal annually, resulting in around six million tons of fly ash. In order to start selling ash, in the branch "Thermal Power Plants and Mines Kostolac", it was necessary to install appropriate equipment and apply appropriate technology. All necessary activities, completed in the previous period, are manifested in the sale of coal combustion products in thermal power plants, increasing the energy efficiency of the system for transporting ash, slag and FGD gypsum, saving electricity. Its use in construction and road building significantly reduces the amount of ash in landfills, which has a positive impact on the environment. By implementing activities in the sale of by-products, for industrial application, positive economic effects are achieved, partly due to the sale itself, and partly due to the reduction in the amount of fees for the deferred amount of combustion products from thermal power plants. In this way, environmental benefits are also increased, as the disposal of ash, slag and FGD gypsum in landfills will be reduced or eliminated, and therefore their impact on the environment.

2. TREATMENT OF BY-PRODUCTS FROM THE KOSTOLAC THERMAL POWER PLANT

Fly ash, which is generated in the process of generating electricity by burning coal in the boilers of both thermal power plants, is the largest waste in terms of quantity in the TE-KO "Kostolac" branch. The necessary documentation for the registration of fly ash in the European Register of Chemicals (REACH) is currently being collected, which is a condition for delivery to the European market. Otherwise, gypsum produced at the Kostolac B thermal power plant is included in the REACH regulation of the European Union on the registration, evaluation, authorization and restriction of chemicals, which ensures its sale in European Union countries. In Serbia, it is sold as non-hazardous waste, and the Law prescribes a document on the movement of non-hazardous waste, which waste control and management engineers fill out and monitor the entire process of handing over waste to operators. The goal is to sell as much gypsum as possible on the Serbian and European Union markets and reduce disposal costs. For example, the quality of gypsum obtained in the flue gas desulfurization process is fully suitable for the production of gypsum products, as confirmed by users from Romania. By the way, the Kostolac branch of the Serbian Electric Power Company has been selling fly ash for several years, thus fulfilling the ecological principle that lignite combustion products are used in the economy, instead of just being disposed of in landfills. Specifically, companies that have been users of these by-products obtained from the flue gas desulfurization process at the Kostolac Thermal Power Plant in the past period are "Conal Group", "Lafarge", "Moravacem & CRH Western Balkans", "Titan" and "Hella" [2]. Figure 1 shows the landfill area, cassettes for storing fly ash and FGD gypsum at the internal landfill of the PK "Drmno".



Figure 1. Landfill area / Loading fly ash into customer trucks

As can be seen from the picture, disposing of by-products requires a significant and organized space. On the other hand, selling eliminates the need for manufacturing, transportation and storage.

The implementation of a flue gas desulfurization system in the Serbian Electric Power Company represents a significant contribution to environmental protection. All blocks of the Kostolac B Thermal Power Plant are integrated into this system. The Kostolac port is of exceptional importance for the efficient distribution of gypsum, located in the former Dunavac branch, connected to the Danube via the Kostolac Canal. Since its commissioning, the port has seen, among other things, an increasing turnover of raw materials, such as gypsum and ash.

3. APPLICATION POSSIBILITIES

Gypsum is not a significant problem at this time, as are ash and slag. They are very similar in their chemical and other properties. They are a mixture of oxides of silicon, aluminum, iron, calcium, and contain heavy metals, radionuclides, and some organic matter. Possible applications include the synthesis of zeolites and geopolymers, the extraction of rare earths, and environmental protection. In construction, ash is used as an additive to cement, so that concrete with the desired mechanical properties can be obtained, and it can be installed directly on the construction site, without prior treatment. Ash is used in the construction and reconstruction of roads in both bound and loose states [3]. In its bound state, it is used in hydraulic mixtures for road stabilization and in concrete for road construction [4]. In its free state, fly ash is used in the base layers of roads as fill, in the construction of dams or to improve soil quality. Fly ash is used significantly in the production of dry, powdered hydraulic binders for masonry and plastering, for stabilizing road surfaces, and for the production of rolled concrete. The application in environmental protection is reflected in the fact that fly ash is used as an absorbent for highly contaminated wastewater, for example from mines.

The fact that the use of ash itself is very profitable is evidenced by the fact that all highly developed countries have a higher consumption of ash than production, the USA, Germany, Japan, the Netherlands, Great Britain, etc. Otherwise, in the Republic of Serbia, the most favorable logistical options available are in Kostolac, because it has a port, silos. However, the port does not have pneumatic filling for barges for transporting ash, which is the only problem at the moment. Another way to transport these by-products is by rail, which is nearing completion.

In addition to landfills in the area of Kostolac, Thermal Power Plants Kostolac A and B (4-Srednje Kostolacko ostrvo, 5-Ćirikovac, 6-Drmno), there are also landfills in the immediate vicinity of Thermal Power Plant Obrenovac (2-TENTA and 1-TENTB) as well as near Lazarevac, Thermal Power Plant Kolubara A (3-Veliki Crljeni).

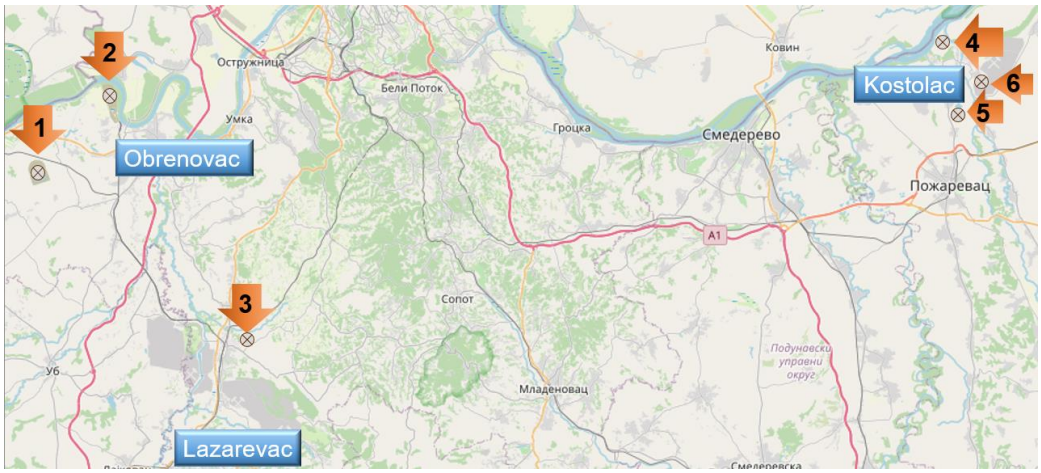


Figure 2. Fly ash landfill locations

4. SPECIFICITIES OF COAL COMBUSTION BY-PRODUCTS IN KOSTOLAC TPP

FGD gypsum in drained conditions has low cohesion values, typically 5 kN/m², and a relatively high angle of internal friction, typically greater than 30° [5]. In undrained conditions, the angle of internal friction is slightly greater than one-half of the angle of internal friction in drained conditions, but the value of cohesion is of the same order of magnitude. This proves that FGD gypsum behaves similarly to sands even when subjected to external loading in drained conditions. The load is taken by the friction force between the particles, not the cohesive force.

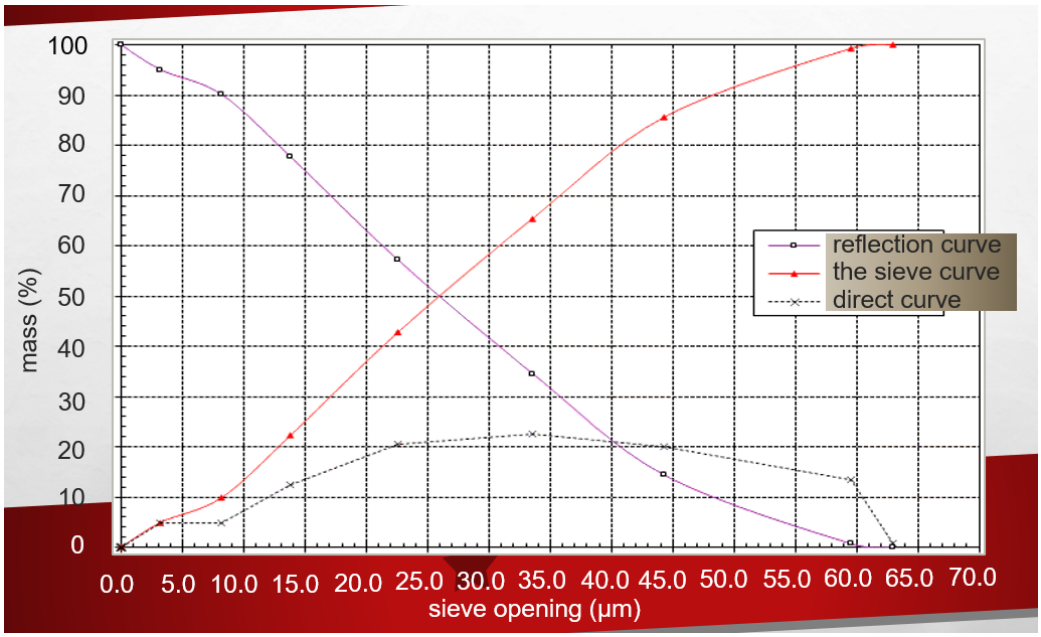


Figure 3. Graphical representation of the particle size composition of gypsum from the Kostolac B thermal power plant [6]

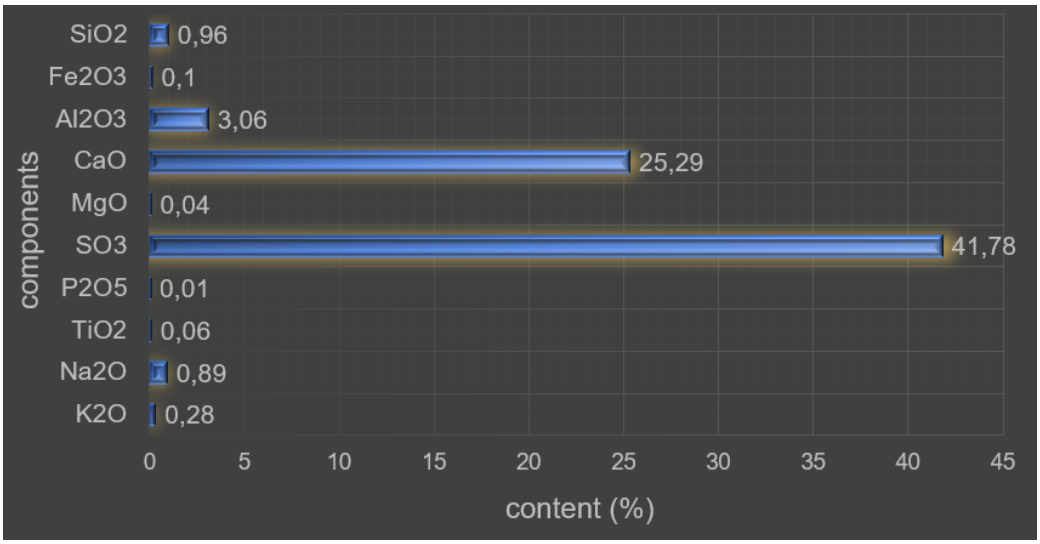


Figure 4. Chemical composition of gypsum from TPP "Kostolac B1"

The following tables show the results of tested samples from three locations: the ash and slag landfill Srednje kostolacko ostrvo (SKO), the Nikola Tesla B thermal power plant (TENT B) and the gypsum landfill from the internal landfill PK Drmno. Figures 5 and 6 show the results of the average values of the 12 tested samples, as well as the min.- max. range, while tables 1 and 2 list the physical and mechanical characteristics of ash and slag.

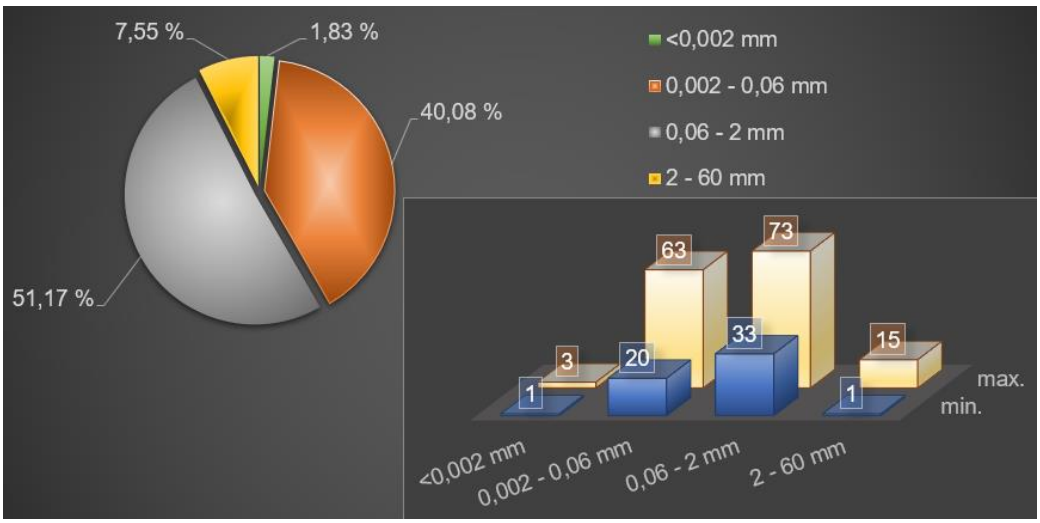


Figure 5. Granulometric composition of ash and slag, landfill "SKO"

Table 1. Physical and mechanical characteristics of ash and slag, landfill "SKO" [6]

HUMIDITY	DENSITY			DIRECT SHEAR D you learn	
***w* (%)**	ρ (Mg/m³)	ρ_d (Mg/m³)	ρ_z (Mg/m³)	Φ (°)	C (kPa)
20,6 – 42,1	0,91 – 1,16	0,73 – 0,83	1,28 – 1,47	26 – 30	0 – 7

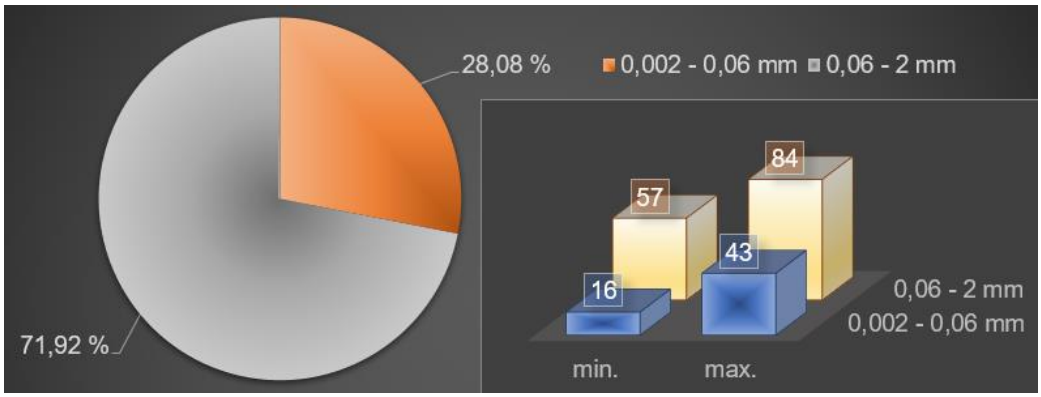


Figure 6. Granulometric composition of ash and slag, landfill "TENT B"

Table 2. Physical and mechanical characteristics of ash and slag, landfill "TENT B" [6]

HUMIDITY	DENSITY			DIRECT SHEAR D you learn	
***w* (%)**	ρ (Mg/m³)	ρ_d (Mg/m³)	ρ_z (Mg/m³)	Φ (°)	C (kPa)
12,4 – 57,7	0,96 – 1,08	0,62 – 0,85	1,32 – 1,43	26 – 30	2 – 5

Figure 7 shows the results of the average values of the 6 tested samples, as well as the min.- max. range, while Table 3 lists the physical and mechanical characteristics of the deposited gypsum.

