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CONTENTS

ЗМІСТ

Architectural Studies
International Journal about Architecture
Volume 10, No. 2

Publicist material – a word from the editor
Публіцистичний матеріал – слово від редактора

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The Ukrainian Academy of Architecture in the face of contemporary challenges – celebrating 80 years since its founding

Abstract. This article examines the most prominent episodes in the architectural history of Ukraine, highlighting the professional achievements and creative contributions of the nation's most talented architects, recognised with prestigious academic titles. It examines the creative output of academics who, in the mid-20th century, were involved in establishing the Academy of Architecture of the Ukrainian Soviet Socialist Republic. Although subsequently dissolved, this institution was revived in the late 20th and early 21st centuries by its former students and followers, who founded the modern Ukrainian Academy of Architecture

THE MAIN PART

The experience of the Academy of Architecture of the Ukrainian Soviet Socialist Republic (Ukrainian SSR) (hereafter referred to as the AA UkSSR or the Academy) with its multifaceted activities in the mid-20th century in the fields of urban planning, residential construction, reconstruction of buildings and restoration of architectural monuments, and various other scientific pursuits, seems particularly relevant for study and application in 2024, given the ongoing RussianUkrainian war. The decree of the Council of People's Commissars of the Ukrainian SSR No. 274 "On the Organisation of the Ukrainian Branch of the Academy of Architecture of the USSR" was adopted on 26 March 1944, long before the end of the Second World War. The renowned Ukrainian architect Volodymyr Zabolotnyi, the author of one of the most iconic architectural works in Kyiv – the House of the Supreme Soviet of the Ukrainian SSR (1936-1939), which in the early 21st century became an integral architectural symbol of the modern Ukrainian capital, was appointed as the head of the branch's Presidium.

At the same time, V. Zabolotnyi, with foresight, immediately began advocating for establishing a more extensive independent institution, the Academy of Architecture of the Ukrainian SSR. And already on 21 June 1945, Decree No. 960 of the Council of People's Commissars and the Central Committee of the Communist Party of Ukraine "On the Organisation of the Academy of Architecture of the Ukrainian SSR" was issued, which approved the organisation of the Academy of Architecture of the Ukrainian SSR with its location in the city of Kyiv and approved the Charter of the AA UkSSR (the first composition was determined in the amount of 7 full members and 18 corresponding members). On July 25-26, 1945, the first organisational general meeting of full members of the Academy was held in the Presidium of the AA UkSSR, at which its President was elected.

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This position was rightfully taken by one of the founders of the Ukrainian architectural school, Doctor of Architecture, a talented scientist and educator, professor, laureate of the State Prize in the field of architecture, an artist of a wide creative range – Volodymyr Zabolotnyi (1898-1962).

The AA UkSSR covered a vast range of issues in its activities. Creative problems of Soviet architecture, the synthesis of architecture, sculpture, and painting; the theory and history of Ukrainian architecture, the analysis of architectural forms, folk art, decorative arts, and new building materials – all these problems were worked on by the Academy's institutes, determining the paths of the building art. The powerful activity of the AA UkSSR made a significant contribution to the formation of the Ukrainian, and in particular the Kyiv, architectural school of the 1940s and 1950s, to the development of the capital of Ukraine and the development of Ukrainian architecture in various regions of Ukraine. Among the most significant achievements of the Academy's activities, it is necessary to note a complex of works on the post-war reconstruction of Kyiv (with the renovation of Khreshchatyk); Donetsk, Zaporizhzhia and other cities and villages of Ukraine; the construction of experimental and demonstration villages, scientific and creative assistance to the construction of the Republic Agricultural Exhibition, the Kakhovka hydroelectric power centre, the South Ukrainian and North Crimean canals, Nova Kakhovka, the development of general plans for cities and villages, the organisation of competitions for the construction of the most significant objects.

In 1955, two pivotal decrees were issued by the Central Committee of the Communist Party of Ukraine and the Council of Ministers of Ukraine: "On Eliminating Excesses in Architecture" and "On Measures to Further Industrialise, Improve the Quality, and Reduce the Cost of Construction". These decrees radically altered the stylistic direction of Soviet architecture, shifting from the use of decorative ordered forms to functionally and structurally sound simple forms of modern architecture. This posed qualitatively new demands on architectural science and necessitated a reorganisation of its system. The Academy of Architecture of the Ukrainian SSR was promptly reorganised with a corresponding reorientation of its main activities, and in 1955, the Academy of Construction and Architecture of the Ukrainian SSR (hereinafter referred to as the ACA UkSSR) was established on its basis. The primary task of the ACA UkSSR became the improvement of construction, the determination of the prospects for the development of construction science, and the coordination of research work in the field of construction and architecture in the Ukrainian SSR. As a result of these transformations, an engineer-builder, Anatolii Komar (1909-1959), rather than an architect, was appointed as President of the newly formed Academy. From 1960, the ACA UkSSR was headed by another President, engineer-builder Pavlo Bakuma (1911-1987), under whom the Academy finally lost its leading role in the development of architectural and construction activities, which led to the government's decision to liquidate it in 1963, with its institutes being transferred to various union and republican departments.

After Ukraine gained independence in 1991, a broad range of Ukrainian architectural scholars, including former graduate students of the AA UkSSR who had become leading figures in contemporary Ukrainian architecture – such as doctors of science, professors, renowned educators H. Lohvyn, N. Chmutina, Yu. Aseiev, D. Yablonskyi, V. Savchenko, V. Yezhov, M. Kolomiiets, M. Domin, I. Fomin, and others – undertook significant organisational work over two years to consolidate all creative forces to revive the "Academy of Architecture of Volodymyr Zabolotnyi", creating its legal successor. Re-established in 1992, the Ukrainian Academy of Architecture (UAA or Academy), as a public organisation but at the same time the legal successor of the State Academy of Architecture of the Ukrainian SSR, thanks to the efforts of its 4th President, Doctor of Architecture, Professor, laureate of state prizes in architecture, academician Valentyn Shtolko (1931-2020), made a significant contribution to preserving and consolidating the scientific and creative potential to address the most pressing challenges of the architectural and urban planning sector in the 1990s and early 2000s.

Another stage in the revival of the Ukrainian Academy of Architecture after a certain stagnation in the late 2010s is taking place right now (2024) – after 80 years. And again, during the terrible destruction caused by the full-scale invasion of Ukraine by Russian troops in 2022. And just as the Academy of Architecture of the Ukrainian SSR played an important role in the post-war revival of Ukraine, devastated by the Nazi invasion, the Ukrainian Academy of Architecture must play a significant role and make every effort to address urgent tasks during the Russian-Ukrainian war. The glorious past of the Academy, which in 2024 celebrates its 80th anniversary, serves as a solid foundation for drawing up work plans and implementing them.

Talented architects representing the current Academy are making joint efforts to return Ukrainian architecture to the realm of "high art". A testament to this is the unanimous election in September 2021 of Oleh Slieptsov as the 5th President of the UAA, thanks to his significant professional achievements between 1989 and 2024. He is widely known among his colleagues as a leading specialist in the field of architecture, a scholar, practitioner, and educator. The main areas of his practical activity and research are large-scale urban development complexes, residential and public building architecture, temple construction, and invention. O. Slieptsov is a Doctor of Architecture, Professor, People's Architect of Ukraine, laureate of the State Prize of Ukraine in the field of architecture, a full member of the UAA, and as of 2024, he heads the Department of Fundamentals of Architecture and Architectural Design at the Kyiv National University of Construction and Architecture (KNUCA).

During these challenging times for Ukraine, coinciding with O. Slieptsov's presidency, the Academy, which unites distinguished scholars and specialists in all areas of architectural activity and, according to its charter, is the leading scientific, creative, and coordinating architectural and urban planning centre of Ukraine, continues to move forward. To achieve this, the current Presidium of the UAA, headed by President O. Slieptsov and Vice-President M. Domin, is engaged in reforming and improving the Academy's structure, attracting new collective and associate members to its activities. The Presidium is actively seeking to integrate into the Academy institutions that are working to revive architecture as an art form in Ukraine. Since 2021, the UAA has been steadily growing and, in 2024, has 141 members. Among them are: full members of the UAA (53), corresponding members of the UAA (58), honorary members of the UAA (10), accredited (9) and collective members (9), foreign members of the UAA (1), and an honorary professor of the UAA (1). The Presidium, updated in 2021, is active in many areas, including developing steps to establish systematic international cooperation with the primary goal of attracting investors to the restoration of Ukraine's architectural heritage, damaged as a result of Russian aggression.

Between 2021 and 2024, several agreements and memoranda were signed with leading architectural academies and associations in Europe and Asia, enabling the UAA to participate in international scientific conferences and forums; implement joint research projects with global partners; and organise exchange programs for students and faculty, contributing to the improvement of architectural education in Ukraine. Furthermore, the Academy actively participates in European and global architectural events, allowing Ukrainian architects to present their work on the international stage and gain recognition worldwide. In this context, it is worth noting that since 2022, ties have been established with the Saxon Academy of Architecture, with an agreement reached to hold a joint scientific and practical conference dedicated to the reconstruction of Ukrainian cities. A delegation from the UAA, led by the Academy's President, has been invited to Berlin and Dresden, where work has begun on organising this important international forum of both academies.

The UAA Presidium has been actively working to establish diplomatic and corporate ties with leading architectural, construction, and scientific-educational organisations in other countries, including Israel, Georgia, Cyprus, Uzbekistan, Japan, and others, where the UAA has already opened or is about to open its representative offices. In October 2022, the first official visit of the UAA President, O. Slieptsov, to the Kingdom of Denmark took place, where the Academy's firstever representative office in Europe was opened. On that occasion, the President signed a memorandum with the mayor of the ancient city of Viborg, Ulrik Wilbek, on cooperation between the UAA and the Viborg community. Separately, in the city of Silkeborg, the UAA President concluded a memorandum with the heads of the leading Danish design firm "SWECO" (with branches in fourteen countries), Anders Kersgaard and Carl Martin Frederiksen, on joint design of destroyed Ukrainian objects in Kharkiv, in particular, the masterpieces of the outstanding Ukrainian architect and pedagogue Oleksii Beketov: the large-scale building of the Court of Appeal (former House of Judicial Decisions, 1899-1902) and the building of the House of Scientists (former mansion of the family of academician O. Beketov, 1900).

These significant steps taken by the new UAA Presidium, demonstrating the presence of a highly professional architectural school in Ukraine to both the West and the East, affirm its right to take its rightful place among civilised nations. The development of an international cooperation network lays the foundation for the implementation of projects, primarily in Ukraine, that will combine global experience and Ukrainian artistic traditions. Since 2021, the Academy has intensified its research activities aimed at addressing current issues in architecture and urban planning. The Academy consistently contributes to solving problems in the theory and practice of preservation, restoration, and comprehensive regeneration of historical and architectural cultural heritage sites. At the request of state institutions, measures are being taken and project proposals are being implemented to restore damaged objects in war-torn regions of the country.

To raise awareness of the tragic consequences of Russia's aggression in Ukraine, the Academy is conducting exhibition activities both in Ukraine and abroad. A particularly important event was organised in Tel Aviv with the support of the Ukrainian and Israeli embassies, titled "War and Architecture", which was exhibited in July 2023 at the premises of Israel's leading architectural bureau "MOSHE ZUR", where renowned Israeli architects had the opportunity to familiarise themselves with photographs of the devastating destruction of historical and architectural heritage caused by the Russian-Ukrainian war. Simultaneously, a memorandum was signed between Israel and Ukraine by the UAA President, O. Slieptsov, with the Israeli architectural bureau headed by Professor Moshe Tzur. Both sides agreed on the first steps of their cooperation, including a joint International Architectural Student Competition. During a business trip to Georgia in January 2023, the UAA President met with the Chargé d'Affaires of Ukraine in Georgia, Andrii Kasianov, to strengthen international cooperation in the field of scientific activity. In addition, memoranda of cooperation were signed with the National Academy of Sciences of Georgia and the Union of Architects of Georgia.

To activate the Academy's activities, business cooperation with state and public scientific, and artistic institutions is being strengthened, such as the National Academy of Sciences of Ukraine, the National Union of Architects of Ukraine, the National Academy of Arts of Ukraine, the Academy of Construction of Ukraine, and the National Union of Artists of Ukraine; several leading architectural and construction universities in Ukraine, and numerous state historical and cultural and national historical and memorial reserves of Ukraine. A total of 36 memoranda of cooperation and interaction have been signed with the aforementioned institutions. Importantly, in 2023, the Association of Reserves and Museums of Ukraine was established under the UAA to coordinate actions, with the National

Conservation Area "St. Sophia of Kyiv" headed by its general director, Nelia Kukovalska, playing a leading role.