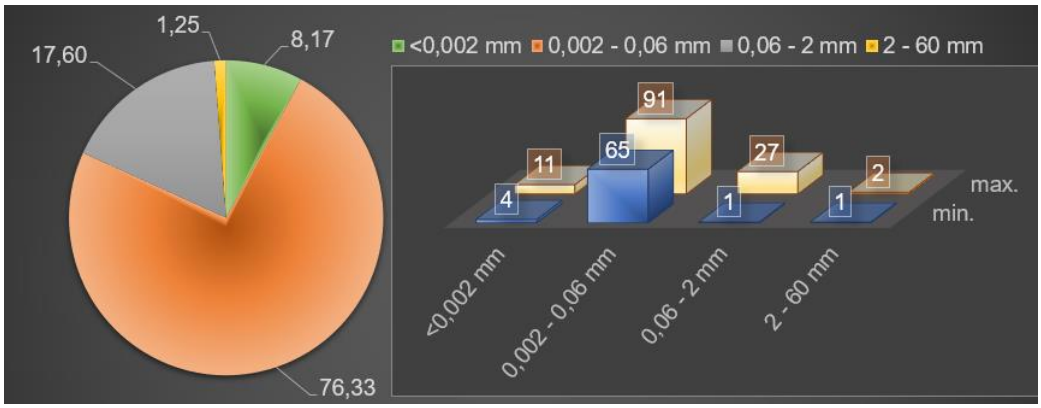


Figure 6. Granulometric composition of gypsum, landfill at the internal landfill PK Drmno

Table 3. Physical and mechanical characteristics of gypsum, landfill at the Drmno landfill [6]

HUMIDITY	DENSITY			DIRECT SHEAR D you learn	
***w* (%)**	ρ (Mg/m³)	ρ_d (Mg/m³)	ρ_z (Mg/m³)	Φ (°)	C (kPa)
12,7 – 33,0	1,37 – 1,90	1,03 – 1,69	1,40 – 1,95	21 – 24	8 – 15

5. CONCLUSION

The most common use of fly ash is in the production of concrete. Using fly ash helps create materials that are less susceptible to cracking or warping at extreme temperatures. This makes it an excellent stabilizer not only for the base of the subgrade but also for the road surface itself. Fly ash is also used in building products such as bricks, reducing the

amount of cement needed, as well as the need for other natural resources. Can also be used as a soil amendment. It provides plant nutrients and minerals that increase soil fertility, which improves plant growth and water retention. Fly ash geopolymers can act as magnets for water pollutants. These impurities bind to the porous fly ash, ensuring easier removal during wastewater treatment. Fly ash is a source of rare earth elements that are expensive and inefficient to mine, but are essential in the production of devices such as smartphones, electric vehicles and wind turbines.

The use of ash, slag and FGD gypsum brings numerous environmental, economic and technical advantages, especially in the construction industry and waste management:

- the costs of storing and disposing of these by-products are reduced or neutralized;
- these materials are reduced or replaced instead of using mineral raw materials;
- carbon dioxide emissions are reduced;
- reduced or eliminated environmental impact;
- reduction or elimination of spatial degradation;
- fly ash from thermal power plants (used as a substitute for cement in concrete, improves the workability of concrete, extends setting time and increases longevity, reduces shrinkage and cracking of concrete, is used in waste recycling);
- slag (used as an additive to cement or aggregate in concrete and asphalt, increases the resistance of concrete to chemicals and frost, has a smaller ecological footprint than traditional construction materials, and acts as a substitute for natural resources such as sand and gravel);
- FGD gypsum (used as a raw material for the production of gypsum boards and gypsum mortars, can be used in the cement industry as an additive, used in agriculture because it improves soil structure and reduces acidity, recycling avoids landfilling and saves space in landfills).

Some of the disadvantages of using fly ash:

- the ratio of concrete to fly ash must be strictly controlled in order to ensure the necessary quality of concrete;
- not suitable for all types of concrete;
- If too much fly ash is mixed into the concrete, it can reduce the strength of the concrete.

REFERENCES

[1] Stojiljković Dragoslava, Jovović Aleksandar, Jovanović Vladimir, Manić Nebojša, Milovanović Đorđina, Petrović Sanja, Rubov Lin, Gavrić Mihajlo, Žbogar Zrinka, **Selection of the optimal technical solution for the flue gas desulfurization plant at TPP 'Kostolac B'**, *Termotehnika*, 2009.

[2] EPS / Serbian Electric Power Company, https://www.eps.rs.

[3] REPORT: **"Guidelines for users of by-products and the use of secondary raw materials in road construction"** taken from the Project for the Republic of Serbia G2G09/SB/5/4 within the short G2G program, 2010.

[4] Goran Tadić, Miladin Gligorić, Aleksandar Došić, Radenko Grujić, **USE OF FLY ASH IN ROAD CONSTRUCTION**, *Journal of Engineering & Processing Management*, 2015. DOI: 10.7251/JEPMSR1507125T

[5] Nebojša Kostović, Milošević Dragan, Vlajić Dijana, Radosavljević Milinko, Đerisilio Aleksandar: **Provision of space for the expansion of the plaster landfill at OP "Drmno" for the needs of thermal power plant Kostolac B1 and B2**, *Technical mining project,* Beograd, 2021.

[6] **Reports on testing samples of ash, slag and FGD gypsum**, *Documentation of the Mining Institute*, Belgrade, 2024.

doi.org/10.62683/SINARG2025.053

Review paper

AESTHETIC THEORIES AND THEIR PATHS IN ARCHITECTURE: MILUTIN BORISAVLJEVIĆ AND HIS SCIENTIFIC APPROACH TO AESTHETICS OF ARCHITECTURE

Irena Kuletin Ćulafić[1]

Abstract

Aesthetics as a philosophical discipline emerged in the 18th century, though key aesthetic questions were already present in its pre-philosophical phase in antiquity. The task of separating architectural aesthetic thought from the broader development of philosophical aesthetics remains largely unfinished, with few architects having addressed it directly. One of the pioneers in this area was Milutin Borisavljević, who, in the 1920s, earned his doctorate at the Sorbonne in Paris in the field of aesthetics. Borisavljević focused on the aesthetic experience of architecture and laid the foundation for studying aesthetics of architecture on scientific grounds. While philosophical aesthetics maintained a speculative and deductive research apparatus, Borisavljević's approach prioritized experimentation as the most reliable and objective method. He developed an original aesthetic framework grounded in experimental psychology, visual perception physiology, and neurological studies. In his exploration of the aesthetic experience of architecture, Borisavljević paid particular attention to phenomena such as harmony, composition, rhythm, proportion, symmetry, and asymmetry. Seeking to establish the laws governing the sensory experience of architecture, he remained faithful to the classical tradition of the École des Beaux-Arts, applying its principles in practice through numerous residential buildings and villas constructed in Belgrade between the two world wars. This paper examines the early formation of aesthetic thought beginning in antiquity, tracing the relationship between architecture and nature, as well as between architecture and human nature — a central focus of Borisavljević's scientific aesthetics of architecture. The enduring challenge of defining criteria and rules for explaining architectural beauty and its sensory effects on humans continues to inspire, enriching the dialogue between engineering and art.

Key words: *Aesthetics of architecture, Aesthetic experience, Milutin Borisavljević's scientific aesthetics of architecture, Experimental methodology*

[1] PhD, Assistant Professor, University of Belgrade – Faculty of Architecture, Department of History and Theory of Architecture and Art, Belgrade, Serbia, kuletin@arh.bg.ac.rs, ORCID: https://orcid.org/0000-0001-7052-4596

1. INTRODUCTION

The development of aesthetic thought can be traced back to the times of antiquity and philosophical thoughts on issues of beauty and art. It was not until the 18th century that aesthetics was established as an independent philosophical discipline. Through the important endeavours of Baumgarten, Lessing, Goethe, Herder, aesthetics made its way primarily in the fields of poetry, literature, and the arts of painting and sculpture. In the era of the philosophers of German idealism, through the works of Fichte, Schelling and finally the great aesthetician Hegel, aesthetics paved the way for an independent discipline that remained closely connected to the philosophy, history and theory of art to this day.

Regarding architecture, treatises on aesthetics remained very poor and scientifically little-explored field of research. In this sense, Borisavljević's research on aesthetics of architecture represents a major international contribution to the theory and aesthetics of architecture.



Figure 1. Milutin Borisavljević, Villa Flašar, Kornelija Stanković Street, Neimar, Belgrade, 1932. Recognized as a cultural monument and protected by the Cultural Heritage Preservation Institute of Belgrade. Photo by Irena Kuletin Ćulafić.

Milutin Borisavljević was born in 1889 in Kragujevac, then part of the Kingdom of Serbia, into a respectable middle-class family. His father was a physician, and his mother a homemaker. He was the eldest of five children. He graduated in 1913 from the Technical Faculty in Belgrade and, as a recipient of a military scholarship from the French government, went on to complete his doctoral studies at the Sorbonne University in Paris. His dissertation, supervised by the prominent aesthetician and philosopher Professor Victor Basch, was titled *Essai critique sur les principales doctrines relatives à l'esthétique de l'architecture* (*Critical Essay on the Principal Doctrines of the Aesthetics of Architecture*). It was published in 1926 by the renowned Parisian publishing house Payot [1].

After his return to Belgrade in 1927 until the beginning of the Second World War, he was very actively engaged in the architectural design practice. He founded the architectural and construction company "Partenon" and built over 130 buildings (123 are located in Belgrade). In addition to his very successful career as an architect (Figure 1), he was actively engaged in criticism and theory and aesthetics of architecture. He wrote critical texts concerning architecture and urbanism for many daily newspapers and published several books and many scientific papers during the period between the two world wars. After the Second World War in 1950, together with his wife Jelena, he emigrated to Paris, where he lived on the edge of existence from a small state pension. He lived in Paris until his death in 1969, and in this last phase of his life he devoted himself completely to the research of theory and aesthetics of architecture and the optical-physiological perspective and its application to architecture.

The encounter with Paris in his youth marked Borisavljević's entire later career. In Paris, the cradle of art and architecture, Borisavljević acquire refined French taste that he applied to his architectural design work. Borisavljević's astonishing villas and houses, still today, adorn many parts of Belgrade [2]. His authentic aesthetic handwriting is recognizable in the refined treatment of façades, the sense of proportion, order and harmony, which stood out from the overly eclectic and aesthetically uneven architecture that characterized Belgrade in the 1920s and 1930s [3].

In the 1920s, Milutin Borisavljević laid the foundation for the study of aesthetics in architecture on scientific grounds. While aesthetics as a philosophical discipline retained a traditional philosophical framework, Borisavljević, in contrast, advocated for experimentation as the most reliable and objective method of research. Accordingly, he developed his own aesthetic conception rooted in the principles of experimental psychology, visual perception, and neurological physiology. He viewed the philosophical concept of aesthetics as overly abstract, allowing excessive interpretive freedom and resulting in each aesthetician constructing a personal system of aesthetic principles. In response, Borisavljević established an autonomous field he termed "scientific aesthetics" — a theory and practice grounded exclusively in verifiable scientific facts and experimental data [4]. This approach offered a novel method of understanding aesthetic phenomena, one firmly based in empirical science and clearly positioned in opposition to deductive reasoning, critical-cognitive methodologies, and traditional philosophical aesthetics.

2. AESTHETICS AND ITS HISTORICAL FOUNDATIONS: FROM NATURE TO ARCHITECTURE

The relationship between nature and architecture is highly complex and, in the broadest sense, can be understood as the interaction between natural and artificial environments. Although architecture is a product of human creativity, both in theory, aesthetics, and practice—from antiquity to the present—it has consistently drawn inspiration from nature.

Although aesthetics as a distinct and independent philosophical discipline emerged in the mid-eighteenth century, aesthetic questions were already being explored by ancient thinkers. Traces of the aesthetic relationship between architecture and nature can be found in the philosophies of the Pre-Socratics. Philosophers such as Thales, Pythagoras, Anaximenes, Heraclitus, Xenophanes, Parmenides, Zeno, and Anaxagoras were deeply engaged with the diversity of nature, prioritizing metaphysical interpretations of the cosmos over individual sensory experience. In the classical world, nature constituted an immutable framework which, from both humanistic and sociological perspectives, was further examined by Socrates, Plato, and Aristotle, building upon the foundations laid by their Pre-Socratic predecessors.

The highest aesthetic values in ancient philosophy were attributed to elements originating from nature, while human-created phenomena such as poetry, music, painting, sculpture, and architecture were generally regarded as possessing lower aesthetic value. Visual arts like painting and sculpture were often viewed as false, mimetic, and deceptive, merely imitating reality rather than expressing deeper truths. Architecture, however, held a somewhat elevated status in comparison, due to its inherent qualities of utility, functionality, and its non-mimetic nature — it did not seek to imitate what already existed in nature, but rather to create purposeful structures in harmony with human needs [5]. Plato argued that the art of poetry, along with the poets themselves, had a corrupting influence on society. He

believed that poets misled people with illusions and emotional manipulations, distancing them from truth and reason. For this reason, in his ideal state described in *The Republic*, he advocated that poets be excluded, as their work did not contribute to the rational and moral education of citizens [6].

The primary reason for the negative perception of the arts in ancient times lay in their ethical-aesthetic evaluation. Art was seen as pursuing sensual pleasure rather than wisdom, which rendered it illusory and deceptive. Consequently, it was believed that the arts could not possess high values, especially not moral ones, as they were seen to undermine divine and ethical principles. Aesthetic knowledge was also deemed unreliable because it depended on the fallible judgment of the senses rather than on rational or philosophical understanding [7]. The very sensory dimension of knowledge, which was viewed with skepticism in ancient aesthetic thought, became the foundational principle upon which Alexander Gottlieb Baumgarten, in the 18th century, established aesthetics as *scientia cognitionis sensitivae* — a science of sensory cognition [8].

The most significant architectural treatise from antiquity is *De architectura libri decem* (*Ten Books on Architecture*) written by Marcus Vitruvius Pollio, which laid the foundation for subsequent practical and theoretical discourse on architecture. The importance of Vitruvius' work lies in the fact that it is the oldest surviving architectural text, though it functions more as a technical manual offering guidance to architects than as a sophisticated aesthetic treatise. Vitruvius acknowledges beauty as an essential component of architecture and articulates the famous triad *firmitas, utilitas et venustas* (strength, utility, and beauty), asserting that architectural beauty is inherently dependent on structural integrity and functional purpose [9]. Vitruvius draws upon Pythagorean teachings on harmony and symmetry, according to which the concept of beauty is realized when a building, in all its parts, exhibits appropriate proportions of height and length, and fully meets the requirements of symmetry. For Vitruvius, the same principles of harmony and symmetry apply not only in architecture, but also in painting, sculpture, and nature itself — serving as universal ideals by which all human creation should be guided.

The aesthetic theory of the early Middle Ages in art does not adhere to Aristotle's concept of mimesis, or imitation of the real world, but instead follows the Platonic principle of the ideal world of ideas. The Neoplatonist philosopher Pseudo-Dionysius the Areopagite, in his work *De divinis nominibus*, formulates beauty through the dualism of harmony of proportions and brilliance (*consonantia and claritas*). The term "brilliance" refers to light and remains somewhat vague, a characteristic often associated with mysticism, which seeks to reconcile Platonic ideas with Christian doctrine [10]. In the scholastic tradition, the ancient notion of aesthetics is continued by the medieval thought of Thomas Aquinas, who links beauty to cognitive ability. According to Aquinas, things that are pleasing to the eye are considered beautiful [11].

Renaissance aesthetics of architecture was primarily built upon the experiences of antiquity. Leon Battista Alberti transforming Vitruvius' triad into *necessitas, commoditas, and voluptas* (necessity, convenience, and pleasure) [12]. In the spirit of humanism and Neoplatonism, Alberti's perception of the beauty of architecture focuses on *voluptas* as the sensual pleasure that an architectural work evokes in us. Alberti emphasizes the subjectivity of sensory perception, which is subordinated to Renaissance idealism in the search for the absolute values of architecture, which are reflected through *decorum* and *concinnitas* — principles based on appropriateness, harmony, and the perfection of proportions. According

to Alberti, the beauty of an architectural work is expressed through the mathematical, logical, geometric, musical, philosophical, symbolic, and aesthetic relationships between the whole and its parts, where it is impossible to add or subtract anything without altering the ideal harmonious unity [13]. For Alberti, the beauty of architecture is reflected in the connection of the system of proportions that are derived from nature and from man (anthropomorphism) and applied to architecture. In this view, the architectural structure is understood as a universal organic unity, where the microcosm reflects the macrocosmic unity and harmony.