The UAA is not only strengthening its international ties but also its scientific and pedagogical activities, supporting all powerful initiatives of lecturers and students of architectural and construction specialities, as demonstrated by the International Conference Development of Architecture in Europe During the War in Ukraine and After Victory Over the rf, organised by the Institute of Architecture and Design of the Lviv Polytechnic National University, based on which the Western Representative Office of the UAA was created in Lviv. It is headed by the Director of the Institute of Architecture, Head of the Department of Design and Fundamentals of Architecture of the Lviv Polytechnic National University, Full Member of the UAA, Doctor of Architecture, Professor Bohdan Cherkes.

Scientific and practical conferences were also held with the participation of the Academy, KNUCA, and the Slovak University of Technology in Bratislava. Representatives of the UAA also took part in the Lviv Forum "LvivUrbanForum – 2023". The collaboration of the Presidium with the Southern Representative Office of the UAA is also gaining momentum with the participation of members of the Academy from the Odesa Region, headed by a full member of the UAA Anatolii Kovrov, in which the Odesa State Academy of Civil Engineering and Architecture is actively involved. The Central Representative Office of the UAA, with the participation of the Yuriy Kondratyuk Poltava Polytechnic National University, is also very active.

The UAA's activities are directly linked to the development of architectural education in Ukraine and the training of highly qualified personnel: this is one of the glorious traditions inherited from the times of the Academy of Architecture of the Ukrainian SSR, which was initiated by its 1st President, academician V. Zabolotnyi. The 80-year history of the UAA reflects all the achievements and challenges of the scientific and pedagogical school, which in the past was formed primarily at the departments of architecture in the Kyiv Art Institute (now the National Academy of Fine Arts and Architecture, NAFAA) and the Kyiv Civil Engineering Institute (now the Kyiv National University of Construction and Architecture, KNUCA). The founders of the architectural school in Ukraine were such outstanding architects as D. Diachenko, V. Krychevskyi, P. Aloshyn, V. Zabolotnyi, Y. Karakis, P. Kostyrko, P. Yurchenko, V. Obremskyi, O. Verbytskyi, Ye. Katonin, and others. The contribution of contemporary teachers and scientists from the Department of Fundamentals of Architecture and Architectural Design at KNUCA – O. Slieptsov, M. Domin, Ya. Vih, Yu. Serohin, V. Kutsevych, who successfully trained personnel in line with the traditions established in the Academy of V. Zabolotnyi, is particularly significant.

The contemporary Academy pays special attention to supporting young professionals in the field of architecture. Since 2021, numerous competitions, seminars, and workshops have been organised for students and young architects. A support program has been launched to implement innovative projects by young architects, which has allowed for the discovery of new talents and contributed to the development of architectural creativity in Ukraine. An important event in the summer of 2023 was the successfully organised and implemented First All-Ukrainian Student Architectural Competition, announced by the Ukrainian Academy of Architecture with the participation of the Sumy City Administration, the chief architect of Sumy, and full member of the UAA Volodymyr Bykov, for the best project to restore Independence Square in the centre of Sumy, which was significantly damaged at the beginning of the full-scale invasion in February-March 2022. Against the backdrop of the task set by the President of Ukraine V. Zelenskyi before the Verkhovna Rada regarding the adoption of a law on the restoration of Ukraine, this competition acquired state significance. The competition, which revealed new names of talented young designers, demonstrated that student projects meet their level of professionalism, a creative approach to implementing their own concept, along with the search for a new image of the central square of Sumy from the perspective of an architect-artist. It was after this competition that President Oleh Slieptsov, together with Vice-President of the Academy Mykola Domin, initiated the creation of a youth branch of the Ukrainian Academy of Architecture, which was supported by the entire Presidium.

The preservation and protection of architectural heritage is of paramount importance to the UAA and is considered a priority for every civilised nation. That is why the Chernihiv City Council turned to the Ukrainian Academy of Architecture with a request to assist in the restoration of several objects damaged in Chernihiv as a result of Russian aggression. Given the great attention that academic architects pay to educating their successors – a young generation of talented architects who strive to contribute their own efforts to the reconstruction of Ukraine, the Academy decided to involve the collective of the Department of Fundamentals of Architecture and Architectural Design of KNUCA in this responsible project, including not only teacher-academics but also students. In the first stage of this large-scale work, the department's team developed a project to rebuild a public building destroyed by the war – the "Ukraine" hotel. As a result of the "cooperation of generations", young creators, under the guidance of experienced architect-teachers, offered their original vision of the architecture of a new Ukraine, in which they would like to live.

It is also important to note that to popularise the public position of the UAA, 26 informational and documentary films have been created and distributed through social media. Members of the Academy are also actively engaged in scientific publishing and educational activities. One of the key areas of the UAA's work has become interaction with the public and the popularisation of architecture among a wide audience. It can be argued that the academicians of the UAA are highly qualified specialists who know the extremely useful post-war experience of the Academy of Architecture of the Ukrainian SSR in the mid-20th century. They are involved in the search for effective methods and means of revitalising Ukrainian cities and villages at the beginning, demonstrating high professionalism in solving numerous problems in the design and construction of residential buildings and public facilities; in making informed decisions regarding the effective use of foreign investments during the restoration of architectural heritage sites.

Summarising the work of the renewed Ukrainian Academy of Architecture, headed by its President Oleg Slieptsov, it can be confidently said that the UAA is successfully coping with the tasks set before it and actively developing architectural science and practice in Ukraine. The UAA's achievements in the field of scientific research, international cooperation, support for young architects, and interaction with the public testify to the high level of professionalism and dedication of the Academy's members.

A SUMMARY

Throughout the development of Ukrainian architecture from the Second World War to the present day, the UAA has played a pivotal role. Under various names, the UAA has consistently aimed to influence advancements in architectural practice, theory, and history, responding to societal demands for change within these fields. Throughout its history, which mirrors that of Ukraine, the Academy has been led by five Presidents, each striving to address pressing issues. A primary goal has been to voluntarily unite "top-tier professionals" to address challenges in architectural development under new conditions, restore the prestige of the profession, and focus efforts on creating a harmonious living environment. The Academy has consolidated its scientific and creative potential and, over the years, has experienced several ups and downs. It has undertaken important work in creating a legislative and regulatory framework for the further development of architecture. In 2024, the UAA continues to move forward in many directions, conducting educational activities, highlighting issues of theory and practice in the preservation, restoration, and complex regeneration of historical and architectural heritage sites, and most importantly, establishing international cooperation, searching for investors and entrepreneurs who will become reliable partners of the Academy and support industry initiatives.

VISUAL MATERIAL

Volodymyr Zabolotnyi (1898-1962)
President of the Academy of Architecture of the UkSSR in 1945-1955

Anatolii Komar (1909-1959)
President of the Academy of Construction and Architecture of the UkSSR in 1955-1959

Pavlo Bakuma (1911-1987)
President of the Academy of Construction and Architecture of the UkSSR in 1959-1963

Valentyn Shtolko (1931-2020)
President of the Ukrainian Academy of Architecture in 1992-2020

Oleh Slieptsov (born 1958)
President of the Ukrainian Academy of Architecture since September 2021

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Українська академія архітектури в контексті сучасних викликів. До 80-річчя від заснування

Анотація. В даному матеріалі йдеться про найбільш яскраві сторінки архітектурної історії України, пов'язані з професійною діяльністю та творчістю найталановитіших українських майстрів зодчества, відзначених високими академічними званнями. Розглянуто творчість академіків, хто дотичний в середині XX ст. до створення в Україні Академії архітектури Української Радянської Соціалістичної Республіки, згодом ліквідованої, проте відродженої в кінці XX – на початку XXI століття їхніми учнями та послідовниками – академіками новоствореної Української академії архітектури

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Passive individual residential building overview and concept for a continental temperate climate

Abstract. The research relevance is determined by the need to develop energy-efficient and climate-resilient living spaces to ensure sustainable development and reduce environmental impact. The study aimed to analyse the integrated concept of a passive individual residential building specially adapted to the conditions of the continental temperate climate, with a focus on maximum energy efficiency and ensuring a high level of comfort for residents. While the research, analytical, classification, functional, synthesis and other methods were employed. The article examines the trend of improving the energy efficiency and environmental friendliness of individual residential buildings that meet the requirements of carbon neutrality and sustainability. The use of modern thermal insulation materials and optimisation of the concept of minimising heat-conducting inclusions has helped to dramatically reduce the building's heat transfer losses. The result is an integrated design that uses high-quality insulation materials, optimally positioned windows to maximise solar energy and efficient ventilation systems with heat recovery. However, infiltration losses remain

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significant, and improving the efficiency of ventilation system recovery and regeneration is a key area of research. To reduce transmission losses, it is important to consider internal and external heat gains in individual buildings. Organising aspects that consider the house as a biosphere-compatible and energy-efficient structure is an urgent task, and the study is aimed at developing an engineering and applied project concept. The practical significance of this research is determined by the creation of an innovative housing solution that not only optimises energy consumption and ensures environmental friendliness, but also meets the specific requirements of the continental temperate climate, contributing to the sustainability and efficiency of the construction sector

Keywords: energy efficiency; comfort; thermal insulation materials; heat recovery; integrated design

INTRODUCTION

Studying passive individual residential buildings for continental temperate climates is relevant in terms of the current challenges associated with climate change and sustainable development. The growing awareness of energy efficiency and the environmental impact of construction requires innovative approaches to the design of living spaces. Passive houses, specifically adapted to temperate climates, have the potential not only to significantly reduce energy use but also to create a comfortable environment for residents. Individual residential buildings show a trend towards greater energy efficiency and environmental friendliness, which aligns with global requirements for carbon neutrality, environmental sustainability, and energy autonomy, while the use of advanced thermal insulation materials and improved concepts for minimising heat-conducting inclusions significantly reduce the amount of heat loss through the building envelope. It is worth noting that infiltration losses continue to be significant, and it is important to maintain a balance so that their minimisation does not lead to a reduction in ventilation, which is a key parameter for the formation of sanitary and hygienic comfort.

The research problem is determined by the need to improve the energy efficiency and climate change resilience of residential buildings for continental temperate climates. Climate change and increased awareness of environmental issues are challenging the construction industry to create living spaces that not only reduce energy consumption but are also adapted to specific climate conditions. Challenges include the need to find optimal structural and energy-efficient solutions, consider the impact of external factors on building performance, and develop integrated concepts aimed at creating housing that uses resources efficiently while ensuring comfort and sustainability in a rapidly changing climate.

B. Dykiy & A. Hlushchenko (2023) emphasise the need to improve the energy efficiency and climate resilience of residential buildings in continental temperate climates, but the study does not consider the possibility of using alternative energy sources. Ye. Borodin & M. Myrhorodska (2022) emphasise the importance of ensuring comfortable living conditions in buildings while minimising environmental impact, and I. Arutiunian *et al*. (2023) highlight the relevance of developing integrated concepts for passive individual residential buildings.

Aspects of using high-quality insulation materials require detailed consideration, and therefore are analysed in many modern studies. N. Bolharova *et al*. (2020) emphasise the important issue of optimising thermal insulation materials and efficient heat recovery ventilation systems, which makes the possibility of improving the efficiency of ventilation systems in the context of providing clean air in buildings. A. Rogovyi & M. Dubina (2023) highlight a significant contribution to the development of innovative and long-term solutions in the field of housing construction and the use of green technologies to optimise heat loss. This topic is also considered in the study by V. Chala *et al*. (2023), where researchers emphasise the importance of green building and environmental compatibility in the concept of a passive house.

V. Deshko *et al*. (2022) raise the issue of internal and external heat gain in individual houses, which is important to consider when creating climate-resilient living spaces, but the study does not address the socio-cultural aspects of sustainability and the perception of innovations in housing construction. At the same time, M. Savytskyi *et al*. (2021) recommend the use of high-quality insulation materials and efficient windows to retain heat in winter and remove it in summer. D. Isaienko & V. Scochko (2019) formulate general approaches to modelling processes that affect the microclimate conditions of energy-efficient buildings.

The study aimed to analyse the integrated concept of a residential building operating on the principles of passive architecture and specially adapted to the conditions of a continental temperate climate.

MATERIALS AND METHODS

The analytical method was used to investigate the effectiveness of innovative thermal insulation materials, reveal trends in the development of the concept of minimising heat-conducting inclusions and determine their impact on the overall heat loss of the building. The method was also used to determine the optimal balance between reducing infiltration losses and ensuring the necessary level of air exchange to ensure the health and comfort of the occupants.

The functional method was used to identify the main functions and requirements that a passive individual residential building should fulfil in continental temperate climates. This method was used to conduct a comprehensive review of internal and external factors affecting energy efficiency and indoor comfort. In particular, the functional method was used to determine the optimal location of windows and doors to maximise solar energy and minimise heat loss, and to consider smart heating and ventilation control systems to ensure optimal conditions in the building during different periods of the year.

The deduction method was used to identify the main principles and strategies for the development of a passive individual dwelling house for a continental temperate climate and to organise scientific and technical knowledge to logically derive the key principles that form the basis of the concept. The method was also used to develop a conceptual model that considers the interaction between the various elements of the building and its environment.