Renaissance aesthetics of architecture sought to explore in detail the relationship between nature and man, who is not an outsider in the world of nature, but is placed within the universe of nature. His highest goal is to create architecture in accordance with the laws of nature, geometry, music, and divinity. Alberti remains the greatest Renaissance aesthetician within the Neoplatonic and mystical conceptions of beauty, which, in subsequent epochs, became an important field of aesthetic research. The renowned treatises of Sebastian Serlio, Giacomo Barozzi da Vignola, Andrea Palladio, and Vincenzo Scamozzi approached the theory and aesthetics of architecture in a much more rational and programmatic manner.

Aesthetics, as a separate and independent discipline, distinct from philosophy, was officially founded by the German philosopher Alexander Gottlieb Baumgarten. He introduced the term *aesthetica* derived from the Greek word meaning sensation or perception. In 1750, Baumgarten published his seminal work *Aesthetica*, with the second volume being released in 1758 [14]. Baumgarten was a student of Christian Wolff and was profoundly influenced by the philosophy of rationalism proposed by Gottfried Wilhelm Leibniz. Leibniz's system, centered around the concept of monads, emphasized the idea of cosmic harmony, which he attributed to the governance of God [15].

Baumgarten founded aesthetics as an independent philosophical discipline based on the study of sensory cognition. Prior to his work, the question of knowledge had been primarily viewed through the lenses of rationalism, where reason formed the basis of logical thought, and empiricism, where experience served as the foundation of practical knowledge. Baumgarten, however, shifted the focus to sensory cognition, which began to gain increasing attention from philosophers and came to be recognized as a distinct form of knowledge that could complement and even challenge the traditional dominance of logical, rational cognition.

During the Enlightenment and subsequently in the Romanticism, sensory cognition increasingly drew the attention of thinkers, writers, and philosophers, particularly within the realms of literature and art. Aesthetics, as a philosophical discipline, began to define its object of study within these domains of human creativity, with architecture assuming a distinctive position. In alignment with the prevailing rationalist philosophy of the 18th century, sensory cognition was often regarded as a lower form of knowledge. Both rationalists and empiricists approached beauty from a functionalist perspective — asserting that what serves a practical purpose is thereby beautiful. David Hume, for instance, argued that everyday objects such as tables, chairs, chimneys, carriages, and plows, along with works of art, are considered beautiful insofar as they fulfill their intended functions [16]. In contrast to the eighteenth-century notion of beauty as functional fitness, Edmund Burke offered a significant critique in his treatise *A Philosophical Inquiry into the Origin of Our Ideas of the Sublime and Beautiful* [17]. Burke argued that many objects are undoubtedly beautiful, yet no notion of utility can be attributed to them. In a similar departure from utilitarian aesthetics, Gotthold Ephraim Lessing, in his treatise *Laocoön, or On the Limits of Painting and Poetry*, explored the distinctions

between visual and literary arts. He articulated aesthetic principles that prioritized imagination and creative expression over imitation, and he was among the first to acknowledge the legitimacy of the aesthetics of the ugly [18].

The most significant contribution of the empiricist tradition to aesthetics lies in the articulation of the concept of aesthetic experience, which is rooted in sensory perception and occurs immediately, independent of rational cognition. Aesthetic experience constitutes a distinct form of engagement, often detached from reason or functional considerations. As a result, the ideas of eighteenth-century empiricists laid fertile ground for the development of aesthetics as a field with increasing theoretical rigor and scientific autonomy. To this day, the phenomenon of aesthetic experience remains central to aesthetic inquiry, although it was originally considered exclusively through the lens of beauty. In this broader intellectual context, Milutin Borisavljević's investigations into aesthetic phenomena in architecture represent a noteworthy contribution, particularly in the evolution of aesthetic theory and architectural discourse in the 20th century. In his analysis of aesthetic experience, Borisavljević placed great importance on Immanuel Kant's insights, which he further elaborated within his own framework of a scientific aesthetics of architecture [19].

Modern aesthetics begins with Immanuel Kant and his attempt to reconcile the limitations of both empiricism and rationalism. Kant proposed that cognition arises from the interaction between a priori forms of understanding and sensory experience — asserting that pure reason without experience is empty, while sensory knowledge without the guidance of reason is blind [20]. The foundations of aesthetic appreciation of both natural and built environments can be traced to Kant's *Critique of the Power of Judgment*, where he introduces the concept of functional beauty as a key element of aesthetic experience. According to Kant, aesthetic satisfaction arises not from sensory impressions or rational concepts, but from a subjective necessity — an immediate response that is both universal and disinterested [21].

Kant's notion of aesthetic disinterestedness plays a central role in Milutin Borisavljević's aesthetic theory. Disinterestedness, as defined by Kant, refers to a distinct type of aesthetic experience that stands apart from rational-cognitive, religious, or moral forms of engagement. In this framework, the aesthetic object is perceived and evaluated independently of its utility or practical function — appreciated solely for its formal qualities. This concept draws from Aristotle's insights on cognitive experience and aligns with Thomas Aquinas's idea that beauty is perceived through an intuitive sense of clarity and immediacy. Kant's position remains within the classical tradition of art, wherein a work is considered beautiful when it elicits a sense of pleasure without a discernible reason. For Kant, aesthetics must be divorced from interest, meaning that aesthetic judgment should be free from considerations of usefulness or purpose.

Kant's notion of taste refers to the capacity to make judgments about beauty that are entirely free from personal interest. For Kant, something is deemed beautiful if it elicits a feeling of satisfaction in the observer that is independent of desire, usefulness, or practical function. This form of judgment is grounded in what he describes as "a purposiveness without purpose" — the idea that a work of art seems to have a form and coherence as if it serves a purpose, yet it does not fulfill any specific utilitarian goal. Through this framework, Kant draws a clear line between the aesthetic experience of beauty and mere sensual pleasure or emotion rooted in daily human activities. By establishing this distinction, he provides a philosophical foundation for understanding art and architecture as autonomous fields, separate from commercialism and utilitarian constraints. This distinction marks the boundary

between aesthetic experience and the ordinary perception of everyday objects, a principle that Borisavljević extends in his formulation of a scientific aesthetics of architecture, reinforcing the idea that architecture should be appreciated not merely for function, but as a phenomenon eliciting pure aesthetic response.

In the architecture of the 18th and 19th century, a large number of theories and debates based on supreme kinds of values: truth, good and beauty (*verum, bonum* and *pulchrum*, lat.) were prominent. The theories of French architectural theorists such as Jacques-François Blondel, Germain Boffrand, Charles-Étienne Briseux, Marc-Antoine Laugier, Jean-Louis Cordemoy, Pierre Patte, Claude-Nicolas Ledoux, Étienne-Louis Boullée, among others, were particularly influential. In their significant written treatises, they sought the ideal style in architecture, focusing on *bon goût* (good taste), both universal and individual notions of taste, and concepts such as *vérité* (truthfulness), *simplicité* (simplicity), *naturalism* (naturalness), and *bienséance* (appropriateness) [22]. The aesthetic theories of the 18th century were of great significance for the modern study of aesthetics of architecture, precisely because of their detailed exploration of aesthetic experience, aesthetic judgment, and the nature of aesthetic values, particularly in relation to other forms of value such as moral and historical values [23].

Romantic elements remain recognizable in contemporary aesthetics of architecture, tracing back to the 19th century and the theories promoted in architecture and design by figures such as Augustus Welby Northmore Pugin, John Ruskin, and William Morris [24-28]. Aesthetic and ethical values were unified in the work of the Arts and Crafts movement and its founder, William Morris. Their contribution remains relevant today, particularly in the field of interior design, where the Arts and Crafts style continues to be regarded as synonymous with authentic British design. Morris's core idea in architecture and design was to promote comfort, functionality, and social equality for every user, while preserving nature and its resources. He emphasized small-scale production, craftsmanship, and, above all, the rejection of industrial manufacturing, which he believed had mentally and physically devastated English cities in the 19th century.

Despite these romantic ideals concerning the unity of the natural and architecturally designed environment, aesthetics of architecture had no alternative but to increasingly rely on industrial production and the possibilities offered by standardization. New materials — concrete, reinforced concrete, iron, and glass — gave rise to a new architectural and design aesthetic, first affirmed through the work of the Deutscher Werkbund (Association of German architects, designers, industrialists, and intellectuals), and later through the enduring dominance of modernism in architecture and design. In the first decades of the 20th century, avant-garde thought in architecture was closely linked to art, particularly through movements such as Italian Futurism, Russian Constructivism and Suprematism, the Dutch De Stijl, and the German Bauhaus. The Bauhaus, as the first school dedicated to the modern education of architects and designers, revolutionized both the practice and theory of architecture, establishing modernism as the dominant ideology in architecture.

Most modernist architects did not engage deeply with the theory and philosophy of architecture, with the exception of Le Corbusier, who possessed the gift of eloquence. As the greatest advocate of modernism, he articulated his architectural thoughts in his books and writings [29]. In contrast, most modernist architects expressed themselves more through their buildings. Ludwig Mies van der Rohe, the last director of the Bauhaus and a key figure who, alongside Gropius and other European architects, brought modernism to American soil after

World War II, was not inclined to write about architecture. Nevertheless, his aphorisms, such as “Less is more”, became immensely influential.

Milutin Borisavljević was a contemporary of the emergence of modernist ideas in architecture and one of their most prominent critics. From an aesthetic standpoint, he assigned the lowest aesthetic value to modernist architecture, considering it a disgrace to the discipline — a non-aesthetic orientation and a 'box with holes' that had buried beauty in architecture. According to Borisavljević, modernism was a passing trend that had undoubtedly caused a revolutionary shock in architecture, but he believed that this trend was fading and that architects would inevitably return to the cultivation of traditional academic forms, colors, and materials [30].

3. ARCHITECTURE AS ART OF TIME – SCIENTIFIC AESTHETICS OF MILUTIN BORISAVLJEVIĆ'S ARCHITECTURE

As we have seen in the brief historical overview of aesthetic thought, questions concerning aesthetics of architecture were traditionally closely linked to other forms of art and to general aesthetic views on beauty and creativity. However, they rarely addressed in depth the crucial notion of the aesthetic experience of architecture itself. A significant conceptual shift in this regard can be found in the theoretical research of Milutin Borisavljević. Borisavljević was not only the first Serbian architect to earn a doctorate in philosophy, specializing in the aesthetics of architecture at the Sorbonne in Paris, but also one of the few architects in the world at that time to pursue formal academic specialization in the field of philosophical sciences. Through this unique intellectual trajectory, he established himself as a distinguished expert in architectural theory and history.

As an architect, historian, theorist, aesthetician, critic of architecture, and scientist engaged in the study of optical and physiological phenomena, Borisavljević left behind a rich legacy that includes more than 130 completed buildings, several dozen unbuilt design projects, 18 published books, nearly 170 scientific papers and critical articles published in both Serbian and French academic proceedings and journals [31]. Throughout his life, he remained devoted to developing and articulating his theoretical ideas aimed at establishing a scientific aesthetics of architecture. In his theoretical work until the end he kept the ideological continuity of his aesthetic theory, while remaining consistent with the attitudes and ideas which he conceived in his youth.

Milutin Borisavljević spent nearly thirty years of his life in Paris, a period that had a profound impact on his theoretical work in the field of aesthetics and architecture of optical-physiological perspective. The cosmopolitan influences he encountered in this cultural capital of Europe were essential to the formation and development of his theoretical and ideological positions. While his progressive ideas were often met with limited understanding and acceptance in the Serbian academic and professional context, Borisavljević's work has been widely recognized and highly regarded internationally.

In the 1920s, Borisavljević founded the study of aesthetics in architecture based on scientific principles, opposing traditional philosophical methods. He developed a "scientific aesthetics" grounded in experimental psychology, physiology, and neurological science, focusing on verifiable facts and experimental results. His approach introduced a new way of understanding aesthetics, distinct from general philosophy and traditional aesthetics.

Through the scientific aesthetics of architecture, Borisavljević sought to define the relationship between the lines, surfaces, and shapes in architecture and the inner emotional states experienced by the observer during the aesthetic contemplation of these elements. While our sense of sight is responsible for perceiving architecture as a visual art, Borisavljević emphasized that the aesthetic phenomenon does not end with the eye. It begins there but continues in the brain, where it elicits a specific response from our nervous system to external factors — visual stimuli induced by the architecture [32].

Although he strives to incorporate the precision of the natural sciences into his scientific aesthetics, Borisavljević distances himself from the idea of reducing the perception of aesthetic phenomena to a mere mechanical process. He remains consistent with the concept of *Einfühlung* — the "theory of empathy" — which played a significant role in the work of various philosophers, art theorists and artists during the late 19th and early 20th centuries. The German philosopher Robert Vischer coined the term *Einfühlung*, explaining it as aesthetic sympathy or aesthetic liking. This term later became accepted in Western European culture as "empathy," and its development was explored by German philosophers, aestheticians, and artists, such as Theodore Lips, Alois Riegl, Konrad Findler, Adolf Hildebrand, Wilhelm Worringer, and others [33]. According to Borisavljević's theory of empathy, achieving aesthetic communication requires the subject to become a part of the things they are aesthetically experiencing and to identify with them.

It is important to note that in Borisavljević's scientific aesthetics of architecture, the aesthetic phenomenon is understood as a feeling of satisfaction or dissatisfaction, a concrete fact. If scientific aesthetics were based solely on feelings, it would take on a metaphysical character and would not qualify as a science that investigates specific phenomena, as do physics, chemistry, physiology, and other exact sciences. The primary objective of the scientific aesthetics of architecture is to uncover the physiological determinism of the aesthetic phenomenon, which involves identifying the organic conditions under which aesthetic experiences are generated. In his aesthetic research, Borisavljević begins with formalist aesthetics, focusing on lines as the most basic element of architectural form, then progressing to the study of surfaces, bodies, and collections of bodies – architectural compositions. Through this research process, scientific aesthetics moves towards more complex forms in order to, based on empirical data, uncover a law that governs the relationships between forms. In this manner, the study of the pure form of aesthetic phenomena is achieved, with the main goal being to determine the causes and conditions under which these phenomena occur [34].

In his research, Borisavljević dedicates much of his attention to the aesthetic architectural phenomena of harmony, composition, rhythm, proportion, symmetry, and asymmetry. Within the context of scientific aesthetics, symmetry is seen as an aesthetic phenomenon characterized by peace, seriousness, calmness, sadness, and similar qualities, while asymmetry is associated with movement, restlessness, and exuberance. Composition, according to Borisavljević, is the most challenging aspect of architecture, as it reflects the overall originality of the architect and encompasses all of their creative inventions. The two main elements of composition are proportion and harmony. Rhythm serves as the strongest proof that aesthetic pleasure is both a functional and physiological phenomenon, and it also provides evidence that architecture, from the perspective of scientific aesthetics, is an art of time, rather than space. Borisavljević offered detailed explanations of aesthetic phenomena such as harmony, composition, rhythm, proportion, symmetry, and asymmetry in his

book *Traité d'esthétique scientifique de l'architecture*, which stands as a synthetic work and the pinnacle of his scientific aesthetics of architecture [35].

According to Borisavljević, every aesthetic phenomenon for scientific aesthetics is:

1. optical-physiological, visual phenomenon;
2. optical phenomenon of moving pictures (since architecture is the art of time and its visual perception is successive, according to the scientific aesthetics of architecture, it is considered the art of time, while geometry is the art of space)
3. phenomenon of visual appearance (the visual occurrence of this phenomenon is a subjective impression, which is the subjective perception of truth. According to this, "optical illusion" is considered an error. Optical illusions are only relevant to geometric vision in terms of real objectivity, and never in terms of the perception of appearance);
4. phenomenon of imitation (without the key act of *Einfühlung* – empathy, which signifies our relationship to the world, we would perceive the world as a camera does, in an indifferent way. The things we see would hold no meaning for us. What gives specific meaning to the objects we encounter is our identification with them; we humanize them, they become part of us, and we become part of them);
5. phenomenon equally dependent on the form and content;
6. subjective phenomenon;
7. individual phenomenon;
8. functional psychological phenomenon.