Comprehensive and optimally coordinated solutions for the creation of an individual residential building were developed using the synthesis method. This method involved a comprehensive combination of various elements, considering their interaction to achieve maximum energy efficiency and comfort for residents. The synthesis method was used to combine advanced technologies in the field of thermal insulation and ventilation, rational use of solar energy and the introduction of smart control systems and to consider the influence of environmental factors, local characteristics, and the individual needs of the residents, creating a harmonious combination between technical solutions and sustainability requirements.

The classification method was used to categorise architectural and engineering solutions according to various criteria, such as optimal use of natural light, thermal insulation, ventilation systems. This method was used to identify the key elements that determine the efficiency and sustainability of living spaces and to identify the typologies of buildings that best suit the conditions of the continental temperate climate and to incorporate them into the concept development.

A range of software tools were used in the process of creating the graphic representations for this study to ensure a high degree of quality and representativeness of the visuals. Starting with AutoCAD, used for the development of architectural and technical schemes, drawings and 2D plans, to SketchUp, which provided the possibility of three-dimensional modelling of building structures. The selected software is distinguished by its high efficiency, ability to accurately reproduce complex architectural structures and ease of use to achieve the research objective. The use of these tools made it possible to obtain detailed and realistic graphical representations of the research objects, illustrating key study aspects.

RESULTS

Architectural Solutions. The correct positioning of the building concerning the cardinal points ensures that the amount of solar heat energy gained and lost through translucent structures such as glazed windows and doors is accurately measured. Planning solutions for the building's volumetric layout include placing the most heavily used rooms, such as bedrooms and guest rooms, on the south side, while less used and technical rooms, such as corridors, engineering rooms, kitchen, and bathrooms, are located on the north side.

The area of the windows on the southern facade is designed to compensate for the heat gain from solar radiation to ensure that the heat required to provide a comfortable microclimate in all rooms is not lost. The area of the windows on the north, east and west facades was determined to minimise heat loss and at the same time ensure the required level of illumination in the premises. This is important to ensure that all premises meet the comfort standards for living, working and recreation, considering the sanitary and hygienic requirements for the level of illumination for the health of vision. The house has an additional structure in the form of a combined sun protection, which includes a pergola and an outdoor terrace for relaxation (Spanjar *et al.*, 2022). Furthermore, the part of the roof overhang above the southern façade creates a canopy that connects to the pergola, providing effective sun protection for the southern facade. This avoids overheating during the warmer months and reduces visual discomfort caused by too much light, especially when the sun is higher at its zenith.

The height of the window sills on the southern façade regulates the transmission of only the amount of solar heat energy that is necessary to ensure comfortable indoor conditions. Thus, these window sills partially perform the function of sun protection. The dimensions of each window, both in width and height, are carefully calculated to maintain an optimal balance of heat gain and heat loss within each room, between rooms and within the building as a whole. In particular, the windows on the southern facade are the widest and their window sills are higher compared to the other facades. The windows on the north, east and west facades are narrow and are positioned to provide localised lighting for technical and other rooms. Additionally, some windows on the north façade extend from floor to ceiling to improve the light hygiene of the corridors and kitchen. The windows on the south and north facades are located mainly along conventional axes that are perpendicular to the respective facades. This creates intersecting natural light, which avoids insufficient illumination of work areas in the building's premises during periods when sun protection causes a shadow effect on the southern facade.

The internal walls and partitions separating the living areas from the common and technical areas have translucent door leaves and windows above them. This ensures that natural light can be received on the worktops through the transparent elements of the doors and windows. Internal partitions with doors placed between living rooms, corridors and technical rooms effectively limit and control excessive air exchange between rooms in the north and south directions. This prevents intensive mixing of air of different temperatures, which in turn leads to a reduction in heat loss during the cold season and avoids overheating in summer. In addition, the separation of the staircase from other rooms by additional partitions with doors helps to reduce heat loss through the opening and closing of external entrance doors to the street and the terrace of the second floor of the building.

The staircase of the building has a single flight of stairs with the use of traction devices and three running steps in the upper part (near the ceiling of the second floor). At the same time, the space near all the entrance doors is preserved to the maximum extent possible, which makes it possible to place cabinets, shelves, and other interior items in this area. To further preserve the feeling of openness in the entrance area, the staircase is made without stoppers behind the steps, creating the effect of a "transparent staircase" and allowing for natural light on both sides. The second floor (superstructure) above the staircase is designed in such a way that, without interfering with the movement of people going up or down, it preserves the maximum usable area for the possibility of arranging a work area, study, library, or a combination of these.

The roof slope is oriented from south to north. This solution leads to an increase in the area of the southern facade, which should receive the most solar irradiation and heat energy during the cold season, and a decrease in the area of the northern facades, where heat losses are most intense and should be minimised (Mutani & Todeschi, 2021). In addition, such a roof pitch helps avoid overheating in the warm season and contributes to the additional accumulation of thermal energy in the air masses in the residential (southern) part of the building during the cold season. A single-pitched roof allows for the reduction of the heated volume of the premises at the full height from floor to ceiling, which coincides with the bottom of the roof structure. The slope of the roof above the stairwell is oriented in the opposite direction to the rest of the roof to reduce the volume of the room served by heating.

In the bathroom and sanitary room, which do not have a direct connection to the exterior walls, translucent doors and additional windows above the doors are provided to provide natural light, additional insolation and reduce the electricity used for lighting. The bathroom adjacent to the northern façade also has a window with the same considerations. At the same time, the north-facing orientation of this bathroom helps to avoid the development of harmful fungi and microorganisms. In addition to its sun protection, the terrace on the second-floor extension serves as an additional place for relaxation and entertainment and provides a place for atmospheric exterior elements and ornamental plants. The pergola structure on the superstructure helps to partially keep the load from snow in winter, which improves the operating conditions and extends the service life of the roof. It is important to note that such a superstructure allows us to preserve the artificially used area on the territory around the house. The continuation of the pergola structure to the east creates an ideal place for car parking. The convergence of the car park with the stairwell, which acts as a thermal buffer, allows for an additional entrance door (emergency entrance) to be placed near the car park, and a significant shadow zone from the stairwell façade protects cars from excessive colour fading. The plants that predominate on the site are exclusively local species that do not require significant watering. The trees and shrubs planted on the southern façade are mainly deciduous, while the northern facade is predominantly coniferous.

Construction Solutions. The exterior walls are made of energy-efficient ceramic blocks with a multi-cavity structure. In addition to its high thermal insulation, this material is environmentally friendly, safe, and durable, and provides effective moisture exchange with the environment, which is similar to the moisture exchange in the human body (Turakulovna & Pulatovich, 2023). This increases the comfort of living in the building and improves the emotional state of a person. The interior walls are made of standard ceramic bricks, which are also considered a reliable and environmentally friendly material. The increased density of the bricks of the internal walls ensures high heat storage properties of the building.

The building's insulation is designed with vertical, inclined, and horizontal parts of the insulation materials closely and inseparably connected. High-density mineral wool boards are used to insulate the exterior walls, as the insulation system has an increased thickness. Polyurethane boards are used under the floor. The wall structures are separated from the foundation slab and rafter structures by foam glass inserts. The roof is insulated with sprayed open-cell polyurethane foam at the pore level to provide a "breathable building" effect. To reduce heat loss, all vertical, horizontal, and sloping joints are designed to minimise or eliminate heat conductive inclusions and vulnerable fragments of complex geometry that could become cold bridges (Mallick & Gayen, 2023). A single-pitched roof also helps to reduce heat loss, as it does not have additional zigzags and protrusions. An important technical solution aimed at reducing the number of cold bridges is the almost complete separation of the pergola terrace of the second-floor extension from the building envelope. The superstructure is in contact with the building only at two points on the pillar supports, which are mounted on the internal load-bearing walls. In this case, the load is transferred through the minimum required contact area, and the main part of both pillars is separated from the internal load-bearing walls by effective foam glass iWnsulation. All other superstructure supports are independently located columns that are not connected to the building.

To minimise heat loss caused by cold air infiltration or warm air leakage during the cold season, and vice versa – by warm air inflow or cooled air leakage during the warm season, all internal joints of the building envelope (walls, roofing, foundation slab, windows, and external doors) are equipped with a windproof membrane insulated from accidental air drafts. The project provides for the effective separation of the internal load-bearing walls made of ceramic bricks from the external envelope structures employing layers of high-strength foam glass insulation.

Additionally, the internal walls in contact with the engineering room are not connected to the external walls at all. All internal load-bearing walls act as heat accumulators, the main purpose of which is to localise the heat in the central part of the building. This leads to an increased thermal mass of the building, ensuring longer retention of thermal energy in the cold season and slower heating in the warm season. This, in turn, results in lower energy consumption for heating and cooling. On the other hand, the materials of the stairwell and the staircase itself are designed with wooden structural elements that do not accumulate significant thermal energy (Cabral & Blanchet, 2021). This is because this part of the building, in particular, is the "coldest" during the cold season and the "hottest" during the warm season, due to the presence of four entrance doors, and therefore does not require the use of heat storage materials.

All window structures of the building are designed with double elements, using modern multi-chamber profiles and double-glazed windows to significantly increase the heat transfer coefficient of window systems. The door structures are also made with double elements, which allows them to be opened both inside and outside the building. The layout of the ground and first floor of a biosphere-compatible and energy-efficient individual dwelling house is determined by several key aspects (Fig. 1; Fig. 2). First, it is necessary to consider the optimal location of the house to maximise solar thermal energy (Mostafaeipour *et al.*, 2021). Large windows on the southern facade contribute to light and heat gain. An important aspect is the use of energy-efficient heating systems, such as geothermal heating, and ventilation systems for optimal heat management in the building. High-quality insulation materials help reduce heat loss. The layout of interior spaces should be logical and convenient for occupants. It is necessary to consider the zoning and use of space according to its functionality. Efficient use of water supply and lighting, as well as an effective rainwater harvesting system, contribute to an environmentally friendly environment. The creation of courtyards and recreation areas improves natural ventilation and provides an opportunity to enjoy fresh air. The layout should also consider the maximum use of space to ensure the comfort and aesthetic appearance of the building. In general, the combination of these aspects contributes to the creation of an efficient and biosphere-compatible living space that provides comfort and a balanced relationship with the natural environment.

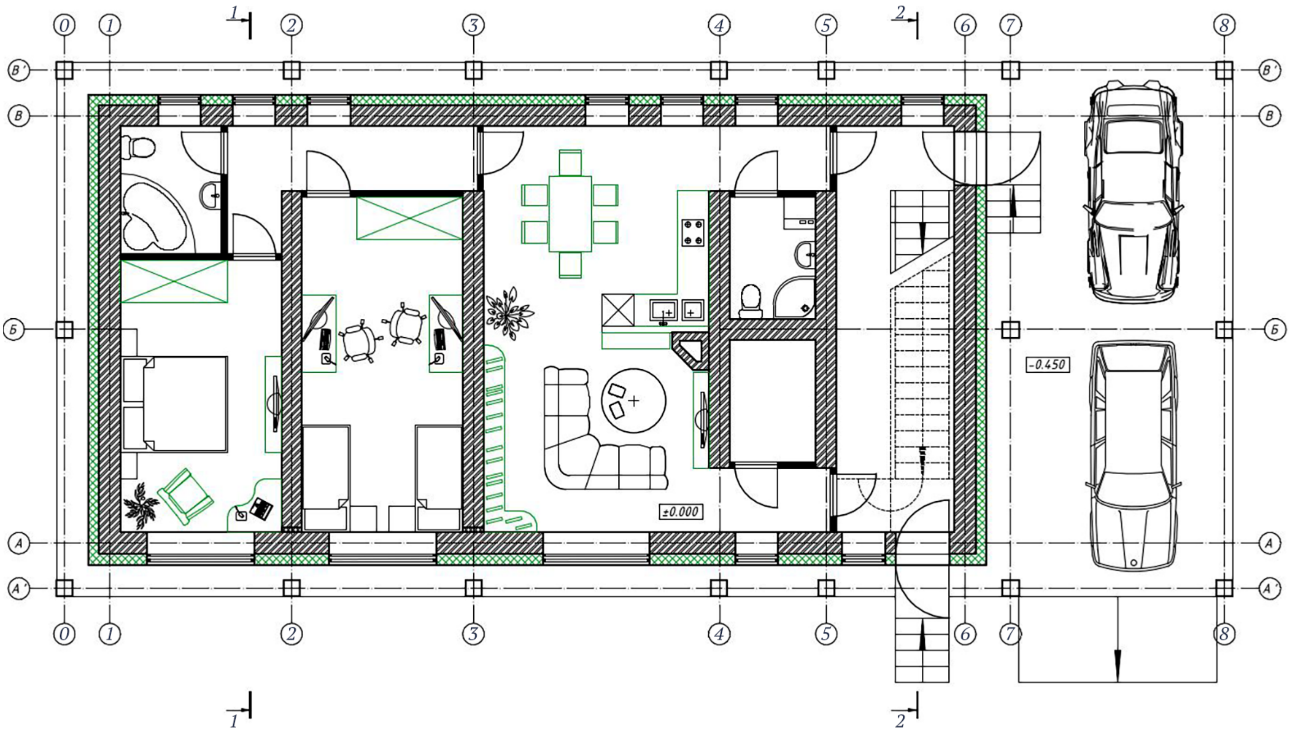

Figure 1. Planning solutions for the first floor of a biosphere-compatible and energy-efficient individual residential building

Source: compiled by the authors

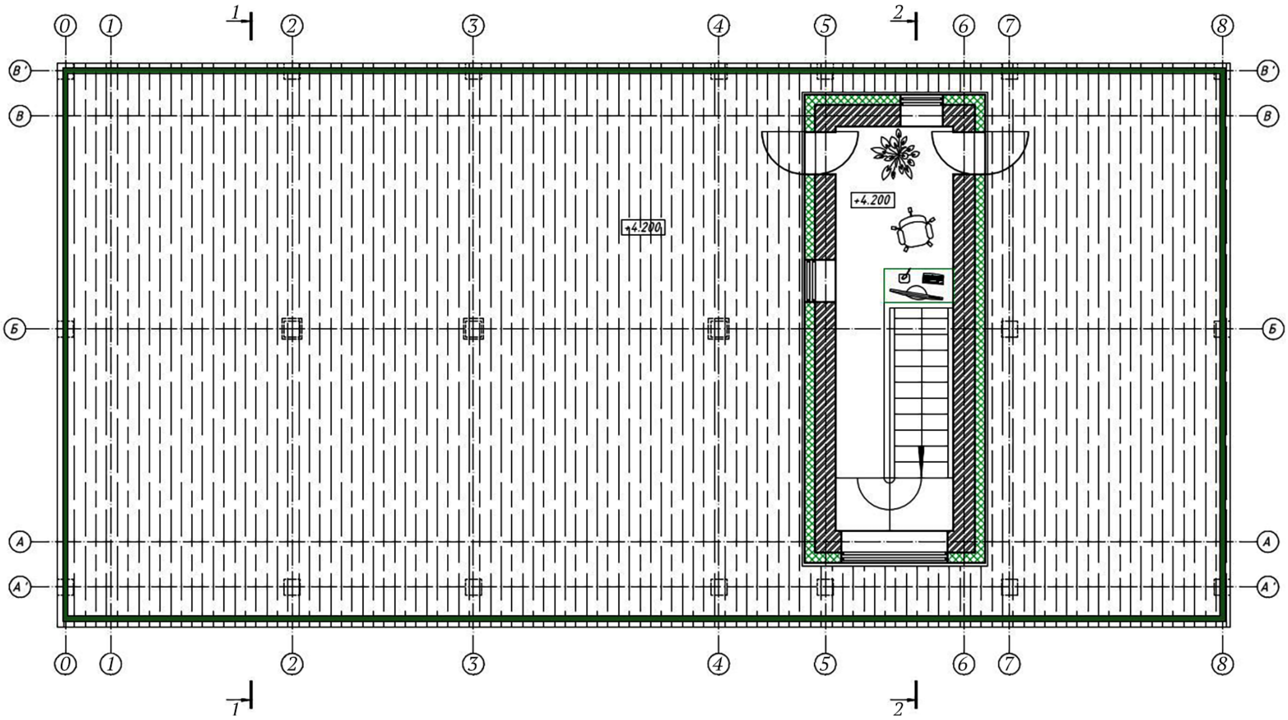

Figure 2. Planning solutions for the second floor and terrace of a biosphere-compatible and energy-efficient individual residential building
Source: compiled by the authors

The exterior of the central façade of a biosphere-compatible and energy-efficient individual residential building is determined by several key aspects that combine aesthetic and functional considerations (Fig. 3; Fig. 4). The architectural style is chosen to be in harmony with the natural environment (Orhan & Yilmazer, 2021).

Figure 3. Exterior of the central facade of a biosphere-compatible and energy-efficient individual residential building
Source: compiled by the authors

Figure 4. Exterior of the central facade of a biosphere-compatible and energy-efficient individual residential building
Source: compiled by the authors

The use of natural materials, such as wood or stone, emphasises the principles of biosphere compatibility. Integrating solar cells into the facade design will not only add aesthetics but also become a source of additional energy. Projections and canopies can serve not only an aesthetic purpose but also a functional one, providing sun protection and comfort in the house. Pond elements and vegetation add biosphere interaction and natural beauty. The design of the lighting elements gives the house a day and night look, emphasising its shapes. By incorporating these aspects, the exterior of the central façade can reflect the aesthetic preferences of the owners, while also meeting the principles of energy efficiency and biosphere compatibility, creating a harmonious image with the natural environment.

Design Solutions. Repair and finishing inside the house are done in the minimalist style, with the interior associated with a loft. The finishing of wall surfaces involves painting or varnishing for interior brick and exterior ceramic block walls. All technical rooms, corridors, bathrooms, the entrance section, and the kitchen are equipped with ceramic tiles, and the floors in the living rooms are laminate. Given the use of wind barrier membranes, the junctions are hidden by wooden overlays. Local LED (light-emitting diode) lighting around the premises is used to create a design effect. The lighting fixtures are mainly equipped with energy-efficient thermal LED lamps. The living room is combined with the kitchen to visually enlarge the space. The living room has a fireplace to create cosiness and improve energy independence. The flooring has a specific pattern, and the colour is in harmony with insolation calculations. The interior walls are decorated with thematic wall paintings. The ceiling is made in light colours for maximum light reflection. The bathrooms are decorated in light colours to maximise natural light. The premises are decorated with many home plants. Environmentally friendly materials were used for construction. The interior is complemented by designer furniture and lighting fixtures.

The entrance and living room interiors of the biosphere-compatible and energy-efficient building are striking in their functionality and convenience, reflecting the concept of an eco-friendly and stylish space (Druta & Ronald, 2021). The entrance group is designed in a minimalist and natural style (Fig. 5; Fig. 6).

Figure 5. Living room interior of a biosphere-compatible and energy-efficient individual house
Source: compiled by the authors

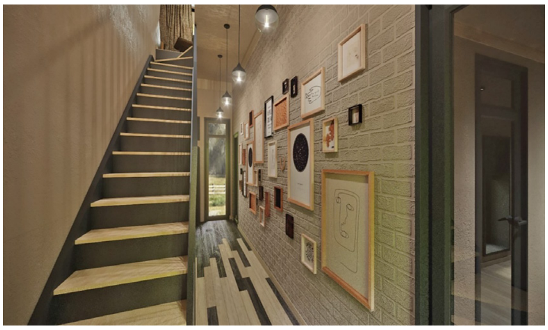

Figure 6. The interior of the entrance group of a biosphere-compatible and energy-efficient individual residential building
Source: compiled by the authors

The use of natural materials, such as wood and stone, gives the room a natural warmth. The light colours of the walls and floor visually expand the space, and the lighting creates an atmosphere of comfort and convenience. The living room, which is connected to the entrance hall, creates an impression of modernity and elegance. The furniture and décor favourably combine natural materials with stylish design. Large windows make the room open and fill it with natural light. The spatial plan is designed to create functional areas, considering the needs of the residents. The overall appearance of the entrance and living room impresses with its aesthetics and harmony, complementing the concept of a biosphere-compatible and energy-efficient building.

Engineering And Technological Solutions. In the new construction approach, an important element is passive adaptation to the environment, which can be achieved through the integration of the latest technologies and careful design. It is specified that the house should be connected to the electricity grid with an input power of 10 kW, acting as a partial backup source. This indicates a strategic approach to ensuring the reliability of the power supply in the face of possible interruptions. However, the key factor that attracts attention is the assessment of the total energy consumption of the building. It is noted that this passive individual house can reach a level of approximately 20 kWh/m^2 per year, considering all aspects, from heating and cooling to hot water supply. This figure indicates an impressive potential for energy efficiency and demonstrates that with the right design and technological solutions, high standards of energy savings can be achieved. The additional emphasis on sustainable interaction with climatic conditions not only ensures interior comfort but also minimises energy consumption for heating and cooling. Based on energy efficiency and ecological principles, this passive house sets a new standard for sustainable housing construction. All of this shows that high-performance housing can be not only innovative but also achievable. Considering the needs of modern society and climate change, such passive houses are becoming a model of sustainable living, where comfort and efficiency merge into a single harmonious space.

The heat supply system uses geothermal probes designed according to modern approaches to optimise energy extraction from a 90-metre-deep borehole for heating and hot water supply (Kulinko *et al.*, 2019). The heat pump operates in compressor mode in winter and reverse mode in summer. The energy-efficient system uses 4-pipe convectors for heating and cooling, and underfloor convectors are installed in the living room, children's room, and bedroom. Hot water is provided by a bivalent boiler. A recuperative ventilation system uses fresh air intake through a green area and tunnel to supply it to the air handling unit. The ecological water supply is obtained from a well of the second aquifer, and the wastewater is treated in individual treatment plants for further use in plant irrigation. The microclimate system in the building includes air purification and humidification functions. Lighting is provided by natural and artificial light using LED lamps. An automated control system allows residents to monitor all the building's engineering systems through a central processor that can receive commands locally or remotely via the Internet.

DISCUSSION

In the continental temperate climate zone, extreme temperature fluctuations and other weather conditions are important to consider. Passive houses are characterised by a high level of thermal insulation and an efficient ventilation system, which ensures a comfortable life for residents with minimal energy consumption. This is important both for reducing energy costs and for reducing the environmental impact of buildings. One of the key concepts is the use of modern renewable energy technologies, such as solar panels. This not only reduces the dependence on traditional energy sources but also contributes to the creation of energy-independent homes. Passive house designs also emphasise the importance of integrating environmental considerations into design and construction. This can include elements such as rainwater harvesting and utilisation systems, efficient use of natural light and other environmentally friendly solutions. So, the overview and concept of a passive individual dwelling house for a continental temperate climate indicate the need to combine innovation, energy efficiency and sustainability in construction to provide optimal living conditions with minimal environmental impact.

According to the results of research by L. Pajek & M. Košir (2021), the strategy of achieving long-term energy efficiency in European single-family buildings through passive climate adaptation is a promising direction in the field of sustainable construction. With its high population density and diverse climatic conditions, Europe is proving to be an ideal laboratory for introducing passive strategies into the building industry. Passive climate adaptation involves the careful design and construction of buildings that are designed to use natural resources efficiently and make the most of climatic features. The use of high-quality insulation materials, building orientation, optimised ventilation systems and the use of solar energy are key elements of this strategy. This strategy is not only aimed at reducing energy consumption and emissions but also at creating a comfortable environment for the occupants. Optimal temperature, good lighting and the best possible ventilation conditions help to ensure healthy and environmentally friendly housing. These findings are in line with the points made in the previous section. The Passive Climate Adaptation Strategy for Energy Efficiency in European Single-Family Buildings sets a new standard for sustainable residential construction, promoting environmental awareness and sustainability in the building industry (Kovalyshyn *et al*., 2023).

Referring to the definition of T. Yang *et al.* (2023), a review of the climate adaptation of phase transition materials incorporated into the building envelope for passive energy conservation reveals promising opportunities in the field of sustainable construction and energy efficiency optimisation. Phase transition materials have unique properties that allow them to deepen and release thermal energy during the phase transition, ensuring efficient thermal regulation in the building (Tsapko *et al*., 2022). The inclusion of such materials in building envelopes helps to stabilise the temperature regime of the premises, which is of great importance for passive energy saving. Their role in regulating the heat balance in the room is especially important, reducing the load on heating and air conditioning systems. It is worth noting that this approach contributes to the creation of buildings that effectively use natural processes to conserve energy while reducing heating and cooling costs. In addition, it reduces the ecological footprint of construction and contributes to sustainable development.

Y. Elaouzy & A. El Fadar (2022) determined that the integration of passive design strategies into buildings offers significant energy, economic and environmental benefits, making this approach a key focus in modern construction. From an energy point of view, the passive design maximises the use of natural resources and climatic conditions to regulate the temperature and lighting in a building. The use of wind energy, optimal solar orientation and thermal insulation materials helps to reduce energy consumption and ensure temperature stability. From an economic perspective, the implementation of passive strategies leads to a significant reduction in energy costs, which becomes a key factor in the cost of operating buildings (Baidrakhmanova *et al*., 2023). Significant savings on heating and air conditioning bills make such buildings financially viable for owners and occupants over the long term. Environmental benefits include reduced emissions of carbon dioxide and other pollutants due to lower energy consumption. Passive design contributes to the creation of energy-efficient, environmentally friendly buildings that meet the requirements of sustainable development and contribute to the conservation of natural resources. These results confirm the study findings, as the integration of passive design strategies into the construction process proves to be important not only in terms of energy conservation but also in terms of cost-effectiveness and positive environmental impact.