According to Borisavljević, the final stage of scientific aesthetics would involve establishing the psychological determinism of aesthetic phenomena. Since cerebral psychology is still a young science, the scientific aesthetics of architecture is constrained to the study of optical and psychological phenomena, along with other physiological responses that accompany aesthetic pleasure, such as changes in body temperature, heart function, breathing, blood pressure, secretion, digestion, nutrition, and the overall effect on muscles and the nervous system. It is therefore understandable why Borisavljević devoted a significant portion of his research to the study of optical physiology, as it is believed to have a direct impact on the scientific aesthetics of architecture.

One of the main focuses and goals of Borisavljević's scientific aesthetics of architecture is the attempt to measure the perceptual experience of the viewer and analyze the results obtained through statistical methods. In his aesthetic practice, Borisavljević adopts the methodology of experimental psychologist Gustav Theodor Fechner, whose research was based entirely on statistical analysis [36]. The *gout commun* (general taste) that Borisavljević and Fechner refer to is determined by statistics and demonstrates the tendency of most people to prefer certain proportions in the visual arts.

Borisavljević believed that his study for discovering these proportional relationships was empirically most provable within the classic architectural and artistic tradition of the École des Beaux-Arts. According to Julien Guadet, this is what ultimately leads to the *canonization definitive* (definitive canonization) of these proportions [37]. This view was also supported by Borisavljević, who believed that it represented a kind of universal declaration regarding masterpieces of architecture, such as the Parthenon, St. Peter's Basilica in Rome, the Louvre, Versailles Palace, and the Gothic cathedrals in Reims, Chartres, and Paris, among others.

4. DISCUSSION

In his continuous effort to justify the scientific foundations of the scientific aesthetics of architecture, Borisavljević developed a distinct scientific metacontext in which he situated this new discipline. The framework of his aesthetic science was grounded in auxiliary fields such as physiology, psychology, medicine, physics, optics, ophthalmology, neurology, and other branches of the natural sciences. In doing so, it positioned itself in clear opposition to the traditional paradigms of continental philosophy, descriptive geometry, and linear perspective. Borisavljević further advanced this scientific aesthetics of architecture through a critical response to the prevailing philosophical aesthetics of his time. Emphasizing the contrast and asserting the complete independence of scientific aesthetics from its philosophical counterpart, he championed experimental and inductive methodologies. His central objective in developing this new metascience was to introduce simplicity, objectivity, precision, and universality into aesthetic contemplation — establishing a model of inquiry aligned more closely with the principles of the natural sciences than with abstract philosophical speculation.

It is important to highlight the duality in Borisavljević's approach to defining scientific aesthetics: on the one hand, he sought to articulate it with precision, clarity, and simplicity; on the other, he acknowledged the inherent complexity and ambiguity of aesthetic experience, particularly those emotional states that arise from the dynamic interaction between the perceiving subject and the perceived object. His ambition was to objectify the subjective experience of aesthetic phenomena by employing statistical methods and precise measurements, aiming to uncover underlying laws that could serve as the foundation of his scientific aesthetics.

In his pursuit of laws, facts, and empirical evidence, Borisavljević adopted a methodologically rigid approach to aesthetics, ultimately limiting its potential for broader scientific development. In seeking simple and scientifically valid principles, he confined his aesthetic theory within a fixed structure in which most elements were predetermined and rigidly defined. This system of strict rules left little room for theoretical evolution, effectively restricting the future growth of his own framework. However, a key strength of Borisavljević's scientific aesthetics lies in its interdisciplinary orientation and its reliance on insights from fields such as psychology, physiology, medicine, physics, and optics. The empirical nature of this approach distances aesthetics from the traditional realms of the artist's studio and philosophical discourse, moving it closer to the methodologies of laboratory-based scientific and experimetal inquiry.

It is true that Borisavljević's efforts to measure experimental results in aesthetic discourse remain undefined. The attempt to quantify perceptual and sensory experiences through statistical analysis serves only as a general framework, forming the foundation for further research. Given the significant advancements in perceptual psychology and physiology, the potential for such research is substantial. With the evolution of scientific knowledge, the scientific aesthetics of architecture could achieve practical relevance and be considered one of the exact sciences, leading to a considerable increase in its significance.

5. CONCLUSION

The study of Borisavljević's aesthetic theory presents a complex challenge, raising numerous questions. In this regard, there are two main approaches to interpreting Borisavljević's scientific aesthetics of architecture: the first sees it as a metascience — an artificially constructed theoretical model with no direct successors in the field; the second regards it as a theoretical and practical approach that, in light of today's scientific advancements, is a realistic direction, considering the progressive development of scientific thought. In conclusion, although Borisavljević's concept of scientific aesthetics had its limitations, it undeniably represented a significant contribution to Serbian architectural theory between the two world wars, allowing it to be integrated into the global discourse on architectural theory through Borisavljević's scientific insights.

It is surprising that today, half a century after the death of Milutin Borisavljević, interest in his work remains relatively modest considering the significant contribution he made to Serbian culture. Borisavljević's name is preserved from oblivion primarily through a few brief studies focused on his architectural design practice, while his theoretical work has only been partially addressed in several academic papers. One possible reason for the limited scholarly attention to his theoretical legacy lies in the fact that many of his written works have never been translated into Serbian, are not held in libraries or archives in Serbia, and are thus difficult to access. Without a doubt, Borisavljević's contribution to the theory and aesthetics of architecture is of global importance and deserves greater scholarly attention in the future.

REFERENCES

[1] Borissavliévitch Miloutine: **Les Théories de l'architecture: Essai critique sur les principales doctrines relatives à l'esthétique de l'architecture**. Thèse pour le doctorat de l'université préséntée à la Faculté des lettres de l'Université de Paris. *Payot*, Paris, 1926.

[2] Kuletin Ćulafić, Irena: **Today's traces of Belgrade Between Two World Wars: Milutin Borisavljević's Disappearing Architectural Heritage**. In: Bogdanović, Ružica (ed.) *On Architecture — Shaping the City through Architecture, Proceedings*. *STRAND*, Belgrade, 2024, pp. 290–299; https://doi.org/10.60152/2r6ipbzo (27.3.2025.)

[3] Kuletin Ćulafić, Irena: **Milutin Borisavljević kao donosilac francuskog bon goût u srpskoj arhitekturi između dva svetska rata: Ukleti neimar britke reči i neshvaćene teorijske misli o lepoti arhitekture**. In: Kadijević, Aleksandar, Ilijevski, Aleksandra, Putnik Prica, Vladana (eds.), *Nagrada za najlepšu fasadu u Beogradu između dva svetska rata*. *Univerzitet u Beogradu – Filozofski fakultet*, Beograd, 2024, pp. 23-24.

[4] Borissavliévitch, Miloutine: **Prolégomènes à une esthétique scientifique de l'architecture**. *Librairie Fiscbacher*, Paris, 1923.

[5] Tatarkiewicz, Władysław: **The History of Six Ideas: An Essay in Aesthetics**. *Martinus Nijhoff*, Warszawa, Hague, Boston, London, 1980, pp. 290-293, pp. 299-303.

[6] Platon: **Država**. *BIGZ*, Beograd, 2002, pp. 72-73, pp. 295-310.

[7] Aristotel: **Nikomahova etika**. *Izdavačka knjižarnica Zorana Stojanovića*, Sremski Karlovci, Novi Sad, 2003, p. 118.

[8] Baumgarten, Alexander Gottlieb: **Aesthetica**. *Felix Meiner Verlag*, Hamburg, 2007.

[9] Vitruvius: **Deset knjiga o arhitekturi**. *Građevinska knjiga*, Beograd, 2003.

[10] Pseudo-Dionysius: **Dionysius the Areopagite: The Divine Names and Mystical Theology**, transl. Clarence Edwin Rolt, *Society for the Propagation of Christian Knowledge*, London, 1920.
[11] Saint Thomas Aquinas: **Summa theologiae**. *Christian Classics Ethereal Library*, 1981, Question 5, Article 4. http://www.ccel.org/ccel/aquinas/summa.html (11.4.2025.)
[12] Alberti, Leon Battista: **L'Architettura [De re aedificatoria]**, transl. Giovanni Orlandi, Introduzione e note di Paolo Portoghesi, *Edizioni Il Polifilo*, Milano, 1966.
[13] Alberti, Leon Battista: **Della architettura, della pittura e della statua**, transl. Cosimo Bartoli, *Instituto delle science*, Bologna, 1782, Libro VI, cap. II (132).
[14] Baumgarten, Alexander Gottlieb: **Aesthetica**. *Felix Meiner Verlag*, Hamburg, 2007.
[15] Lajbnic, Gotfrid Vilhelm: **Monadologija**, *Kultura*, Beograd, 1957.
[16] Hume, David: **A Treatise of Human Nature**. *Oxford University Press*, New York, 1960, p. 364.
[17] Burke, Edmund: **A Philosophical Enquiry into the Origin of Our Ideas of the Sublime and Beautiful**. *R. and J. Dodsley*, London, 1757.
[18] Lesing, Gothold Efraim: **Laookon ili o granicama slikarstva i poezije**. *Rad*, Beograd, 1964.
[19] Borisavljević, Milutin: **Istorija estetike: VI Prekantovska estetika, VII Kantova estetika**. *Francusko – srpska knjižara A. Popovića*, Beograd, 1935.
[20] Kant, Imanuel: **Kritika čistoga uma**. *Kultura*, Beograd,1970; Kant, Imanuel: **Kritika praktičnog uma**. *Kultura*, Beograd, 1979; Kant, Imanuel: **Kritika moći suđenja**. *Kultura*, Beograd, 1975.
[21] Kant, Imanuel: **Kritika moći suđenja**. *Kultura*, Beograd, 1975, p. 16.
[22] Kuletin Ćulafić, Irena: **Estetička teorija arhitekture Marka-Antoana Ložijea**. Doktorska disertacija. *Arhitektonski fakultet Univerziteta u Beogradu*, Beograd, 2011, pp. 105-131.
[23] Kuletin Ćulafić, Irena: **Marc Antoine Laugier's aesthetic postulates of architectural theory**. *Spatium*, No. 23, 2010, pp. 46-50.
[24] Pugin, Augustus Welby Northmore: **Contrasts: or a Parallel Between the Noble Edifices of the Middle ages, and Corresponding Buildings of the Present day**. *John Grant*, Edinburgh, 1898;
[25] Pugin, Augustus Welby Northmore: **The true principles and revival of Christian architecture**. *John Grant*, Edinburgh 1895;
[26] Ruskin, John: **The Seven Lamps of Architecture**. *George Allen*, Sunnyside, etc., 1889;
[27] Ruskin, John: **The Stones of Venice**. *George Allen*, London, 1903;
[28] Morris, William: **News from Nowhere**. *Hammersmith [Eng.] : Printed by William Morris at the Kelmscott Press*, London, 1892.
[29] Le Korbizije: **Ka pravoj arhitekturi**. *Građevinska knjiga*, Beograd, 1999.
[30] Borisavljević, Milutin: **Arhitektura u modernom stilu**. *Srpski tehnički list*, No. 11, 1914.
[31] Kuletin Ćulafić, Irena: **Estetička teorija arhitekture Milutina Borisavljevića**. Doktorska disertacija. *Univerzitet u Beogradu – Arhitektonski fakultet*, Beograd, 2012.
[32] Borisavljević, Milutin: **Fiziologija čula vida**. *Francusko-srpska knjižara A. Popovića*, Beograd, 1939; pp. 11-12.
[33] **Empathy, form, and space: problems in German aesthetics,1873-1893**, Mallgrave, Harry Francis and Ikonomou, Eleftherios (eds.), *The Getty Center for the History of Art*, Santa Monica, 1993.

[34] Borissavliévitch, Miloutine: **Les Théories de l'architecture: Essai critique sur les principales doctrines relatives à l'esthétique de l'architecture**. *Payot*, Paris, 1926; pp. 42-44.
[35] Borissavliévitch, Miloutine: **Traité d'esthétique scientifique de l'architecture**. *Impr. des Orphelins-Apprentis d'Auteuil*, Paris, 1954; pp. 79-103, 105-121, 123-137,139-166, 168-208, 209-262.
[36] Fechner, Gustav Theodor: **Vorschule der Aesthetik**, Vol. I, II. *Druck und Verlag von Breitkopf & Härtel*, Leipzig, 1876.
[37] Guadet, Julien: **Éléments et théorie de l'architecture**, Vol. I, II. *Librarie de la construction moderne*, Paris, 1909.

doi.org/10.62683/SINARG2025.054

Research paper

AGRICULTURAL YARDS IN RURAL AREAS IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT – THE EXAMPLE OF BRODEC VILLAGE

Dimitar Krsteski[1], Aleksandar Radevski[2], Goran Mickovski[3]

Abstract

This paper first analyses the current state of the various elements of sustainability in the village, and then on a representative sample of the households i.e. agricultural yards, according to previously defined sustainability parameters. The analysis of natural, human, spatial and economic resources gives us a clear picture of the existing situation, but also gives us an insight into the potential for sustainable development. The subject of the research will be the agricultural yards in the village of Brodec. This village in terms of size and importance is the most isolated settlement in the area of Skopska Crna Gora. It is a typical mountain village at an altitude of 870 m and is 15 km away from the city of Skopje. There are great opportunities for livestock farming and forestry in the village, but unfavorable conditions for agriculture and traffic. The aim of this research is to understand the way in which agricultural yards can transform and develop sustainably. The village of Brodec has a large untapped potential in pastures and forests, but the main problem of the village is the depopulation. If the village manages to overcome the problem of depopulation and keep young people in the village, with proper investment in the infrastructure and projects for the development of small businesses, the village has a good perspective and future in sustainable development through livestock farming and rural tourism.

Key words: *Village, Rural area, Agricultural yard, Household, Sustainable development*

[1] MSc, Assistant, Faculty of Architecture at University “Ss. Cyril and Methodius” – Skopje, Republic of North Macedonia, krsteski.dimitar@arh.ukim.edu.mk, ORCID N/A

[2] Dr, Full Professor, Faculty of Architecture at University “Ss. Cyril and Methodius” - Skopje, Republic of North Macedonia, radevski.aleksandar@arh.ukim.edu.mk, ORCID 0000-0002-4804-1579

[3] Dr, Associate Professor, Faculty of Architecture at University “Ss. Cyril and Methodius” - Skopje, Republic of North Macedonia, mickovski.goran@arh.ukim.edu.mk, ORCID N/A

1. INTRODUCTION

Research on Macedonian villages compared to research on Macedonian cities in the architectural-urbanistic sense is scarce and therefore more intensive work on that problem is needed in the future. The lost time needs to be made up for with a hard and organized field survey of the current state of agricultural yards and an analysis of their impact on spatial changes in rural areas.

In this paper, an attempt has been made to study the sustainability of rural areas through the example of the village of Brodec, which is a typical mountain village 15 km away from the city of Skopje. By its size and morphology, the village belongs in the group of small dispersed villages.

Sustainable development originates from the ideas of sustainable forest management, which were developed in Europe during the 17th and 18th centuries. In 1987, the United Nations Brundtland Commission defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [1].

Sustainable development in rural areas refers to a development approach that seeks to balance economic growth, environmental preservation, and social well-being within the unique context of rural communities. It aims to improve the quality of life for rural populations while ensuring that natural resources and ecosystems are preserved for future generations.

In rural areas in Macedonia, which cover about 87% of the total area of the country, 45% of the total population lives. The most important economic activity in rural areas is agriculture, which affects the alleviation of poverty and unemployment [2].

Agricultural yards are the basic architectural unit of the village. Their main function is to protect the various buildings and landscaped areas that are necessary for the life and work of the village residents. In addition to the house, agricultural yards usually have facilities for raising domestic animals, storing and processing agricultural products, etc. Such organization of agricultural yards represents a complex in which each component, regardless of whether it is a building or a landscaped area, has a precisely defined purpose. From this it can be concluded that the sustainability of the village is to the greatest extent based on their own capacities.

In his research Turnšek defines five factors of the village sustainability: population, village district, living conditions, infrastructural facilities and condition of households and buildings [3].

These factors cover social, spatial, economic, and physical aspects of rural life, and they provide a framework for assessing the long-term viability and resilience of rural settlements. First factor refers to the demographic structure and dynamics of the village population. Village district includes the spatial organization and land use within and around the village. Living conditions represent the quality of life for village residents. Infrastructural facilities cover the physical infrastructure that supports everyday life. Condition of households and buildings involves the physical state of housing and built structures in the village.

Households and buildings represent the agricultural yards. The household was not just a unit of residence, it was also the unit of production. The agricultural yards were the physical manifestation of that dual function. But agricultural yards are more than functional units, they are also cultural artefacts that reflect the family structure, the economy strategy and climatic and topografic adaptation.

The purpose of this paper is to create a recognizable framework for an effective strategy for the observation, qualitative assessment, protection and sustainable development of rural areas in Macedonia, through the analysis of five factors of village sustainability. The concept of sustainable development of villages must rely on their own capacities because otherwise there is a great chance to destroy the most valuable aspects of rural environments such as the natural landscape and the inherited ambient values of vernacular architecture.

2. HISTORY OF THE BRODEC VILLAGE

Brodec got its name from the fact that it lies "on the boat", i.e. at the place where the mountain Skopska Crna Gora crosses from the Skopska Kotlina in the south to the Binacke Morave district in the north. In historical sources, under the name Brodac, this settlement was first mentioned in 1348. Then, as a smaller village of the larger village of Kučevishte, Emperor Dušan attached it to the Church of the Holy Archangels near Prizren. By the end of the World War I, Brodec was a relatively prosperous village. The population grew rapidly and the economy prospered. Most people lived from livestock and forestry. In the north of the village, in the highly mountainous part of the village area, stronger springs emerge: Virovi and Korito, and at one point there were about 20 summer cottages. At that time, numerous mountain fields were also cultivated. In 1920, Brodec had the largest number of houses - 32 in total. Each household had several members, so in 1937 a modern elementary school was built for 37 children. In the 1970s, the village of Brodec began to slowly die out. The reason for this extinction is the ban on raising goats and selling wood in Skopje, as well as great pressure on the land from the larger surrounding villages [4].



Figure 1. Village of Brodec (map from Google Earth)

At the beginning of the 20th century, the village of Brodec reached its lowest point with only 3 residents. But instead of completely disappearing, today it is slowly starting to recover and increase its population. According to the last census of 2021, 11 inhabitants lived in the village.

3. METHODOLOGY

The methodology for this research should encompass various aspects and should be adapted to the specific objectives, in order to provide accurate data through which precise conclusions can be drawn. The research is largely based on data collected through official statistics, scientific researches and fieldwork.

The data about the population is taken and from the censuses from the World War II to the present day carrieed out by the State Statistics Office of the Republic of Macedonia. The "Encyclopedia of the Villages of the Republic of Macedonia" by Mitko Panov was used to collect the Informations about the village district. For the remaining three factors of village sustainability, field recording was necessary to collect the data needed to conduct the research. First the interviews were made with local residents to get a clearer picture of the living conditions in the village and the real problems they face. The surveyed households were selected randomly, in order to obtain relevant information for the assessment of the existing situation. Then, the data on the infrastructure was collected from the local public services that are in charge of their maintenance. Finally, photographs were taken of the houses and agricultural buildings in the agricultural yards, and some of them were also documented through architectural recording.

4. RESULTS

According to the five factors of village sustainability, the research results are systematically organized and presented through the titles of each chapter.

4.1. Population

Historically, the village of Brodec experienced a significant decline in population due to the difficult living conditions. The table presents a clear trajectory of demographic change in the village from 1948 to 2021, highlighting a steady and severe population decline over the second half of the 20th century [5, 6].

Table 1. Overview of the population in the village of Brodec, according to the State Statistics Office of the Republic of Macedonia in all census years

year	1948	1953	1961	1971	1981	1991	1994	2002	2021
population	191	170	129	44	28	14	6	3	11

From a population of 191 residents in 1948, the village experienced consistent depopulation, dropping to only 3 residents by 2002. This sharp decrease reflects broader rural to urban migration trends and socio-economic transformations that have had a profound impact on the spatial and architectural integrity of the village.

Interestingly, the slight population increase to 11 residents in 2021 introduces a critical point of reflection. Although only 11 residents are registered as residents in the village, the actual number of residents of the village is much higher, given the fact that a large number of them are also registered at other addresses. Though modest, this demographic shift may indicate a renewed interest in rural living, heritage conservation, or the potential for small-scale regeneration.

4.2. Village District

The village of Brodec is located in the northeastern part of the Skopje Valley, and its territory rises on the ridge of the mountain of Skopska Crna Gora and touches the area of the Lipkovo Municipality. Brodec is typical mountain village at an altitude of 870 m and belongs to the Municipality of Chucher-Sandevo. It is 15 km away from the city of Skopje. The village district covers an area of 9.2 km². Forests cover an area of 480.3 hectares, pastures cover 370.8 hectares, and arable land covers 51.7 hectares [7].

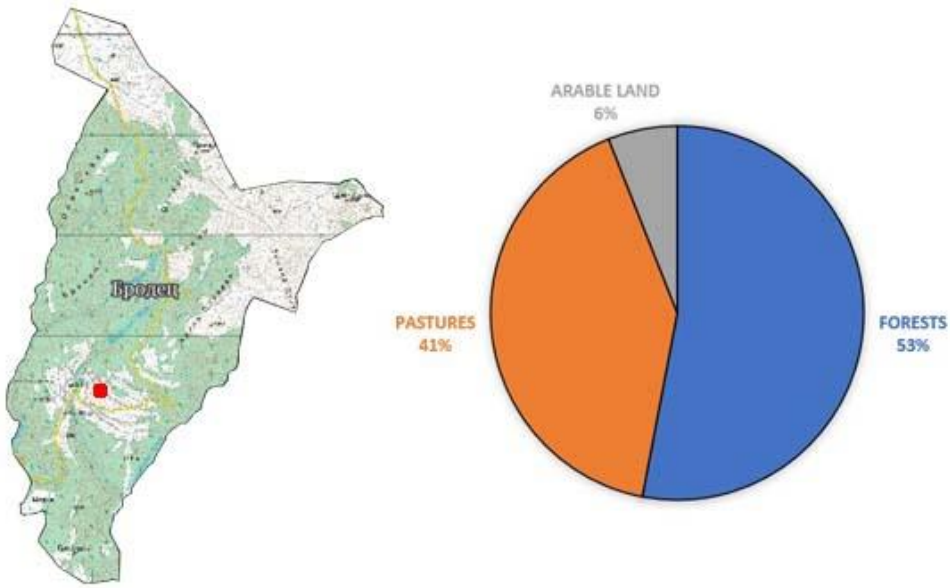


Figure 2. Village district and land use diagram in the village of Brodec

The village district is extremely rich in forests and pastures, which only confirms the fact that the village lived from livestock and forestry.in the past. Land use distribution within the village highlights a landscape dominated by natural and semi-natural features: forests account for the majority of the area, covering 480.3 hectares (approximately 53% of the total), while pastures occupy 370.8 hectares (approximately 41% of the total). In contrast, arable land comprises only 51.7 hectares (approximately 6% of the total), suggesting limited agricultural productivity and reinforcing the village's reliance on pastoralism and forestry rather than crop cultivation.

With today's livestyle pastures and forests can be meaningfully incorporated into rural tourism through ecologically sensitive tourism models. Forests can serve as the foundation for hiking, birdwatching, foraging, photography or wildlife observation and pastures offer scenic open spaces for walking trails, picnic spots, and guided tours of traditional land use.

4.3. Living Conditions

The living conditions in the village of Brodec are currently very limited and reflect the broader issues of rural depopulation.

Table 2. Program contents in the village of Brodec
(●- developed/satisfactory, ■ - exists/unsatisfactory, ▲ - absent/problematic)

program contents	school	health clinic	post office	local community	church	store	resta urant	park
village of Brodec	▲	▲	▲	▲	●	▲	●	■

In the village of Brodec, there is a pronounced lack of facilities of a social, cultural, and health nature. Due to its remote mountain position and extremely small population, the village does not have a school, health clinic, post office, or a store with basic groceries, an absence that significantly affects the quality of life and forces the remaining residents to travel to other villages or the city of Skopje for even the most essential services. There is no active public building functioning as a community hub, although former residential and communal structures exist in an abandoned or partially collapsed state. Historically, the village possessed a stronger social dynamic, but today it suffers from infrastructural and social stagnation. The surrounding mountainous landscape of Skopska Crna Gora offers exceptional natural beauty, clean air, and opportunities for hiking, recreation, and nature tourism. On occasion, hikers and visitors from Skopje and surrounding areas come to explore the area, especially during warmer months. In recent years, isolated efforts by former residents or descendants of Brodec families have led to limited revitalization activities, such as the organization of gatherings around major religious holidays or seasonal visits, often centered around outdoor spaces and remnants of architectural and cultural heritage.

However, these efforts remain architecturally and infrastructurally unsupported, highlighting the urgent need for a more strategic spatial intervention framework. Sustainable reintegration of Brodec into the broader regional context will require targeted investment, adaptive reuse strategies, and a redefinition of its architectural and landscape assets as part of a long-term vision for rural regeneration.



Figure 3. Photos of architectural and cultural heritage in the village of Brodec

4.4. Infrastructural facilities

The infrastructure facilities in the village of Brodec are in a highly deteriorated state, reflecting the effects of long-term depopulation, lack of investment, and geographical isolation.

Table 3. Infrastructure facilities in the village of Brodec
(●- developed/satisfactory, ■ - exists/unsatisfactory, ▲ - absent/problematic)

infrastructure facilities	electrical network	water supply	sewage system	TV - internet	telephone network	waste service	roads
village of Brodec	■	■	▲	■	■	●	■

Basic infrastructure is either minimal or entirely absent. Electricity may be present in all homes, but electrical network needs to be improved. There is no centralized water supply system, and because of that water is sourced from natural springs or wells. There is no sewage system, so the wastewater disposal is mostly handled via improvised septic tanks or direct ground infiltration, which presents risks to hygiene and environmental quality. Telecommunications are available but sometimes the signal is weak or inconsistent due to mountainous terrain. Waste management is organized and municipal services perform their work in a timely manner. The road network is very scarce, so apart from the main street through the village which is asphalted and in good condition, all other streets in the village are narrow due to the terrain and are in bad condition. Public transportation does not serve the village, requiring residents or visitors to have private transport.

Improving the infrastructure in the village of Brodec requires a strategic and context-sensitive approach that respects the natural and cultural heritage, but also provides the minimum conditions necessary for rural regeneration, tourism potential, and basic quality of life.

4.5. Condition of agricultural yards with households and buildings

Several agricultural yards were analyzed in order to gain a clearer picture of the way the functional zones for housing, economy and gardening are organized. The displayed agricultural yards represent the characteristic ways of organizing the space within the parcel.

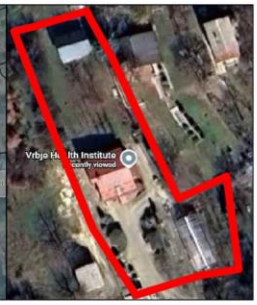
The dominant spatial characteristic of the traditional agricultural yards in Brodec is the presence of a single multifunctional house occupying the entire plot. This multifunctional house was conceived as an integrated unit that accommodated both human and animal habitation. The ground floor functioned as a barn or stable that was housing livestock, while the upper floor was reserved for residential use. During the winter months, the body heat generated by the animals below contributed to warming the living quarters above. This vertical spatial arrangement was not only a response to programmatic efficiency, but also reflected a climatic strategy rooted in local knowledge. Nowadays, these houses no longer serve multifunctional purposes. The ground floors are no longer used to accommodate animals and have typically been converted into storage spaces or living areas. The houses now function solely as private residential homes, adapted to modern standards of comfort and use.

agricultural yard no.1
1.house, 2.warehouse, 3.shed, 4.summer canopy, 5.metal canopy

parcelling



google earth



photography



agricultural yard no.2
1.house, 2.warehouse, 3.shed, 4.summer canopy, 5.bar, 6.goat shelter, 7.barn

parcelling

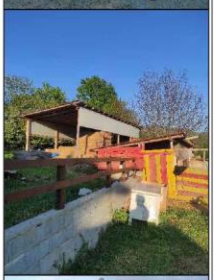


google earth



photography







agricultural yard no.3
1.house

parcelling



google earth

photography



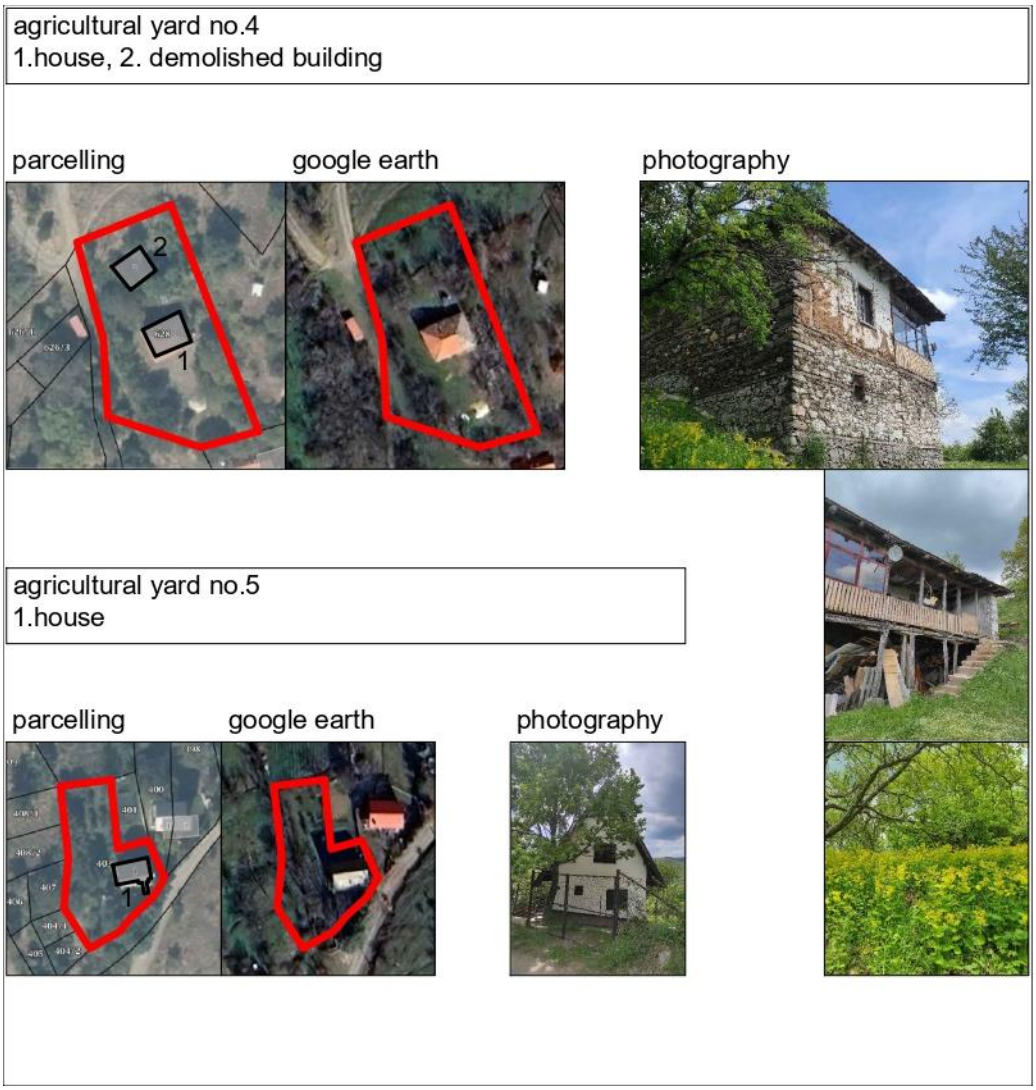


Figure 4. Organization and photos of several agricultural yards in the village of Brodec

Today in the context of agricultural yards, it is evident that those which remain functionally active in agricultural activity (mushroom production and raising goats) tend to occupy larger, consolidated plots. These expanded parcels are typically the result of the merging of two or three adjacent land units, allowing for a more spatially efficient organization of built and unbuilt elements, such as the residential building, economy facilities, and open space for gardening. This process of parcel aggregation reflects both a functional response to contemporary agricultural needs and a transformation in the spatial morphology of the rural fabric.