M. Hu *et al.* (2023) demonstrated that the impact of passive design on indoor thermal comfort and energy savings in residential buildings in hot climates is setting new standards for resource efficiency and sustainable living. A systematic review of this impact reveals several key aspects aimed at ensuring optimal conditions for occupants and minimising energy costs. One of the most important characteristics is the ability of passive design to effectively manage the heat balance in a building. The use of heat-insulating materials, intelligent thermal modelling and proper ventilation make it possible to maintain comfortable indoor temperature conditions, even at high ambient temperatures (Antypov *et al*., 2023). Saving energy in hot climates becomes critical, and passive design is a key tool to achieve this goal. Using natural energy sources, such as solar radiation to generate electricity and ventilation systems to optimise air circulation, makes buildings more energy-efficient and environmentally friendly. It is possible to agree with this opinion that passive design in hot climates not only improves thermal comfort but also accelerates the transition to sustainable living by reducing the negative impact of buildings on the environment and creating more efficient living conditions for residents.

As noted by A. Staszczuk & T. Kuczyński (2021), studying the impact of wall and roofing materials on the summer thermal performance of a building in a temperate climate defines key aspects of energy-efficient construction and a comfortable environment for occupants. Choosing the right materials is important to ensure optimal thermal insulation and response to the external environment. Wall material affects the distribution of heat in a building and can have a significant impact on its thermal performance. Materials with high thermal conductivity can lead to unpredictable heat distribution, while insulated materials can help to maintain a comfortable temperature inside the building (Tsapko *et al.*, 2020). Roofing materials are also important because they interact with solar radiation and determine the degree of thermal penetration. In temperate climates, where temperatures can fluctuate significantly, it is important to consider not only the thermal insulation properties but also the material's ability to regulate humidity and ventilation. Analysing the results and conclusions obtained, the impact of wall and roofing materials on summer thermal performance requires a comprehensive approach, considering the climatic conditions and the building's energy efficiency and comfort needs.

N. Fereidani *et al.* (2021) determined that a review of the energy implications of passive building design and active measures in the face of climate change reveals important aspects for sustainable development and ensuring efficient energy use in construction. Passive design is becoming a key tool in climate change adaptation strategies, as it allows for comfortable building conditions with minimal energy use. Climate change conditions require active measures to ensure energy efficiency and resilience of buildings to extreme weather conditions. Incorporating elements that reduce heat loads, such as solar panels and thermal insulation materials, into architectural solutions is becoming an important step in ensuring the long-term sustainability of building structures. Active measures, such as the use of renewable energy sources and efficient energy management systems, not only help to reduce the building's impact on climate change but also provide economic benefits and reduced utility costs. Furthermore, the energy implications of passive design and active measures in the face of climate change define a new paradigmatic approach to construction that promotes both sustainable development and adaptation to the challenges of a constantly changing environment.

CONCLUSIONS

In light of current trends in construction and the environment, it is important to consider passive individual houses as an effective option for continental temperate climates. An overview of such houses shows innovative solutions and technologies aimed at providing maximum comfort with minimum energy consumption. One of the key elements of the passive house concept is the use of high-quality insulation materials and techniques aimed at retaining heat in the room. Well-designed architecture and an efficient ventilation system allow for the necessary air exchange without significant energy loss. The use of solar panels for electricity generation and efficient use of natural light is also an important element. The integration of energy-saving systems and the use of renewable energy sources makes a passive house not only cost-effective but also environmentally friendly. Other benefits include resistance to extreme weather conditions and reduced heating and air conditioning costs. This creates a comfortable and cost-effective environment for the building's occupants.

This study presents a structured set of aspects and solutions related to the concept of designing and building an individual residential building that is biosphere-compatible and energy-efficient. It is noted that the house should be connected to the electrical grid with an input power of 10 kW, functioning as a partial backup source. At the same time, the assessment of the total consumption of the house demonstrates the possibility of reaching a level of approximately 20 kWh/m^2 per year, considering the needs for heating, cooling, and hot water supply. To summarise, a passive house for a continental temperate climate is an effective combination of innovative technologies, environmental friendliness, and comfort. It opens up new opportunities for sustainable development in construction and contributes to the formation of energy-efficient and environmentally conscious housing. To gain a deeper understanding of passive individual houses for continental temperate climates, optimal thermal protection methods, efficient ventilation models and the integration of modern energy management technologies should be investigated, which, in turn, provides prospects for further research in this area.

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None.

CONFLICT OF INTEREST

None.

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Огляд та концепція пасивного індивідуального житлового будинку для умов континентального помірного клімату

Анотація. Актуальність дослідження полягає в необхідності розробки енергоефективних та стійких до змін клімату житлових просторів для забезпечення сталого розвитку та зменшення впливу на навколишнє середовище. Метою даного дослідження був аналіз інтегрованого концепту пасивного індивідуального житлового будинку, спеціально адаптованого до умов континентального помірного клімату, з акцентом на максимальну енергоефективність та забезпечення високого рівня комфорту для мешканців. У процесі дослідження використано аналітичний, класифікаційний, функціональний, синтез та інші методи. У статті розглянуто тенденцію підвищення енергоефективності та екологічності індивідуальних житлових будинків, що відповідає вимогам вуглецевої нейтральності та сталості. З використанням сучасних теплоізоляційних матеріалів та оптимізації концепції мінімізації теплопровідних включень вдалося різко зменшити трансмісійні тепловтрати будівлі. Результатом є інтегрований дизайн, що використовує високоякісні ізоляційні матеріали, оптимально розташовані вікна для максимального використання сонячної енергії та ефективні системи вентиляції з рекуперацією тепла. Однак інфільтраційні втрати залишаються суттєвими, і підвищення ефективності рекуперації та регенерації вентиляційних систем є ключовим напрямком досліджень. З урахуванням зниження трансмісійних втрат важливо розглядати внутрішні та зовнішні теплонадходження в індивідуальних будинках. Організація аспектів, що розглядає будинок як біосферно-сумісну та енергоефективну структуру, представляє собою актуальне завдання, і дослідження спрямоване на розробку інженерно-прикладної концепції проекту. Практичне значення даного дослідження полягає в створенні інноваційного житлового рішення, яке не лише оптимізує споживання енергії та забезпечує екологічність, але й відповідає конкретним вимогам континентального помірного клімату, сприяючи підвищенню сталості та ефективності будівельного сектору

Ключові слова: енергоефективність; комфорт; теплоізоляційні матеріали; рекуперація тепла; інтегрований дизайн

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Designing infrastructure facilities using modern building materials

Abstract. Infrastructure facilities play a key role in meeting the vital needs of society and economic development. Designing such facilities is becoming increasingly challenging, as it requires a combination of innovative technologies, environmental friendliness and consideration of potential risks. The purpose of the study was to investigate the impact of modern building materials on the quality, sustainability, and efficiency of infrastructure facilities. This study involved a thorough examination of different types of building materials, a literature review of scientific sources, an assessment of the strength and environmental friendliness of materials, testing of their durability, and an analysis of their aesthetic appeal. The analysis revealed that the process of selecting building materials had a significant impact on the efficiency, durability, and sustainability of the infrastructure facility. It was noted that the correct choice of materials helps to achieve an optimal balance of these characteristics, which is key to ensuring the durability and reliability of the structure. The study looked at the use of high-strength steel structures, energy-efficient insulation materials and innovative technologies to increase resistance to various hazards such as earthquakes and fires. The paper presented the methods and steps used in the design of infrastructure facilities with modern building materials in

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mind. The importance of sustainability in the construction of infrastructure facilities was also described, highlighting the need to use environmentally friendly materials and technologies with minimal environmental impact. Achieving sustainability, energy efficiency and environmental sustainability in construction were recognized as key challenges in the modern construction industry. The study concluded that a balanced approach to the selection of building materials and technologies is needed to create infrastructure facilities that meet the requirements of sustainable development and environmental protection. The practical significance of this study is that it provides specific recommendations for the selection of modern building materials and technologies for the optimal design and construction of infrastructure facilities that meet the requirements of efficiency, sustainability and environmental friendliness

Keywords: innovative structures; fire resistance; energy efficiency; strength; design; reinforced concrete

INTRODUCTION

Given the constant development of technology and growing demands on the efficiency and sustainability of structures, the design process is becoming increasingly complex and requires an integrated approach. The use of modern building materials plays a key role in the process of creating infrastructure facilities that meet modern standards of quality, efficiency and environmental friendliness. The latest construction materials help to achieve high quality and reliability of structures, ensure optimum efficiency in the use of resources and energy, and reduce the negative impact on the environment. Such materials allow for the design and construction of buildings that meet modern construction requirements, ensuring a high quality of life and comfort for users and maximum preservation of natural resources for future generations. In this context, it is important to consider the selection and use of materials that ensure structural reliability, operational efficiency and compliance with environmental criteria. The constant development of technology and the expanding range of building materials require research to determine the best solutions in the use of materials and technologies. These solutions must ensure the highest quality of structures, minimal environmental impact and compliance with modern sustainability standards. The purpose of such research is to provide better solutions to the problems associated with the design and construction of infrastructure facilities in the modern world.

The topic of research on the use of modern building materials in the design of infrastructure facilities attracts the attention of many scientists and practitioners in the construction industry. The study by T. Serdiuk *et al.* (2021) focuses on the use of energy-efficient materials in construction to ensure the sustainability and efficiency of facilities. O. Chapiuk *et al.* (2021) study the impact of steel structures on the stability and strength of infrastructure structures in earthquake zones. O. Fomin *et al.* (2022) investigate the use of composite materials to improve the efficiency and reduce the weight of structures. F. Jalaei *et al.* (2021) analyse the possibilities of using alternative building materials to reduce the environmental impact of construction. X. Wang *et al.* (2022) consider new methods and technologies to improve the energy efficiency of building materials. S. Shi *et al.* (2022) investigate the optimal combination of materials and structures to achieve maximum strength and efficiency. A. Ustaoglu *et al.* (2021) examine the impact of sustainability of building materials on the carbon footprint of construction and the ability to reduce greenhouse gas emissions. S.K. Baduge *et al.* (2022) analyse the use of intelligent control systems to optimize construction processes and material use. K.S. Pribadi *et al.* (2021) focus on the development of new methods and technologies to improve the safety and resilience of building structures in response to various hazards. However, there are gaps in understanding the optimal strategies for the selection and use of materials, as well as the need for further research on the impact of these materials on the resilience of infrastructure facilities in different operating conditions. That's why the purpose of the study was to assess the impact of modern building materials on the operational characteristics of infrastructure facilities.

MATERIALS AND METHODS

This study is based on an analysis of the construction materials and infrastructure used in Ukraine. Kharkiv Railway Station and Yevhen Paton Bridge (Kyiv) were chosen as the objects under study. The study has thoroughly examined various types of construction materials such as clay brick, wood, stone and high-strength steel. Each of these materials was examined in detail to determine their characteristics and possible applications in a particular project. A literature analysis of scientific sources on the chosen research topic was also conducted to obtain data on the actual behaviour and characteristics of various materials. This information helped to make an informed choice and identify the advantages and disadvantages of each of them for further use in the project. As part of the study, each building material was assessed for key characteristics such as naturalness, strength, aesthetic appearance, durability and environmental friendliness.

When assessing the naturalness of a material, its environmental impact was taken into account, as well as its origin and recyclability. The environmental sustainability of the material and its impact on the ecosystem were analysed. In addition, the authors of this study assessed production processes and selected raw materials with minimal negative impact on the environment. The possibility of using recycled materials or recycling the material was considered to minimize waste and conserve resources.

When assessing the strength of a material, the authors of this study evaluated its ability to withstand loads, which is a key factor in its performance. Various testing methods were used to determine the strength of the material in real-world conditions. Parameters such as tensile strength, degree of deformation, abrasion resistance and other characteristics that affect the material's ability to perform in conditions where high strength and reliability are required were analysed. The formula for calculating the load was as follows (1):

$$P_{max} = \frac{S_{max}}{SF}, \quad (1)$$

where P_{max} – the maximum load (kg/m²); S_{max} – maximum material strength (MPa); SF – safety margin.

Calculating the wall thickness using the formula for material resistance (2):

$$R = \frac{\sigma \cdot t}{F}, \quad (2)$$

where R – material resistance (N); σ – material strength (MPa); t – material thickness (m); F – safety factor.

The dead weight of the carriageway (3):

$$GG = width \cdot height \cdot tare\ weight. \quad (3)$$

Payload (4):

$$Q = width \cdot payload. \quad (4)$$

Wind load (5):

$$W = width \cdot wind\ load. \quad (5)$$

Snow load (6):

$$S = width \cdot snow\ load. \quad (6)$$

Total load on the bridge (7):

$$P = G + Q + W + S. \quad (7)$$

Reaction in each column (8):

$$R = \frac{P}{number\ of\ columns}. \quad (8)$$

When assessing the aesthetic appearance of a material, the authors of this study evaluated its visual appeal and compliance with the architectural intent. The characteristics that affect the overall appearance of a structure or object, such as harmony with the environment, architectural style and design intent, were considered.