The households i.e. agricultural yards were analyzed in terms of the size, form. built surface, zoning of functional units, number and quality of the buildings, as well as the number and types of households. One of the tasks was to assess whether the households are oriented toward an agricultural economy or dependent on other jobs in the surrounding villages or the city of Skopje. The collected data for agricultural yards with households and buildings are given in the next table.

Table 4. Presentation of the current state and sustainability of analyzed agricultural yards with households and buildings the village of Brodec, (small agricultural yard – up to 1000m², large agricultural yard – over 1000m²)

agricultural yards with households and buildings	no.1	no.2	no.3	no.4	no.5
size of the agricultural yard - м²	1982 (large)	2853 (large)	1131 (large)	1827 (large)	580 (small)
built surface of the agricultural yard - м²	352 (18%)	345 (12%)	72 (6%)	87 (5%)	60 (10%)
number of parcels in the agricultural yard	3 irregular	3 irregular	2 irregular	1 irregular	1 regular
zoning of functions in the agricultural yards (resident./econom./ garden)	1+1+1 yes	1+1+1 yes	1+0+0 no	1+0+1 no	1+0+0 no
number of buildings in the agricultural yards	5	7	1	1	1
quality of the buildings in the agricultural yard	new buildings	new buildings	new building	traditiona l building	new building
number of members in a household	2	3	2	1	1
household type	mixed	agricultural	non-agricultural	agricultural	non-agricultural

The table of the selected agricultural yards in Brodec reveals distinct patterns in parcel configuration, functional zoning, and building typology, reflecting varying degrees of continuity with traditional rural spatial models. The larger plots composed of few parcels exhibit a higher number of buildings, often including both residential and economic structures, and show more complex zoning of use that is clearly visible. In contrast, smaller plots represent the more compact model, composed of a single regular parcel with only one building and minimal built surface.

From an architectural perspective, the built-up surface percentage ranges from 5% to 18%, indicating a generally low-density development pattern consistent with traditional agricultural yards. The prevalence of new buildings in most yards, however, points to a trend of reconstruction or infill, with varying levels of sensitivity to traditional architectural character.

The household composition varies significantly, with larger, multifunctional yards typically supporting mixed or agricultural households, while smaller, mono-functional yards correlate with non-agricultural or single-person households. This suggests that functional diversity and spatial complexity in the yard are often tied to household size, activity type, and long-term occupation.

Overall, the analysis reveals a gradual spatial and functional transformation of agricultural yards, shaped by two dominant architectural and land-use patterns. The first transformation typology is characterized by the amalgamation of multiple parcels into a unified property structure, resulting in expanded yards with an emphasized economic function, typically supporting agricultural production, auxiliary buildings, and flexible working zones. This model reflects a horizontal intensification of rural land use, where spatial consolidation enables more

efficient organization of built and open areas. The second typology involves the retention of singular, compact plots with a minimal built footprint, often reprogrammed for residential or accommodation use. These yards shift away from productive agriculture toward domestic or tourism-oriented functions, representing a form of functional repurposing within a reduced spatial scale. Architecturally, such transformations suggest a redefinition of the yard, from a working agricultural compound to a residential enclave or potential rural hospitality unit, responding to emerging economic opportunities and demographic shifts.

In the village, there is still a small number of older traditional houses in stone and timber frame construction, most of which are in poor condition and non-functional. With their renovation, the traditional ambient values of the village would be restored.



Figure 5. Photos of traditional architecture in the village of Brodec

5. DISCUSSION

The agricultural yard as basic architectural unit, represents a fundamental spatial typology in rural settlements. In the village of Brodec, this typology reflects the complex interaction between topography, economy, climate, and vernacular building practices. Analyzing agricultural yards through the lens of architectural logic and sustainable development reveals both the challenges and potentials of reactivating these spaces in the contemporary rural context.

The observations in the village of Brodec reveal two dominant trends in the transformation of agricultural yards. The first involves parcel aggregation, where multiple parcels are combined into a larger economic unit, preserving the multifunctional role of the yard but often with the introduction of new buildings that deviate from the traditional vernacular style. The second is the reduction of function and scale, where smaller yards with minimal built structures are repurposed for non-agricultural uses, most often as weekend houses or tourist accommodations. These typological shifts raise architectural concerns. In many cases, new construction lacks contextual sensitivity that are ignoring site slope, traditional materials, or the proportionality of built-to-open space. Conversely, the yards that remain in their original form suffer from neglect, structural deterioration, or partial collapse. Without active use or strategic intervention, the spatial coherence and architectural identity of the agricultural yard risk being lost.

The sustainable potential of agricultural yards lies in their capacity to integrate ecological, economic, and cultural dimensions within a single spatial entity. The architectural and spatial configuration of agricultural yards in the village of Brodec, holds considerable potential for adaptive reuse in the context of rural tourism. The thick stone walls, simple construction techniques, and multifunctional interiors provide a strong foundation for restoration,

especially for purposes such as guesthouses, eco-lodges, or educational spaces that promote sustainable heritage experiences. Their compact size and integrated functions make them ideal for conversion into small-scale accommodations that retain the authenticity of the original structure while serving new contemporary uses. However, due to their limited scale and the fragmented nature of surrounding land plots, these yards are generally not suitable for more extensive agricultural production.

The transformation of these yards into tourist-use buildings would also require minimal land consumption, preserving the original footprint and respecting the ecological balance of the site. Additionally, this model supports the principles of heritage conservation through use, ensuring that preservation is economically and socially sustainable, rather than static and museum-like.

The agricultural yard, as seen in Brodec, is more than a unit of land, it is an architectural typology that encapsulates the rhythms of rural life, the ingenuity of vernacular design, and the principles of sustainable development. Its revival depends not only on restoration but on creative reinterpretation, where traditional spatial values inform new functions and programs. In this way, agricultural yards can evolve from forgotten spaces into architectural frameworks for a sustainable rural future.

6. CONCLUSION

The field analysis and historical data clearly indicate that Brodec is suffering from a multi-layered form of abandonment: physical, social, and institutional. The collapse of built structures, the absence of basic services such as water supply, sewage system, road maintenance, and the disappearance of social infrastructure (schools, shops, communal centers) have transformed Brodec into a space of memory rather than a space of daily life.

But, the case of Brodec demonstrates that agricultural yards, though often overlooked, are essential components of rural sustainability. Their architectural form and multifunctional logic, position them as strategic assets for revitalizing the rural space. When supported by appropriate infrastructure, sensitive policy, and community engagement, they can be transformed into hybrid systems that bridge heritage, productivity, and tourism. Sustainable development in Brodec and in similar rural contexts depends on this layered, adaptive understanding of the agricultural yard not just as a remnant of the past, but as a foundation for the future.

Future planning should incorporate interdisciplinary strategies that integrate conservation, sustainable land use and low-impact tourism to ensure a culturally and ecologically resilient future for the village of Brodec.

REFERENCES

[1] World Commision on Environment and Development: **Our Common Future**. *Oxford University Press*, Oxford, 1987.

[2] Ministry of Agriculture, Forestry and Water Economy: **National Strategy for Agriculture and Rural Development for the period 2021-2027**. *Goverment of Republic of North Macedonia,* Skopje, 2021.

[3] Turnsek Branko: **Village Knez Selo in the context of sustainable Development.** *2nd ICAUD International Conference in Architecture and Urban Design,* Epoka University – Tirana – Albania, 2014
[4] Trifunoski Jovan: **Skopska Crna Gora**. *Univerzitetska pecatnica*, Skopje, 1971.
[5] State Statistical Office of the Republic of Macedonia: **Population by age and sex, by settlements, according to the censuses conducted in the Republic of Macedonia after World War II.** *Goverment of Republic of Macedonia,* Skopje, 1948-2002.
[6] State Statistical Office of the Republic of North Macedonia: **Total resident population of the Republic of North Macedonia by ethnicity, by populated areas, Census 2021**. *Goverment of Republic of North Macedonia,* Skopje, 2021
[7] Panov Mitko: **Енциклопедија на селата во Република Македонија**. *Patrija,* Skopje, 1998.

doi.org/10.62683/SINARG2025.055

Research paper

APPLICATION OF THE SIMULATION MODEL FOR READY MIXED CONCRETE SUPPLY

Biljana Matejević-Nikolić[1], Lazar Živković[2], Nenad Stojković[3], Nikola Velimirović[4]

Abstract

The construction of many buildings requires ready mixed concrete (RMC) delivery from concrete plants. It is common to supply multiple construction sites, simultaneously, from one or more concrete plants. In such cases, a crucial task is planning the appropriate delivery schedule to each construction site in order to minimize or avoid machinery idling. This paper presents the application of an original model developed in AnyLogic simulation software. The model is based on a hybrid approach, combining two simulation techniques: discrete event and agent-based simulation. This model addresses the supply chain problem, or transportation problem, and can solve the duration and cost of concrete delivery from up to three concrete plants to a maximum of three construction sites simultaneously. The model allows for cost optimization and several other analyses. The fleet of mixers included in the model can be adjusted before running the simulation through the OptionPlant excel file. This paper analyzes a case study based on real parameters obtained from a specific concrete plant and construction sites. Two construction sites and one concrete plant are considered. The costs of transportation, total costs, as well as pump and mixer penalty costs, are calculated. Different analyses and discussion based on conducted results are provided to improve the concrete delivery process.

Key words: *Cost, Simulation, Delivery, Transportation, Ready Mixed Concrete, Supply Chain*

[1] PhD associate professor, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, biljana.matejevic@gaf.ni.ac.rs, ORCID 0000-0001-9228-9021
[2] MEng teaching assistant, PhD student, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, lazar.zivkovic@gaf.ni.ac.rs, ORCID 0000-0002-0765-4854
[3] PhD assistant professor, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, nenad.stojkovic@gaf.ni.ac.rs, ORCID 0000-0002-6892-7908
[4] PhD assistant professor, University of Niš, Faculty of Civil Engineering and Architecture, Serbia, nikola.velimirovic@gaf.ni.ac.rs, ORCID 0000-0002-6298-8216

1. INTRODUCTION

Proper planning of concrete delivery (Ready-Mix Concrete Delivery Problem – RMCDP) is a challenge, especially when pouring takes place simultaneously at different construction sites supplied by the same concrete plant. This issue becomes even more complex when different construction sites require different types of concrete. The RMCDP becomes significantly more complicated when multiple construction sites simultaneously require various types of Ready-Mix Concrete (RMC), necessitating the involvement of multiple concrete plants [1]. Challenges include supply in crowded areas, setting up pump supply lines, determining the quantity of the last Transit Mixer (TM), and the need for advance planning. A delay at one site, for any reason, will alter the schedule of the entire delivery line. Additionally, regular repairs and maintenance of the plant, pump, and truck mixers during peak seasons add to the complexity, as does the coordination and timing of dispatch and the distance from the plant to the site [2].

The majority of ready-mix concrete orders require precise timing and the staggered operation of several trucks [3]. The use of a larger number of truck mixer vehicles with different drum volumes can result in unnecessary costs due to improper scheduling.

The decision-maker must determine how many vehicles of each type to use, given a mix of vehicle types with differing capacities and costs. They must also decide when to begin picking up the orders and when each order should be assigned to a vehicle, ensuring that the orders are optimized into an efficient delivery route. The operational decision-making process involves determining the minimum total cost, which includes fixed vehicle costs, variable routing costs, and penalty costs for violating time windows [4].

Constructors require an uninterrupted supply of concrete; therefore, the time between consecutive deliveries must be minimized as much as possible [5].

Since this process involves risk and is subject to elements of probability, stochastic planning and decision-making methods are most effective for determining the optimal parameters. This paper presents an original model developed in AnyLogic© software to address the problem of supplying multiple construction sites with ready-mix concrete from multiple plants in a stochastic environment [6].

2. METHODOLOGY AND INPUT PARAMETERS

In this paper, the problem of simultaneous concrete pouring for foundations at two construction sites supplied by the same concrete plant is analyzed. To address the issue of finding the optimal combination of mixers, a simulation model developed in [6] was applied. Based on data collected from the construction sites and the concrete plant, which serve as the input parameters (Figure 1), the process was simulated. The model was run 50 times for each fleet combination across different mixer combinations available at the considered concrete plant. Additionally, five extra combinations, which are not available at the considered concrete plant, were included to examine the potential benefits of using them.

The amount of concrete required for the counter slab on the first construction site is 325.00 m^3 of class C35/45 (MB45) concrete, out of a total of 2,597.00 m^3.

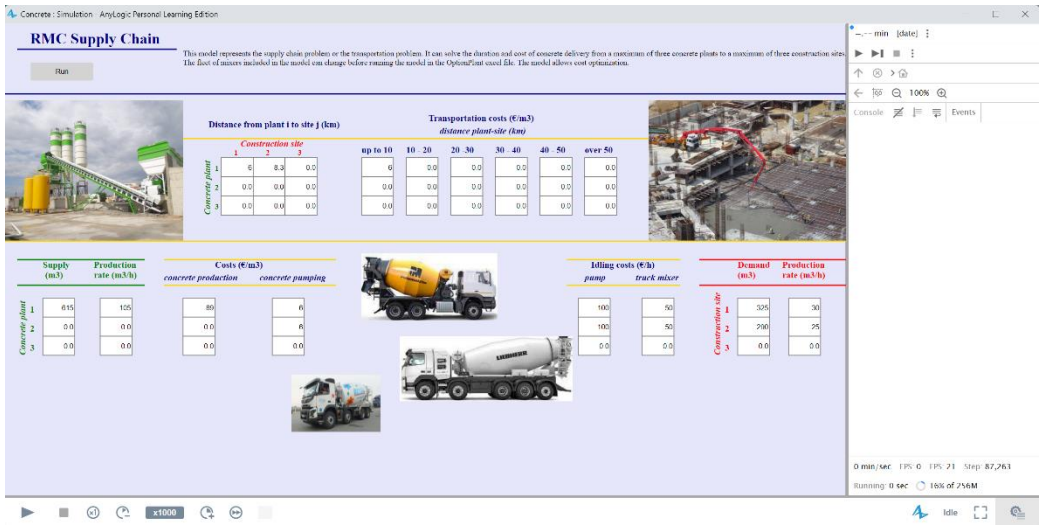


Figure 1. RMC delivery process simulation model: input parameters, author's own creation

The pouring of the counter slab on this project is carried out in 8 stages. The amount of concrete required for the foundations of the single columns at the second construction site is 290.00 m³ of the same concrete class. The first stage of the counter slab at construction site 1 and the foundation columns at construction site 2 are performed simultaneously, with concrete supply coming from the same concrete plant. The concrete plant has a capacity of 105 m³/h and operates with 2 mixers, each with a volume of 7 m³, 3 mixers with a volume of 9 m³, and 3 mixers with a volume of 11 m³. Concrete pumps at the construction sites achieve a performance of 30 m³/h at the first site and 25 m³/h at the second site.

The production cost of concrete for the specified class is 89 €/m³, while the concrete pouring charge is 6 €/m³. The transportation cost is 6 € per m³ for distances up to 10 km. The first construction site is 6 km away, and the second site is 8.3 km from the concrete plant. According to data from the concrete plant, additional charges for waiting time apply only if the waiting time exceeds 45 minutes. If the waiting time exceeds this threshold, each additional 45-minute interval is charged at the applicable rates: 100 € for the pump and 50 € for the truck mixers.

The concrete plant and construction sites are located in the city of Niš.

The idling costs in the model are calculated based on the input unit costs, as shown in equation (1):

$$\text{Penality cost} = \sum_{j=1}^{2}(Cost\ of\ truck\ mixer\ idling_j + Cost\ of\ pump\ idling_j) \quad (1)$$

And total cost of process as shown in equation (2):

$$\text{Total cost} = \sum_{i=1}^{1}\sum_{j=1}^{2}(Production\ cost_i + Transportation\ cost_{ij} + Penality\ cost_j + Pouring\ cost_j) \quad (2)$$

Where:

Penality cost$_j$ – cost of idling (truck mixer and pump) at site *j* (€),

Cost of truck idling$_j$ – cost of idling truck mixer at site *j* (€),

Cost of pump idling$_j$ – cost of idling pump at site *j* (€),

Total cost – total cost of concreting (€),
Production cost$_i$ – cost of concrete production in plant *i* (€),
Transport cost$_{ij}$ – cost of concrete transport from plant *i* to site *j* (€),
Pouring cost$_j$ – cost of concreting with pump at site *j* (€)
n=1 – number of concrete plants
m=2 – number of construction site

Unit cost is calculated according equation (3):

$$\text{Unit cost} = \frac{Total\ cost}{Total\ amount\ of\ concrete}\ \left(\text{€}/m^3\right) \tag{3}$$

The goal of applying the simulation model is to find a combination of mixers that minimizes waiting costs for both the pump and the mixers. During the simulation, the process was monitored using a process chart (Figure 2) and a 2D view (Figure 3).

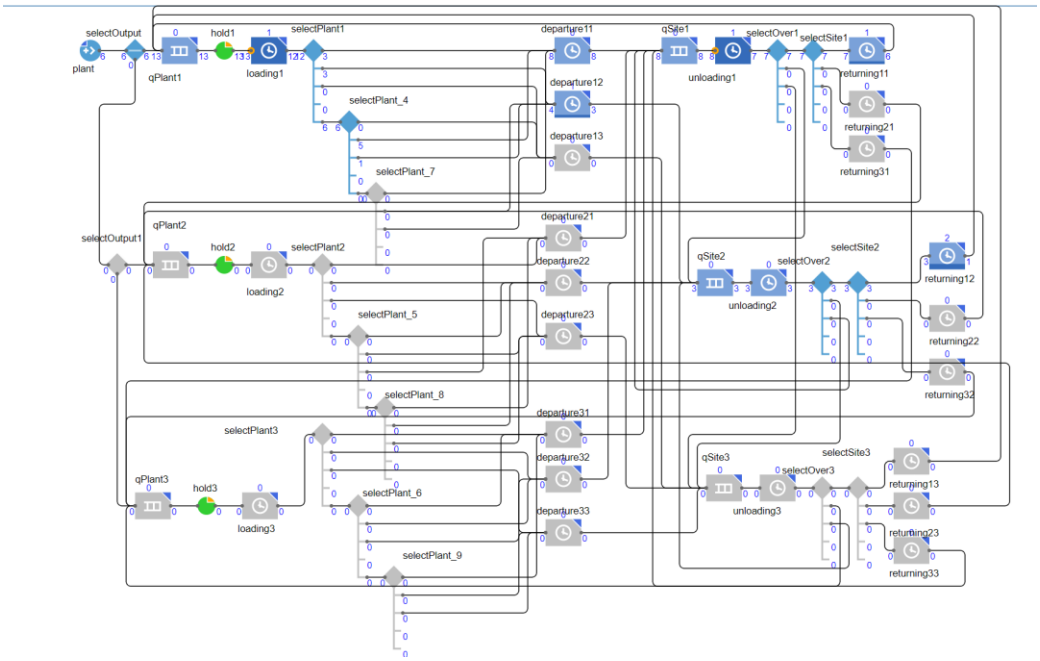


Figure 2. RMC delivery process simulation model: one concrete plant and two construction sites are used, author's own creation

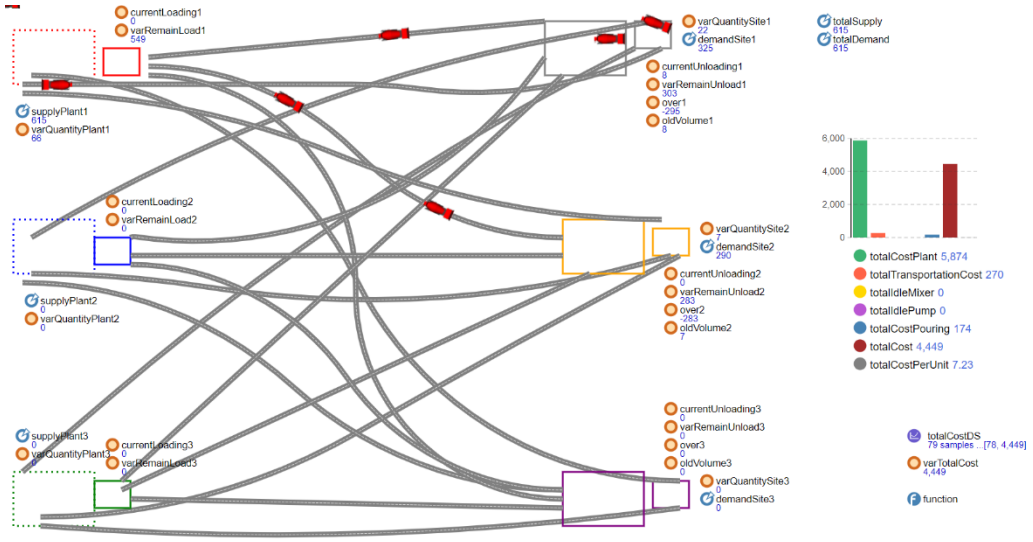


Figure 3. RMC delivery process simulation model: 2D view during simulation, author's own creation

3. RESULTS OF THE SIMULATION EXPERIMENT

All possible acceptable combinations of mixers available at the concrete plant were considered, totaling 18, along with an additional five combinations featuring mixer volumes that the concrete plant does not possess but were assumed to yield better results. A simulation experiment was conducted for each combination by running the simulation 50 times, followed by a statistical analysis.

Table 1 presents the considered scenarios for different truck mixer fleets with their total volumes. The last column of the table shows the process duration as a result of the simulation. The truck mixer fleets that were additionally included are shown in the shaded rows.

Table 1. Fleet combination and duration of process

Scenario	Number of truck mixer in fleet	Truck mixer combination	Total truck mixer volume (m^3)	Process duration (min)
1	3	1×7+1×9+1×11	27	1625
2	4	2×7+2×9	32	1363
3	4	2×7+1×9+1×11	34	1335
4	4	1×7+2×9+1×11	36	1318
5	4	1×7+1×9+2×11	38	1267
6	4	1×7+3×11	40	1222
7	4	2×9+2×11	40	1239
8	5	5×8	40	1141
9	5	2×7+3×9	41	1162
10	5	3×8+2×9	42	1133
11	5	2×7+2×9+1×11	43	1137

12	5	2×8+3×9	43	1124
13	5	5×9	45	1123
14	6	3×7+3×8	45	1070
15	5	2×7+1×9+2×11	45	1148
16	5	2×7+1×9+2×11	45	1116
17	5	2×7+3×11	47	1137
18	5	1×7+2×9+2×11	47	1109
19	6	2×7+3×9+1×11	52	1023
20	6	2×7+2×9+2×11	54	995
21	6	3×9+3×11	60	968
22	7	2×7+3×9+2×11	63	852
23	7	2×7+3×9+3×11	74	764

For each scenario, the idling cost, as well as the total and unit costs, are presented in Table 2. The transportation cost is 3,690 €, the pouring cost is 3,690 €, and the plant production cost is 54,735 €. These costs are constant for all fleet combinations and are excluded from the table.

Table 2. Cost for different fleet size

Scenario	Truck mixer idling cost (€)	Pump idling cost (€)	Total idling cost (€)	Total cost (€)	Unit cost (€/m^3)
1	0	1000	1000	63115	102.63
2	0	400	400	62515	101.65
3	0	600	600	62715	101.98
4	0	600	600	62715	101.98
5	0	300	300	62415	101.49
6	0	400	400	62,515	101.65
7	0	600	600	62715	101.98
8	0	100	100	62215	101.16
9	0	100	100	62215	101.16
10	0	100	100	62215	101.16
11	0	100	100	62215	101.16
12	0	100	100	62215	101.16
13	0	100	100	62215	101.16
14	0	0	0	62115	101.00
15	50	200	250	62365	101.41
16	150	300	450	62565	101.73
17	100	200	300	62415	101.49
18	100	100	200	62315	101.33
19	350	0	350	62465	101.57
20	400	0	400	62515	101.65
21	300	0	300	62415	101.49
22	200	0	200	62315	101.33
23	150	0	150	62265	101.24

Figures 4 and 5 show the cost structure for construction sites 1 and 2, respectively. It can be observed that the largest share of costs comes from concrete production (88%), while other costs are less significant. This cost structure chart represents the best mixer combination after the simulation was completed.

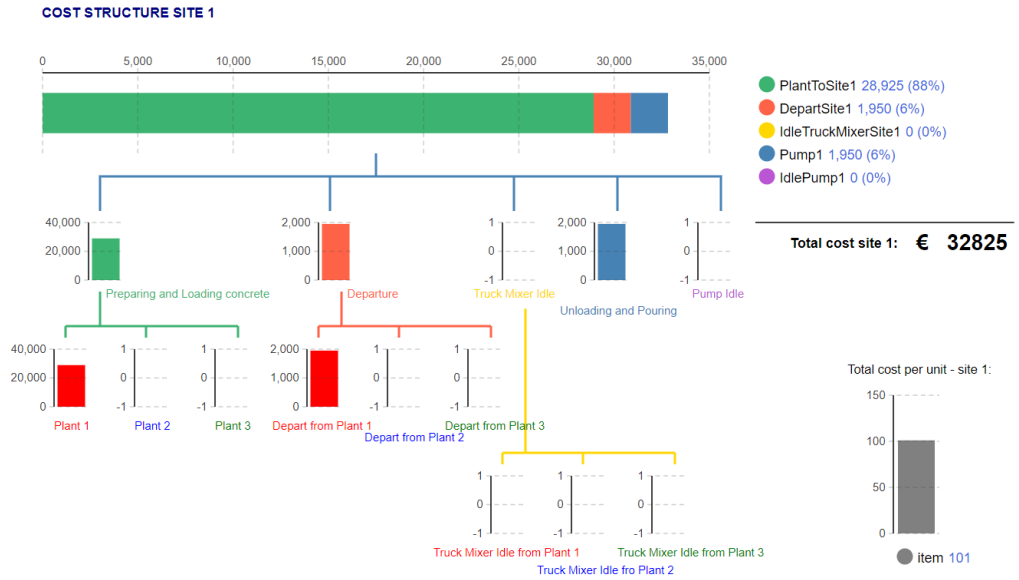


Figure 4. RMC delivery process simulation model: cost structure on site 1, author's own creation

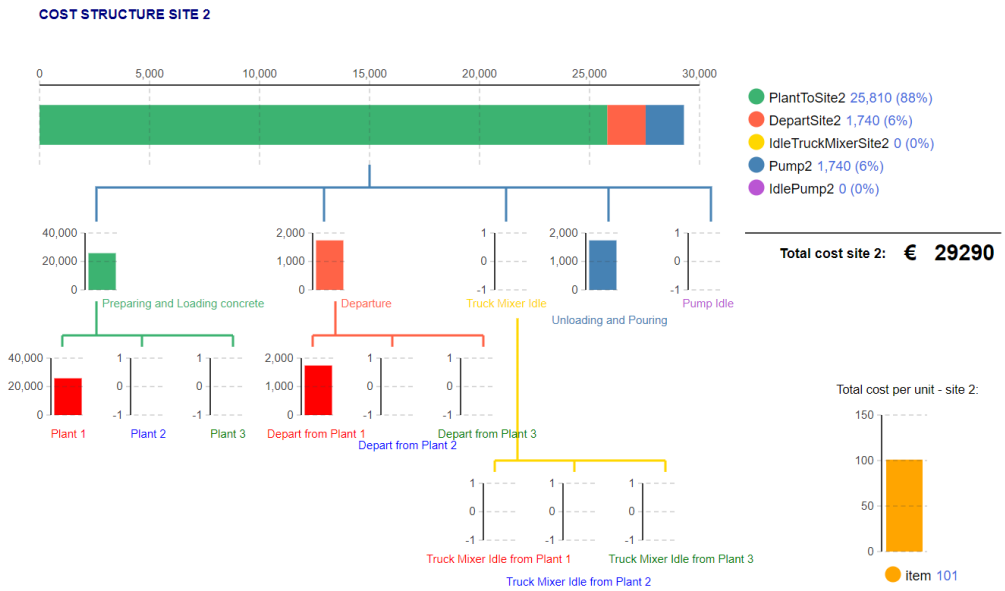


Figure 5. RMC delivery process simulation model: cost structure on site 2, author's own creation

Based on Tables 1 and 2, a graphical presentation of idling costs for different truck mixer fleets is shown in Figure 6, unit costs in Figure 7, and process duration in Figure 8. In each graph, the combinations that provide the best solutions are highlighted.

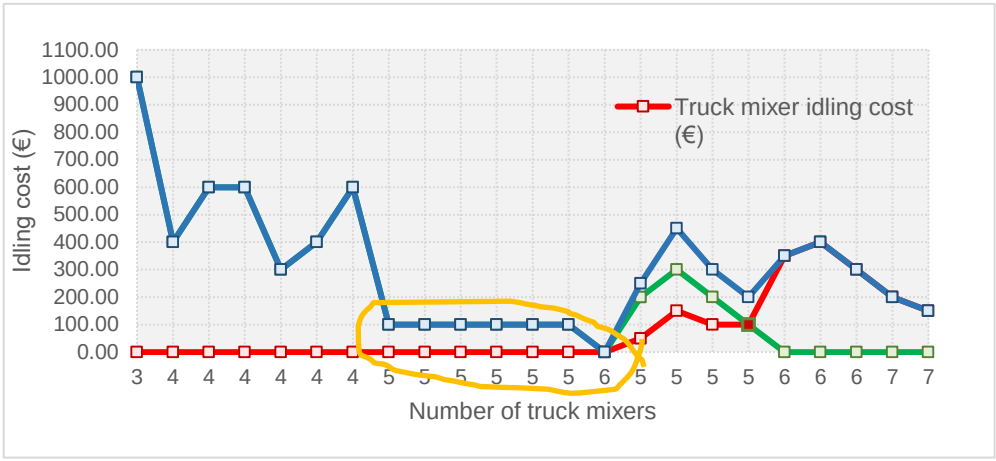


Figure 6. Idling cost for different fleet size, author's own creation

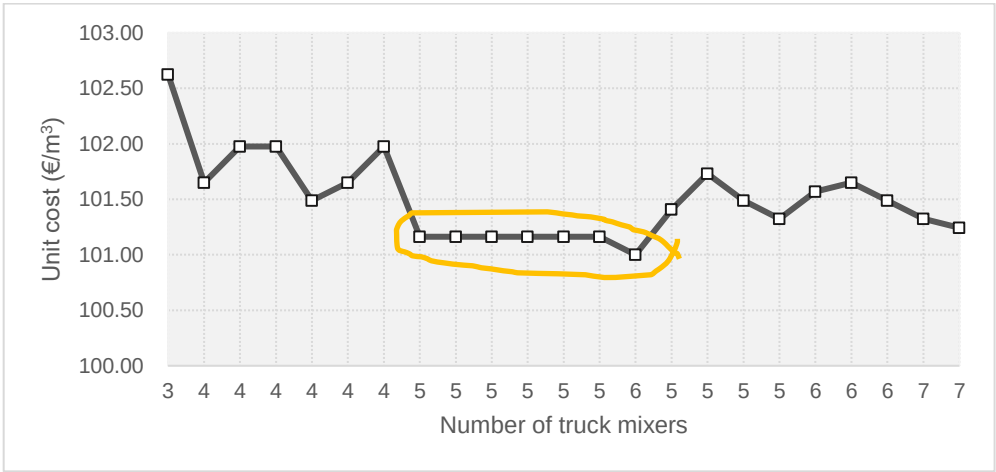


Figure 7. Unit cost for different fleet size, author's own creation

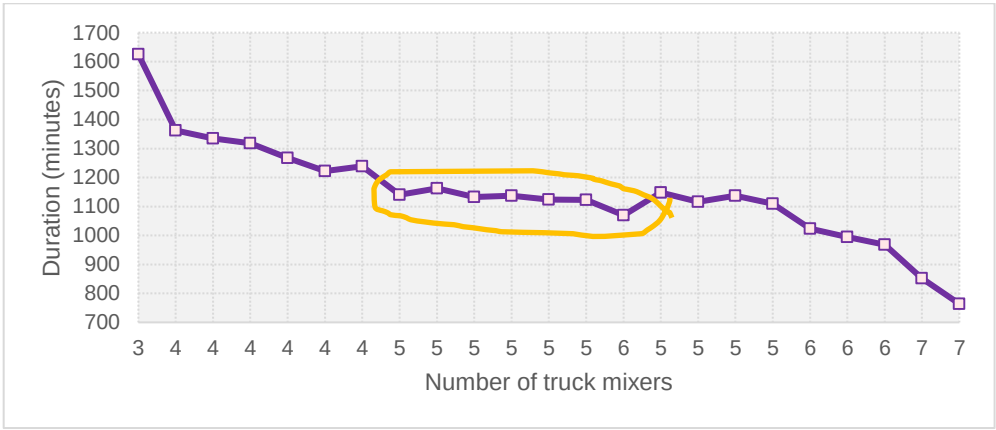


Figure 8. Duration for different fleet size, author's own creation

4. DISCUSSION OF THE RESULTS

The results of the simulation experiment, which varied the number of truck mixers, show that both the number and volume of truck mixers influence idling costs. Based on Figure 6, as the number of truck mixers increases, idling costs at the construction site rise, while a decrease in the number of truck mixers leads to higher pump idling costs. Lower total idling costs were observed in six combinations with five truck mixers and one combination with six truck mixers.