When assessing the durability of a material, the authors of this study analysed its resistance to wear, ageing and external factors. The assessment included an analysis of the material's response to various wear agents, such as friction, impact, corrosion, abrasion and other mechanical or chemical influences. The authors of this study also assessed the material's resistance to changes in climatic conditions, ultraviolet radiation, temperature, humidity, and other external factors that can affect its physical and chemical properties over a long period of operation. Then the possibility of maintaining or restoring the material's characteristics over time, which is important for predicting the service life of the structure or object in which it is used, was considered.

When assessing the environmental friendliness of a material, the level of damage it can cause to the environment during its life cycle was determined. All stages of the material's life cycle were analysed, from raw material extraction to production, transportation, use, and recovery or recycling. The energy and environmental efficiency of production processes, emissions, waste generation, and the impact on water resources, soil, and air were taken into account. The possibility of using recycled materials or recycling the material to reduce the environmental impact was also assessed. The analysis was carried out in the context of the material's compliance with the requirements of sustainable development and conservation of natural resources.

RESULTS

Construction, as an industry of material production, plays an important role in the development of infrastructure and shaping the face of cities and villages. It covers a wide range of activities, including new construction, reconstruction, repair, and restoration of buildings and structures. However, the economic reforms taking place in Ukraine have brought about significant changes in this sector. One of the key trends that defines the current state of construction in Ukraine is the rapid growth of new construction, especially in cities and their surroundings (Bannikov *et al.*, 2022). This growth is driven by the increasing demand for new residential and commercial space arising from population expansion and business development. In this regard, construction companies are actively expanding their operations and investing in new projects. However, this growth has also been accompanied by increased competition and higher demands on the quality and efficiency of construction projects. In 2024, the use of advanced technologies and materials will become increasingly important as they not only ensure the high quality of buildings, but also contribute to energy efficiency and environmental friendliness of construction. Thus, the construction industry in Ukraine is undergoing a period of intense change, driven by economic reforms and growing demand for housing and commercial space. To ensure the successful development of the industry, it is necessary to improve technologies, enhance the quality of construction projects and take into account the environmental aspects of construction (Table 1).

Table 1. Integrated materials for modern infrastructure

The design stage	Type of material	Purpose	Properties
Planning	Composite panels	Exterior of the facility	High strength, lightweight
	Steel structures	The basis of the building	High strength, corrosion resistance

Table 1. Continued

The design stage	Type of material	Purpose	Properties
Design	Double-glazed windows	Windows and facades	High thermal insulation, noise insulation
	Solar panels	Energy supply	Renewable energy, reducing energy costs
Construction	Concrete blocks	Walls and partitions	Durability, fire resistance
	Environmentally friendly insulation materials	Insulation	Environmental friendliness and energy efficiency
Completion	LED lighting	Interior lighting	Energy efficiency, service life
	Water treatment systems	Waste water treatment	Cleaning efficiency and environmental friendliness

Source: compiled by the authors

The Table 1 allows systematizing information about the use of different materials at different stages of the design and construction of an infrastructure facility. In construction, the choice of materials plays a crucial role in achieving a balance between various parameters such as quality, durability, environmental friendliness and cost-effectiveness. Thanks to advances in science and technology, modern building materials offer a wide range of options to achieve these goals (Lam *et al.*, 2023).

One of the key aspects of choosing materials is their properties. Steel, for example, is renowned for its high strength and long service life, making it a popular choice for structural applications. Concrete also plays a central role in construction due to its ability to be easily moulded and its high strength, which allows for stable and reliable structures. In addition, glass is widely used in construction as a material for windows, facades and interiors, due to its transparency and aesthetic appearance, which adds to the attractiveness and functionality of buildings. However, the choice of materials is not limited to their physical characteristics. It is also important to consider the environmental aspect. The use of environmentally friendly materials and technologies helps to reduce the environmental impact of construction and conserve natural resources. Clay brick, wood and stone are building materials that are natural, durable and aesthetically pleasing. Clay bricks are made by firing clay and have high strength, durability and fire resistance, making them a popular material for construction. Wood is known for its natural beauty, warm appearance and renewability as a resource, and is used to create a comfortable and cosy environment in buildings. Stone, on the other hand, has unsurpassed strength, fire resistance and a unique look that makes a building aesthetically pleasing and reliable. These materials also meet the requirements of environmental friendliness, as they are natural and do not harm the environment during production.

For example, in 2024, composite materials are of great interest, as they can be more resistant to corrosion and have a longer service life, while having less negative impact on the environment. At the same time, cost-effectiveness is also important when choosing materials. In addition to the cost of the material itself, it is worth considering its transportation, installation, and maintenance costs throughout its lifetime. This can include an analysis of the service life, maintenance requirements and recyclability of materials, which can reduce costs and increase economic benefits in the future. Thus, the choice of materials in construction is a complex task that requires careful analysis of various factors. Considering quality, durability, environmental friendliness and cost-effectiveness, it is possible to ensure the optimal choice of materials for construction projects that meet the needs of modern society and the requirements of sustainable development.

Built in the 20th century, Kharkiv Railway Station is known for its high modernity and popularity among other Ukrainian railway stations (Dreval *et al.*, 2024). It is fascinating not only for its enormous size and practicality, but also for its unique architectural style, which combines elements of classicism with modern trends. This building serves as an excellent example of the successful use of the latest building materials and advanced technologies in infrastructure construction (Fig. 1).

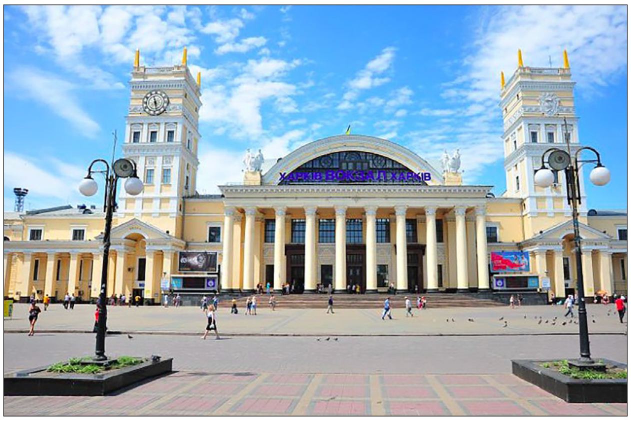

Figure 1. Kharkiv railway station
Source: Kharkiv Railway Station (n.d.)

The modern construction materials used in the construction of Kharkiv Railway Station are represented by a variety of high-quality components. High-strength steel is a material characterized by high strength, usually in the range of 500 to 700 megapascals (MPa). Its high strength allows it to withstand significant mechanical loads without serious deformation or fracture. In addition, high-strength steel is highly resistant to corrosion, making it an effective material for use in environments where there is interaction with moisture or chemically aggressive environments. This ensures the durability of structures made of high-strength steel, which can exceed 100 years. This steel is perfect for building durable and reliable structures. High-strength steel was used for the load-bearing structures and the roof of the station, providing strength, corrosion resistance and durability. This material made it possible to create spacious waiting rooms, platforms and other premises, taking into account their resistance to loads. The maximum load on the roof of the station using high-strength steel was calculated using the formula for calculating the maximum permissible load on a structure (1). Substituting the permissible value: $P_{max} = \frac{500 \text{ MPa}}{2} = 250$ MPa. Thus, the maximum load that high-strength steel can withstand with a given safety margin is 250 kg/m².

The facade of the station is made of stone and brick, which reflects its monumental appearance and provides high resistance to weathering. The material has a strength in the range of 10 to 20 MPa, which corresponds to the average values for stone and brick. The thickness of the facade walls ranges from 500 to 600 mm. These characteristics, together with the aesthetic appearance, create a reliable and attractive appearance of the station. To calculate the wall thickness using formula (2), the average material strength $\sigma = 15$ MPa and wall thickness $t = 550$ mm (average value) should be used for the material resistance. The safety factor $F = 2$. $R = \frac{15 \text{ MPa} \cdot 0.55 \text{ m}}{2} = \frac{825}{2}$. Therefore, the material resistance $R = 412.5$ N.

Wood is used for interior decoration and furniture making, adding cosiness and comfort to the room. Wood has a strength of 5 to 10 MPa, depending on its type and quality. This means that wood can withstand a certain load without breaking or deforming. Wood has a cosy and comfortable look that adds warmth and natural beauty to the room. Its natural texture and colour create an atmosphere of cosiness and luxury. Wood can last from 50 to 100 years, depending on the conditions of use, treatment, and care. Proper maintenance can significantly extend its service life, ensuring long-lasting comfort and aesthetic appearance of the interior. The innovative technologies used in the construction of Kharkiv Railway Station reflect the modernity and progress in the construction industry. Reinforced concrete structures formed the basis for creating spacious waiting rooms and platforms, providing the station with resistance to significant loads. The high-strength steel frame provides not only strength but also resistance to wind and snow. Modern heating, ventilation and air conditioning systems provide comfortable conditions for passengers at any time of the year, maintaining the optimum temperature and humidity. The station's electric lighting is based on energy-saving technologies, making it more environmentally friendly and efficient. The station is also equipped with modern information systems that provide passengers with access to train timetables, ticket availability information and other useful services, increasing the level of comfort and convenience for all users.

High-strength steel structures play a crucial role in construction, ensuring the stability, reliability, and efficiency of facilities. Their use has become an important step in the development of the construction industry, ensuring a high level of safety and durability of buildings. Steel is a material with high strength and durability, which allows for the creation of structures with high loads and at the same time ensures their stability even in the most difficult conditions. Steel structures are known for their quick installation and easy modification, which makes them efficiently used in any construction project and reduces the time required to complete the work. In addition, steel is highly resistant to various hazards, such as fire and earthquakes, making it an indispensable material for the construction of structures subject to safety and reliability requirements. It is also worth noting the environmental friendliness of high-strength steel structures. The use of steel in construction helps to reduce the environmental impact as it can be recycled and reused, reducing waste and contributing to sustainable development. This approach helps to conserve natural resources and reduce the negative impact of construction on the environment, in line with modern requirements for sustainable development and environmental protection. In light of the growing need for sustainable, safe and efficient building solutions, high-strength steel structures remain an integral part of modern construction. Their importance lies in ensuring the reliability and stability of buildings in all conditions, making them an indispensable element in the construction of the future (Tong *et al.*, 2021).

Yevhen Paton Bridge in Kyiv is one of the oldest and most famous bridges in Ukraine (Fig. 2). It was completed in 1953 and, at that time, was one of the longest welded bridges in the world. The Paton Bridge is an excellent example of how modern steel can be used to create strong, reliable and aesthetically pleasing infrastructure. About 28 thousand tonnes of St3SP steel were used in the construction of the bridge. This steel is known for its high strength and resistance to corrosion, making it an ideal material for structures that are subject to significant loads (Lobanov *et al.*, 2021). The use of modern steel has made it possible to create a strong and reliable bridge that can withstand significant loads. Thanks to this, the Paton Bridge has remained one of the most important transport arteries in Kyiv for many years. The use of modern steel in the construction of the Paton Bridge has brought a number of benefits, including increased strength and stability. The bridge can withstand significant loads and vibrations, making it safe to operate for many years. Reduced weight: due to its lightweight construction, the bridge required fewer materials and energy to build, making it more environmentally friendly. Increased durability: modern steel is resistant to corrosion and other types of damage, which significantly increases the service life of the bridge. Aesthetic appeal: the elegant design of the bridge makes it not only functional but also visually appealing. It is important to note that the Paton Bridge was built in 1953, when bridge construction technologies were significantly different from todays. However, this bridge is an excellent example of how modern steel can be used to create a strong, reliable and aesthetically pleasing infrastructure.

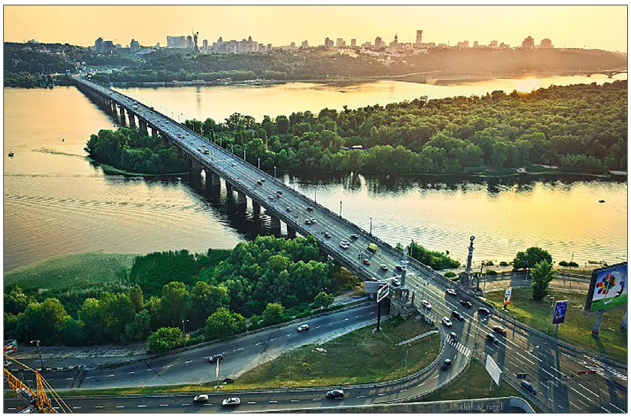

Figure 2. Yevhen Paton Bridge
Source: N. Shakilov (2013)

The unladen weight of the carriageway (denoted as G) is calculated using formula (3), which takes into account the width, height, and density of the material. In this case, G=10 m · 0.4 m · 28 t/m^3 = 112 t. The payload (denoted as Q) is calculated using formula (4), which considers only the width of the carriageway and the value of the payload. As a result of the calculations, Q = 10 m · 20 t/m = 200 t/m. The wind load (denoted as W) is calculated using formula (5), which considers the width of the carriageway and the value of the wind load. As a result, W = 10 m · 2 t/m = 20 t/m. The snow load (denoted as S) is calculated using formula (6), which also considers only the width of the carriageway and the value of the snow load. The result of the calculation is S = 10 m · 1.5 t/m = 15 t/m. The total load on the bridge is calculated using formula (7), which sums the dead weight, payload, wind, and snow loads. As a result of the calculations, P = 112 t/m + 200 t/m + 20 t/m + 15 t/m = 347 t/m. The reaction in each column (denoted as R) is calculated using formula (8), which divides the total load by the number of columns. After performing the calculations, $R = \frac{347\ t/m}{4} = 86.75\ t/m$.

In construction, where the demand for materials with high strength and lightness is constantly growing, steel composites are becoming an interesting solution for many projects. These materials combine the advantages of steel with the properties of other composite materials, which opens up great opportunities for creating the most durable and lightweight building structures. One of the main advantages of steel composites is their high strength (Sajan & Selvaraj, 2021). Due to the unique combination of steel with other lightweight and strong materials, such as glass fibre or carbon fibre, composite materials provide high stability and durability of structures with minimal weight. This reduces the weight of building elements, which is particularly important in the case of large structures or in environments with limited ground loads. The use of steel composites helps to improve the efficiency of the construction process, reduce transportation and installation costs, and ensure that structures are more resistant to various environmental influences. In addition, steel composite materials are highly flexible and have a high degree of corrosion resistance. This makes them an ideal choice for construction in aggressive environments or in areas with high levels of humidity. Such materials ensure the durability and reliability of structures even in the most difficult operating conditions. They can successfully withstand extreme conditions and ensure the stability of building structures over time, making them an attractive choice for a wide range of projects and applications. The use of steel composites in construction opens up wide prospects for creating innovative and sustainable structures. They allow for the realization of even the most complex design ideas and ensure a high level of safety and reliability of structures. Therefore, the use of steel composite materials in construction is a reasonable step towards achieving sustainable, innovative and efficient construction projects.

In light of the growing awareness of environmental issues and the need for sustainable development, the issue of sustainability is becoming increasingly relevant in construction. Taking environmental aspects into account when choosing materials and technologies is becoming a prerequisite for reducing the negative impact of construction on the environment and creating sustainable and environmentally friendly construction projects. One of the key components of green construction is the selection of environmentally friendly building materials. The use of materials such as recycled steel, wood from regenerated forests, or biodegradable polymers helps to reduce emissions and environmental pollution. In addition, it is important to consider not only the sustainability of individual materials, but also their interaction with nature during production, use, and disposal. For instance, the use of materials that can be easily recovered or recycled without great environmental damage contributes to a more sustainable construction that conserves natural resources and minimizes its impact on the ecosystem. In addition, an important aspect of green building is the use of energy-efficient technologies and the development of green infrastructure solutions. This includes the installation of solar panels to generate the own electricity, which reduces dependence on traditional energy sources and helps to save energy. In addition, the use of water drainage and treatment systems reduces water consumption and minimizes the discharge of polluted water into the environment. Green roofs and walls are also an important element of green infrastructure, as they contribute to improving air quality by absorbing carbon dioxide and other harmful substances, as well as reducing heat emissions and retaining moisture, which helps to maintain a comfortable microclimate in the building. All these measures are aimed at creating environmentally friendly and sustainable construction projects that meet the requirements of modern society for sustainable development and environmental protection. Environmental friendliness in construction is not only important for reducing the negative impact on nature, but also helps to create healthy and comfortable conditions for residents and users of construction projects.

Careful consideration of architectural and aesthetic aspects is a key element in the creation of infrastructure facilities that exist in the visual context of their surroundings. When designing any infrastructure facility, it is necessary to take into account not only its technical characteristics and functional purpose, but also its visual interaction with the environment (Ghomejshi, 2021). Ensuring the harmonious integration of an object into the visual context of the surrounding space requires a thorough study of the local architecture and landscape. This allows integrating a new facility into the existing aesthetics of the environment, creating a single, harmonious environment. It is important not only to comply with architectural design standards, but also to consider the unique features and cultural aspects of the local heritage. This approach to designing infrastructure facilities contributes not only to their aesthetic appeal, but also to a positive impact on the psychological and emotional state of people who use them. A sense of harmony and harmony with the environment creates a favourable atmosphere for living, working and recreation, which is an important factor in improving the quality of life of the population and creating sustainable and aesthetically pleasing communities.

DISCUSSION

When designing an infrastructure facility using modern construction materials, a thorough analysis of various aspects was carried out. Starting with the choice of materials, the authors of this study took into account their technical characteristics, resistance to loads, environmental friendliness and efficiency of use. Kharkiv Railway Station was a unique architectural structure that combined the best traditions of classicism and modern architectural solutions. The use of various types of building materials, such as clay brick, wood, stone and high-strength steel, allowed for the creation of a unique architectural structure that reflected both historical traditions and modern needs and standards. The Yevhen Paton Bridge in Kyiv is one of the oldest and most famous bridges in Ukraine, built in 1953. The use of St3SP steel made it possible to create a strong and reliable bridge that can withstand heavy loads and remains an important transport artery in Kyiv. The advantages of using this steel include increased strength and stability, reduced structural weight, increased durability and aesthetic design.

Researchers J. Zhao & S. Li (2022) found that life cycle assessment of building materials is an important step in choosing the best material for construction. A comparative analysis of energy and environmental impacts allows to assess the environmental impact of each material, from raw material extraction to disposal. Improving environmental efficiency can be achieved through the use of environmentally friendly materials and optimization of production processes. The use of standards and certifications helps to ensure the objectivity of comparative analysis and contributes to the creation of more environmentally sustainable construction projects.

According to the results of recent studies by B. Bickel *et al*. (2010), the design and manufacture of materials with the desired deformation properties is an important step in engineering and industrial activities. This process involves not only the selection of a suitable material, but also the development of its structure and processing to achieve certain mechanical characteristics. It is important to consider various factors, such as strength, elasticity, ductility and other properties, depending on the specific application of the material. To achieve the desired deformation properties, various material processing methods are often used, such as casting, rolling, moulding, and others. In addition, composite materials and nanomaterials technologies allow for the creation of materials with unique properties that can be precisely tailored to meet specific needs (Zakharova, 2024). These data are consistent with the points made in the previous section. Another important aspect of material design is the consideration of economic and environmental factors. Efficient use of resources and minimization of waste are key challenges in developing materials with the desired deformation properties. In addition, it is important to ensure that materials are safe and sustainable in service, so that they not only have the required mechanical properties but are also durable and safe for the environment and humans (Ratushnyak *et al*., 2023).

Modern construction technologies were also studied to ensure efficient use of the selected materials and maximum quality and durability of the facility. Referring to the definition of X. Chen *et al*. (2022), the introduction of technology in the construction industry is an integral part of the modern construction process. Construction companies are constantly introducing new technologies to improve efficiency, reduce costs and shorten construction time. One of the key areas of technology adoption is the use of information systems and software for project management, resource planning and automation of construction processes. This helps to optimize project management, improve coordination between construction stakeholders and reduce the time required to complete the work.

As noted by B.J. Meacham (2022), fire performance and regulatory requirements in modern construction play a key role in ensuring the safety of buildings and their occupants. Modern construction methods require careful selection of fire protection materials and technologies, as well as careful design of fire safety systems. Regulatory requirements apply not only to materials but also to evacuation, fire alarm and extinguishing systems. The use of modern technologies, such as automated fire detection and extinguishing systems, helps to improve the effectiveness of fire protection measures. However, it is important not only to install, but also to properly design and maintain these systems to ensure their reliability and efficiency. It is worth noting that the introduction of technology plays a key role in the development of the construction industry, contributing to its competitiveness, improving the quality of construction and reducing the negative impact on the environment. However, it is also important to take into account the need to train specialists in new technologies and adapt legislation to the changing realities of the construction industry.

During the design process, it was important to consider not only technical aspects but also architectural and aesthetic requirements. It was necessary to ensure that the choice of materials matched the appearance and functionality of the facility, in accordance with its purpose and the nature of the area. P.V. Ghom & A. George (2021) state that aesthetics in architecture determines the appearance and interior design of buildings, influencing the perception and emotions of observers. It manifests itself through architectural styles, shapes, colours and textures, creating a variety of visual experiences. Aesthetics is also related to the functionality and usability of space, and the efficiency of materials and technologies. A successful balance between these aspects allows to create not only attractive, but also functional and efficient buildings that meet the needs of modern society.

Researchers Y. Yuan *et al*. (2021) identified that architectural design plays a key role in shaping the consumer experience, especially for buildings and structures used in public or commercial settings. Efficient use of space, original design and convenient arrangement of elements inside the premises can significantly increase user satisfaction and comfort. In doing so, architects take into account not only aesthetic aspects but also functional requirements, as well as the needs and preferences of end users. An important factor in architectural design is the creation of spaces that stimulate positive impressions and emotions in users. This may include considering natural light, creating pleasant views from windows, using environmentally friendly and healthy materials, and organizing functional areas to meet the needs of users. Thus, architectural design is closely related to consumer experience, as it has a direct impact on the comfort, convenience, and aesthetic perception of buildings and structures. Understanding the needs and preferences of users is an important aspect in the development of architectural solutions aimed at creating a positive and satisfactory user experience (Kuznetsov, 2024). These results confirm the above study, as careful consideration of architectural and aesthetic aspects allowed to create an infrastructure facility that not only meets the technical requirements and functional purpose, but also harmoniously fits into the visual context of the environment, perceiving feedback from the architecture and aesthetics of the surrounding space.

In addition, it was important to consider the environmental aspect during the design process. The selected building materials had to meet modern environmental standards, so they had to be selected with due regard to their environmental friendliness and safety for the environment. It was important to ensure that the building materials not only met the requirements of technical and aesthetic quality, but also had a minimal negative impact on nature, helping to maintain ecological balance and ensure the health of residents and the environment for the long term. Referring to the work of P. Lamba *et al*. (2022), plastic waste recycling in the construction sector can contribute to sustainable development by reducing the use of natural resources and the amount of plastic waste in the environment. However, innovative recycling technologies and waste management strategies are needed to successfully implement this idea. It is necessary to improve the quality and sustainability of the materials obtained, ensure energy efficiency of recycling processes and take into account the environmental aspects of these activities. It is also important to encourage the use of recycled materials in construction by creating incentives for manufacturers and construction companies. To achieve the goals of sustainable construction, cooperation between various industry players and government agencies is needed to develop new recycling methods and implement effective waste management strategies.

Researchers T.-T. Liu *et al*. (2022) have shown that interest in green building materials has increased significantly in recent decades due to the awareness of environmental issues and the need for sustainable development. Green building materials are materials that are produced with minimal impact on the environment and have high energy efficiency during their production, use, and disposal. These materials can be either naturally occurring or synthetic, but they are usually characterized by lower energy consumption and less environmental impact than traditional building materials. Examples of green building materials include wood from sustainably managed forests, clay, hemp, cellulose insulation materials, and concrete using admixtures from recycled waste. These materials have several advantages, including good thermal insulation properties, environmental friendliness, renewable resources and reduced harm to human health and the environment. There is no doubt that green building materials play an important role in creating healthy and sustainable buildings, contributing to the reduction of greenhouse gas emissions, energy savings and construction waste (Stepanov *et al*., 2023). In addition, their use contributes to a more conscious and responsible approach to construction and sustainable development in general.

Another important stage of the process was to determine the architectural solution for the facility. The use of modern construction materials allowed to implement the best architectural ideas, ensuring not only practicality but also the aesthetics of the building. Referring to the definition of M. Condotta & E. Zatta (2021), the use of recycled building materials in architectural practice and European standards faces a number of challenges. The uncertainty of standards and classification of materials makes it difficult to verify their compliance with building codes. The quality and safety of such materials are also important, as they can be defective or worn out. To address these issues, standardized quality and safety testing procedures need to be developed and certification systems introduced. The use of recycled materials should be actively promoted through financial and tax instruments. This could help develop a market for used construction products and reduce the negative environmental impact of construction.

Researchers A. Almssad *et al*. (2022) found that masonry, especially brickwork, plays an important role in creating sustainable buildings. Bricks are one of the oldest and most traditional building materials, but their importance in modern architecture is maintained and expanding. This overview of the role of bricks in architecture examines their contribution to the creation of buildings that meet the principles of sustainable development and environmental safety. One of the key aspects of using bricks is their energy efficiency. Bricks have good thermal insulation, which reduces energy consumption for heating and air conditioning in a building. This helps to reduce carbon dioxide emissions and reduce the negative impact on the environment. Thus, the use of bricks in construction contributes to the creation of buildings with low energy consumption and contributes to the sustainable development of urban infrastructure (Mysak *et al*., 2016).