It can also be noted that with an increase in the number of truck mixers, the concreting duration decreases (Figure 8). Transportation costs, plant production costs, and pouring costs remain constant due to the fixed amount of concrete; they are calculated per unit of concrete.

The number of truck mixers affects the reduction in concreting duration, as increasing the number of truck mixers reduces concrete idling time, resulting in a shorter overall time. However, due to longer mixer unloading times, idling costs increase, and the quality of concrete may also be compromised.

Based on the analysis of the model in the considered case study, the optimal truck mixer scenario is scenario 14 (three mixers with a capacity of 7 m^3 and three mixers with a capacity of 9 m^3). By applying this truck mixer combination, waiting costs for truck mixers and the pump at the construction site are minimized, i.e., reduced to zero (Figure 6).

However, this scenario does not yield the shortest concreting duration (Figure 8). The shortest duration is achieved with scenario 23, but the total costs for this scenario amount to 62,265 €, which is 0.24% higher than the total costs for scenario 14 (62,115 €). It is difficult to achieve a minimum for all criteria (work duration and all costs). The criterion for optimal selection may vary.

Given that the objective is to find a truck mixer combination that minimizes idling costs for the considered case, this is best achieved by applying the combination from scenario 14. Simulation results show that selecting the right combination can significantly reduce waiting costs for both mixers and the pump, minimizing idling time and ensuring timely concrete placement without compromising its quality.

5. CONCLUSION

This paper presents the application of an original simulation model to determine the optimal combination of mixers for transporting concrete from a single concrete plant to two construction sites simultaneously. The results indicate significant cost savings when an adequate number of mixers with appropriate drum volumes are used for concrete transportation. These cost savings become even more substantial in large-scale concreting operations.

The simulation model is based on specific parameters derived from years of experience in monitoring concreting processes in the city of Niš. The model is user-friendly, allowing most interested parties to utilize it. By entering the number of mixers and their corresponding volumes into an Excel file before running the simulation, the fleet size is defined. Running the simulation with the given parameters (input data, characteristics, costs, etc.) generates a series of numerical and graphical results.

ACKNOWLEDGMENTS

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.

REFERENCES

[1] Begić, Hana, Mario Galić, Uroš Klanšek: **Active BIM system for optimized multi-project ready-mix-concrete delivery**. *Engineering, Construction and Architectural Management,* Vol. 31, No. 12, 5057-5084, 2024, https://doi.org/10.1108/ECAM-11-2022-1064

[2] Gaikwad, A., Thakare, S.: **APP for optimizing number of trucks for dispatching operation of concrete plant**. *Journal of Engineering Design and Technology*, Vol. 8, No 12, 1885-1887, 2019.

[3] Melan, M., Sabar, R., Anuar, N., Omotayo, A., Alonge, O.: **An Innovative of Simul Model for Ready-Mix Concretes in The Concept of Third Party Logistics and Supply Chain Management in Malaysia and Thailand**. *Int. J. Supply Chain Manag*, Vol 9, No 5, 908-914, 2020.

[4] Low, C., Chang, C. M., Li, R. K., Huang, C. L.: **Coordination of production scheduling and delivery problems with heterogeneous fleet**. *International Journal of Production Economics*, Vol. 153, 139-148, 2014. https://doi.org/10.1016/j.ijpe.2014.02.014

[5] Schmid, V., Doerner, K. F., Hartl, R. F., Salazar-González, J.-J.: **Hybridization of very large neighborhood search for ready-mixed concrete delivery problems**. *Computers & Operations Research*, Vol. 37, No 3, 559–574, 2010. https://doi.org/10.1016/j.cor.2008.07.010

[6] Matejević-Nikolić, Biljana, Živković Lazar: **Development of the simulation model for ready mixed concrete supply chain cost structure**. *Technical gazzete*, Vol. 30, No. 1, 102-113, 2023, https://doi.org/10.17559/TV-20220310120002

LIST OF REVIEWERS

Adrijana Savić, PhD, Kennesaw State University, Georgia, United States of America
Ajla Mulaomerović-Šeta, PhD, Faculty of Civil Engineering, University of Sarajevo, Bosnia and Herzegovina
Aleksandar Janković, PhD, Faculty of Architecture and Design, Norwegian University of Science and Technology, Norway
Aleksandar Jovanović, PhD, Belgrade Metropolitan University, Serbia
Aleksandar Milojković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Aleksandar Radaković, PhD, Institute for Information Technologies Kragujevac, University of Kragujevac, Serbia
Aleksandra Đorđević, PhD, Faculty of Architecture, University of Belgrade, Serbia
Aleksandra Ilić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Aleksandra Milinković, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Ana Momčilović Petronijević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Ana Perić Momčilović, PhD, School of Architecture, Planning and Environmental Policy, University College Dublin
Ana Radivojević, PhD, Faculty of Architecture, University of Belgrade, Serbia
Ana Špirić, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Ana Vranješ, PhD, Faculty of Mining and Geology, University of Belgrade, Serbia
Ana Vukadinović, PhD, Faculty of Occupational Safety, University of Niš, Serbia
Anda-Ioana Sfinteș, PhD, Synthesis of Architectural Design Department, "Ion Mincu" University of Architecture and Urbanism, Romania
Andor Wesselényi-Garay, PhD, Faculty of Architecture and Civil Engineering, Obuda University Ybl Miklós, Hungary
Andreas Savvides, PhD, Department of Architecture, University of Cyprus, Cyprus
Angela Munteanu, PhD, Faculty of Urban Planning and Architecture, Technical University of Moldova, Moldova
Ani Stefanova, PhD, Faculty of Geodesy, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Anica Draganić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Biljana Matejević-Nikolić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Biljana Mladenović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Bojan Popović, PhD, Institute of Archaeology, Serbia
Bojana Zeković, PhD, Faculty of Architecture, University of Belgrade, Serbia
Borjan Brankov, PhD, Institute of Architecture and Urban & Spatial Planning - IAUS, Serbia
Božidar Stojadinović, PhD, Department of Civil, Environmental and Geomatic Engineering of the Swiss Federal Institute of Technology - ETH Zürich, Switzerland
Brankica Milojević, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Danica Stanković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia

Danijela Đurić Mijović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Darija Gajić, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Dejan Vasović, PhD, Faculty of Occupational Safety, University of Niš, Serbia
Despoina Zavraka, PhD, School of Architecture, Aristotle University of Thessaloniki, Greece
Diana Stupar, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Dijana Simonović, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Đorđe Alfirević, PhD, Faculty of Contemporary Arts, Serbia
Dragan Milićević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Dragan M. Djordjević, PhD, Faculty of Sciences and Mathematics, University of Niš, Serbia
Dragan Marinković, PhD, Faculty of Mechanical Engineering and Transport Systems, Technical University of Berlin, Germany
Dragan Radivojević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Dragana Konstantinović, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Dušan Grdić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Dušan Ranđelović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Elefterija Zlatanović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Elena Lucchi, PhD, Politecnico di Milano, Italy
Emina Hadžić, PhD, Faculty of Civil Engineering, University of Sarajevo, Bosnia and Herzegovina
Esin Bölükbaş, PhD, Department of Architecture, Antalya Bilim University, Turkey
Goncalo Castro Henriques, PhD, Rio de Janeiro Federal University (FAU-UFRJ), Brazil
Goran Jeftenić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Igor Jokanović, PhD, Faculty of Civil Engineering Subotica, University of Novi Sad, Serbia
Igor Maraš, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Isidora Đurić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Iva Despotović, PhD, Faculty of Mechanical and Civil Engineering Kraljevo, University of Kragujevac, Serbia
Ivana Bogdanović Protić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Jan-Frederik Flor, PhD, School of Architecture, Building and Design, Faculty of Innovation & Technology, Taylor's University, Malaysia
Jasmina Tamburić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Jasna Grujoska-Kuneska, PhD, Department of Architecture, Faculty of Engineering, International Balkan University, North Macedonia

Jasna Guzijan, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Jelena Andrić, PhD, Department of Civil Engineering, Xi'an Jiaotong-Liverpool University (XJTLU), China
Jelena Bijeljić, PhD, Academy of Applied Technical and Preschool Studies Niš, Serbia
Jelena Đekić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Jelena Dimitrijević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Jelena Ivanović, PhD, Faculty of Architecture, University of Belgrade, Serbia
Jelena Pejović, PhD, Faculty of Civil Engineering, University of Montenegro, Montenegro
Jelena Savić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Jelena Stanković Aćić, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Josif Josifovski, PhD, Faculty of Civil Engineering Skoplje, University "Ss. Cyril and Methodius", North Macedonia
Katarzyna Banasik-Petri, PhD, Faculty of Architecture and Fine Arts, Andrzej Frycz Modrzewski Krakow University, Poland
Konstantina Hristova, PhD, Faculty of Architecture, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Ljiljana Jevremović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Ljiljana Vasilevska, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Maja Milić-Aleksić, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Maksym Karpash, PhD, Faculty of Public and Applied Sciences, King Danylo University, Ukraine
Marija Spasojević Šurdilović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Marija Jevrić, PhD, Faculty of Civil Engineering, University of Montenegro, Montenegro
Marija Miloshevska Janakieska, PhD, Department of Architecture, Faculty of Engineering, International Balkan University, North Macedonia
Marija Nedeljković, PhD, Rijkswaterstaat, Ministry of Infrastructure and Water Management, Netherlands
Marija Stamenković, PhD, Faculty of Technical Sciences in Kosovska Mitrovica, University of Priština, Serbia
Marijana Lazarevska, PhD, Faculty of Civil Engineering Skoplje, University "Ss. Cyril and Methodius", North Macedonia
Marina Carević Tomić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Marko Ćećez, PhD, Faculty of Civil Engineering, Džemal Bijedić University of Mostar, Bosnia and Herzegovina
Marko Jovanović, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Marko Marinković, PhD, Faculty of Civil Engineering, University of Belgrade, Serbia
Marko Nikolić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Marko Rukavina, PhD, Faculty Of Architecture, University of Zagreb, Croatia

Md Samdani Azad, PhD, Department of Architectural Engineering, Inha University, South Korea
Michal Kraus, PhD, Faculty of Technology, Institute of Technology and Business in České Budějovice, Czech Republic
Mihajlo Zinoski, PhD, Faculty of Architecture Skoplje, University "Ss. Cyril and Methodius", North Macedonia
Milan Đorđević, PhD, Faculty of Sciences and Mathematics, University of Niš, Serbia
Milan Gocić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Milan Trifković, PhD, Faculty of Civil Engineering Subotica, University of Novi Sad, Serbia
Milena Metalkova-Markova, PhD, School of Architecture, Art and Design, University of Portsmouth, United Kingdom
Milena Grbić, PhD, Faculty of Civil Engineering Subotica, University of Novi Sad, Serbia
Milica Igić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Milica Ljubenović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Milica Maksić Mulaić, PhD, University of Belgrade, Serbia
Milica Marković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Milica Vračarić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Miljan Šunjević, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Miloš Aranđelović, PhD, Faculty of Architecture, University of Belgrade, Serbia
Miloš Šešlija, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Miomir Miljković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Mirjana Devetaković Radojević, PhD, Faculty of Architecture, University of Belgrade, Serbia
Mirko Stanimirović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Miroslav Malinović, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Nataša Petković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Nemanja Marković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Nenad Ristić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Nenad Stojković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Nikola Velimirović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Nina Serdar, PhD, Faculty of Civil Engineering, University of Montenegro, Montenegro
Nuria Casais, PhD, Aarhus School of Architecture, Denmark
Olivera Nikolić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Oluwafemi Akande, PhD, Faculty of Environmental Sciences, Nile University of Nigeria, Nigeria
Oya Babacan, PhD, Antalya Bilim University, Turkey
Petar Vranić, PhD, Mathematical Institute of the Serbian Academy of Science and Art, Serbia

Peter Nikolov, PhD, Faculty of Architecture, Varna Free University "Chernorizets Hrabar", Bulgaria
Predrag Petronijević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Radivoje Dinulović, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Radovan Cvetković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Ramón Reyes Rodríguez, PhD, University of Guadalajara, Mexico
Ranjit Das, PhD, Universidad Catolica del Norte, Chile
Rene Lisac, PhD, Faculty of Architecture, University of Zagreb, Croatia
Rodrigo Garcia Alvarado, PhD, University of Bío-Bío, Chile
Sandra Milanović, PhD, Faculty of Economics, University of Niš, Serbia
Slaviša Kondić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Slaviša Trajković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Snezana Đorić-Veljković, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Suzana Draganić, PhD, Faculty of Technical Sciences, University of Novi Sad, Serbia
Tijana Vujičić, PhD, Faculty of Architecture, Civil Engineering and Geodesy, University of Banja Luka, Bosnia and Herzegovina
Vesna Jovanović, PhD, Faculty of Mechanical Engineering, University of Niš, Serbia
Violeta Gjeshovska, PhD, Faculty of Civil Engineering Skoplje, University “Ss. Cyril and Methodius”, North Macedonia
Vladan Nikolić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Vladana Petrović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Vladimir Kovač, PhD, Faculty of Architecture, University of Belgrade, Serbia
Vladimir Mandić, PhD, Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia
Vlatko Sheshov, PhD, Institute of earthquake engineering and engineering seismology, University “Ss. Cyril and Methodius”, North Macedonia
Vojislav Nikolić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Vuk Milošević, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Yakubu Aminu Dodo, PhD, College of Engineering, Najran University, Saudi Arabia
Yassen Kyossev, PhD, University of Architecture, Civil Engineering and Geodesy, Bulgaria
Žarko Petrović, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia
Zlatko Zafirovski, PhD, Faculty of Civil Engineering Skoplje, University “Ss. Cyril and Methodius”, North Macedonia
Zoran Bonić, PhD, Faculty of Civil Engineering and Architecture, University of Niš, Serbia

SPONSORS

PLATINUM SPONSOR

PUT INŽENJERING

PLATINUM SPONSOR



PLATINUM SPONSOR



SILVER SPONSORS

DAMBO®

MORAVACEM
A CRH COMPANY

isomat
building quality
for a sustainable future

MC
BE SURE. BUILD SURE.

BRONZE SPONSORS

- **KAPAPROJEKT**
- **Sika**