The process of designing an infrastructure facility using modern building materials required a comprehensive approach and consideration of various factors. This approach allowed to create a high-quality, efficient and aesthetic facility that meets modern requirements and satisfies the needs of consumers. The result of this process was the creation of an infrastructure facility that not only meets technical standards, but also harmoniously fits into the visual and functional environment, contributing to comfortable and safe use by consumers. As noted by K. Herman & Ł. Drozda (2021) in times of social distancing caused by the COVID-19 pandemic, green infrastructure is becoming especially important for the urban environment and living space. City authorities are forced to revise their urban policies and tactics, paying more attention to the creation of green areas, parks, squares and public spaces that contribute to the physical and psychological well-being of citizens. Green infrastructure is not only a means of beautifying the urban environment, but also a powerful tool for mitigating the negative effects of social exclusion and improving the quality of life. The development of green infrastructure in urban environments during the pandemic poses several tasks and challenges for city authorities. It is important not only to create new green spaces, but also to ensure their accessibility and affordability for all groups of the population, including people with disabilities and low-income groups. In addition, strategies for the sustainable use of green spaces need to be developed, providing for their maintenance and care to preserve their value and attractiveness in the long term.

Following the results of F. Dadakhanov *et al*. (2022), the prospects for the production of innovative building materials are reduced to the development of environmentally friendly composites, the use of advanced technologies such as 3D printing and nanomaterials, and the creation of smart materials adaptive to environmental changes. Successful realization of these prospects requires a combination of research, creativity, investment, and compliance with quality and safety standards. It is important to ensure that new materials are available on the market to support the sustainable development of the construction industry. Analysing the results and conclusions, green infrastructure plays a key role in adapting cities to new living conditions during the pandemic and social distancing. It not only helps to improve the physical and psychological health of citizens, but also contributes to the formation of more sustainable, healthy and harmonious urban environments.

CONCLUSIONS

The design of an infrastructure facility using modern building materials is an important component of the construction industry, as it determines the quality and functionality of the future structure. The use of modern materials in the design process allows to achieve a high level of efficiency and environmental friendliness of the facility. Kharkiv Railway Station is an excellent example of the use of modern building materials and innovative technologies in infrastructure construction. The Paton Bridge is a great example of how steel can be used to create efficient and sustainable infrastructure. The use of this steel has created a bridge that is not only safe and reliable, but also aesthetically pleasing.

The study confirmed that the use of modern building materials is a key factor in ensuring maximum strength and durability of structures. The use of the latest production and material processing technologies makes it possible to create structures that are resistant to weather, mechanical damage and other negative influences, thereby ensuring their durability and reliability over a long period of operation. The table of integrated materials for modern infrastructure provided valuable information on various building materials. This information helped to select the best materials based on quality, efficiency and environmental performance. In addition, the use of modern materials has helped to reduce energy consumption and improve the energy efficiency of buildings. Innovative materials and advanced thermal insulation technologies allow for efficient heat retention in the premises, reducing heating and air conditioning costs, resulting in lower energy consumption and resource savings.

The study confirmed the importance of environmental friendliness of building materials and their impact on the environment. The choice of environmentally friendly materials has a double effect: it helps to reduce emissions of toxic substances into the atmosphere and protects the ecosystem from negative environmental impact. This approach was an important step towards sustainable development of construction, helping to preserve natural resources and ensure a healthy environment for future generations. Designing an infrastructure facility using modern building materials is a complex and responsible process that requires a comprehensive approach and careful consideration of various aspects. Taking all these factors into account allows creating a building that will meet the requirements of modernity, ensuring comfort and safety for its users.

The limitation of this study is the limited amount of available information on the impact of the use of specific modern building materials on the environmental footprint of construction. The impact of the use of modern building materials on the cost and technical complexity of infrastructure construction needs to be investigated.

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CONFLICT OF INTEREST

None.

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Проєктування інфраструктурних об'єктів з використанням сучасних будівельних матеріалів

Анотація. Інфраструктурні об'єкти відіграють ключову роль у забезпеченні життєвих потреб суспільства та розвитку економіки. Проєктування таких об'єктів стає все більш складним завданням, оскільки вимагає поєднання інноваційних технологій, екологічності та врахування потенційних ризиків. Мета дослідження полягала у вивченні впливу сучасних будівельних матеріалів на якість, стійкість та ефективність інфраструктурних об'єктів. У цьому дослідженні використовувалися ретельне вивчення різних типів будівельних матеріалів, літературний аналіз наукових джерел, оцінка міцності та екологічності матеріалів, тестування їхньої довговічності, а також аналіз їхньої естетичної привабливості. У результаті аналізу було виявлено, що процес вибору будівельних матеріалів мав значний вплив на ефективність, міцність та стійкість інфраструктурного об'єкту. Було зазначено, що правильний вибір матеріалів сприяє досягненню оптимального балансу цих характеристик, що є ключовим для забезпечення довговічності та надійності споруди. Дослідження розглянуло використання високоміцних сталевих конструкцій, енергоефективних ізоляційних матеріалів та інноваційних технологій для підвищення стійкості до різних небезпек, таких як землетруси та пожежі. У роботі було представлено методи та кроки, які використовувалися при проєктуванні інфраструктурних об'єктів з урахуванням сучасних будівельних матеріалів. Також було описано значення екологічності в будівництві інфраструктурних об'єктів, що підкреслило необхідність використання екологічно чистих матеріалів та технологій з мінімальним впливом на довкілля. Досягнення стабільності, енергоефективності та екологічної стійкості у будівництві були визнані ключовими завданнями в сучасній галузі будівництва. Висновок дослідження полягав у необхідності збалансованого підходу до вибору будівельних матеріалів та технологій для створення інфраструктурних об'єктів, що відповідають вимогам сталого розвитку та збереження навколишнього середовища. Практичне значення цього дослідження полягає в тому, що воно надає конкретні рекомендації щодо вибору сучасних будівельних матеріалів та технологій для оптимального проєктування та будівництва інфраструктурних об'єктів, що відповідають вимогам ефективності, стійкості та екологічності

Ключові слова: інноваційні конструкції; пожежостійкіть; енергоефективність; міцність; дизайн; залізобетон

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The technology of masonry and processing of stone materials in the buildings of the 13th-century castle of King Danylo Romanovych in Kholm

Abstract. The relevance of the study is conditioned by the great cultural significance of King Danylo's Castle, one of the most unusual architectural objects of the 13th century Rus'. The purpose of the study was to reveal construction technologies, techniques for processing and carving architectural details made of stone, which are used in the construction of castle objects. The research methodology was based on a detailed analysis of the remains of buildings and individual construction or architectural details discovered due to architectural and archaeological research. The study analysed the characteristics of the used natural stones. Archaeological remains of the defensive wall, towers, foundations, and walls of several buildings, the purpose of which has not yet been clarified, present objects created by a highly professional construction workshop. Excavations have revealed a large number of carved decorative architectural details made of glauconitite and limestone, the use of which indicates the richness of architecture and presents specific architectural forms of the Romanesque style. At the first stage, the castle was built only of stone, and at the second stage, brick was also used. The oldest buildings were made of natural glauconite stone. In addition to local green glauconite sandstone, limestone, and fossilised chalk were also used. An interesting feature of the castle is the use of typical Romanesque masonry technology, stone block hewing techniques, and carving of decorative stone details. Based on the results of research, it can be stated that a standard set of hand tools was used. The remnants of carved stone details show the rich plastic structure of the castle's facades and interiors. Similar products and technologies are not found in other castles of Rus' at that time. Finds of masonry tools in the castle ruins suggest that most of the technological process of stone processing

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took place right there in the castle yard. The results of the study allow presenting for the first time a detailed description of the masonry artel of "Master Avdii" – a character in the chronicles about the construction of the castle in Kholm

Keywords: building materials; architectural details; stone; processing techniques; masonry tools

INTRODUCTION

The city of Kholm (modern Chełm on the territory of Poland) was founded by the King of Rus', Danylo Romanovych, in the middle of the 13th century. At first it was a small castle with a town at the foot, but later, realising the favourable location of this settlement, at the time when the Mongol army captured the Eastern part of the state, Danylo rebuilt and reinforced it, and turned it into a capital. Buildings of the 13th century have been preserved here only in the form of archaeological remains of the foundations and lower parts of the walls. The great historical significance of this town and the castle buildings led to the establishment in 2010 of an archaeological group at the Institute of Archaeology and Ethnology of the Polish Academy of Sciences to study the remains of the castle's building structure. The interdisciplinary team consisted of Polish and Ukrainian researchers who worked under the guidance of Professor A. Buko (2019). Archaeological research of the castle grounds revealed a system of fortifications, examined the remains of the main buildings, and provided rich material about the construction and technological solutions of objects. The various artefacts and information obtained by archaeological excavations will serve for scientific interpretations, understanding of everyday culture, reconstructions of castle objects, substantiating material about its construction stages and the nature of architecture. The analysis of the archaeological remains of buildings, the study of the technology of their construction and techniques for processing stone materials are important for answering the question of how a large metropolitan city could have emerged in a short time in the 13th century.

Papers on regional history often contain a presentation of material about stonemasonry regional traditions, but they mostly describe these traditions as lost and without a deeper explanation of the processes of stonemasonry (Gorbanenko *et al.*, 2021). The most common building material for the construction of representative buildings (cathedrals and castle complexes) in the 13th century on the territory of Kyivan Rus' was stone. Carefully crafted stone blocks were used to build plinths, corners of buildings, frames of window or door openings and cornices. Stone blocks were most often used to build the front part of the walls, but the interior was often filled with chipped or field stones (Gazda & Bevz, 2020). Operations of processing stone raw materials to produce construction and architectural and decorative blocks have a long history. Centuries of practice gave birth to the profession of a stonemason and led to the development of tools and traditional techniques for splitting, hewing, grinding, and carving stone material. Brick was used mainly in Lombardy, Southern France and Northern Germany, Denmark and the Netherlands. As a building material, brick began to spread in Eastern Europe only from the end of the 12th century, and in Rus'-Ukraine, chipped stone in combination with Byzantine plinth bricks were used for the construction of prestigious buildings. In Poland, the first brick buildings appeared in the early 13th century. Lime mortar was used in the masonry of walls to join stones or bricks. Residential and palace buildings, and the entire fortification complexes both in the Rus' and in Poland before the 13th century, were often built using wood and clay as the main building material. A similar tradition existed in neighbouring countries and Scandinavia (Wiewióra *et al.*, 2024).

Many years of archaeological research on the castle hill in Kholm revealed the destruction of stone and brick, but the scientific interpretation of the remains of the walls showed that the oldest authentic structures of the castle were built of natural and artificial stone. The most interesting result of archaeological discoveries was that the oldest buildings and structures (defensive walls, palace, church) were built from a local green glauconite stone (Buko, 2019). Its use in the construction of architectural buildings in the 13th century should be considered a unique construction phenomenon on the territory of Kyivan Rus' and Poland. Glauconite is a sedimentary rock with interesting aesthetic and technical qualities, unique among stone materials. This stone is found only in the vicinity of Kholm and occasionally in Western Volhynia (Gazda, 2017). Glauconite stone is relatively easy to process, which allowed the production of building blocks for walls and decorative elements – profiled glyphs of window and door frames and relief details with a relatively complex composition.

In addition to a large number of conventional rectangular hewn blocks used to build the walls, excavations on Vysoka Hirka (the name of the site where the castle was located) revealed a large number of carved architectural and decorative details made of glauconitite and limestone (Buko, 2019). The use of green and white stone materials testifies to the desire of King Danylo to create an architectural object decorated in the traditions of the Tuscan school (Gazda & Bevz, 2020). The Romanesque architectural forms used here also show the European orientation of the founder. The artistic carvings used to create the interior and exterior decoration of the palace and other buildings have analogues in the residences of the neighbouring countries of the Czech Republic, Hungary, and Poland (Jusupović, 2019; Fehér *et al.*, 2022).

The purpose of the study was to analyse all archaeologically discovered remains of walls and foundations, and separately found architectural details, to reveal construction technologies for the construction of buildings, techniques for processing stone blocks and carving architectural details, which are used in the construction of castle objects at the first stage of construction.

MATERIALS AND METHODS

The research methodology was based on a detailed analysis of the remains of buildings and individual architectural details that were discovered as a result of more than 10 years of architectural and archaeological research of the castle. The study first highlighted the characteristics of natural stones used, then revealed the technology of laying foundations and walls; the next stage was devoted to the analysis of techniques for cutting, processing, and carving stone blocks; at the last stage, the technique of manufacturing architectural decor parts – profiled rods, cornices, columns, capitals, etc. – was analysed and reconstructed. Special attention was paid to deciphering the traces of processing stone surfaces with various types of tools. The information obtained helped to understand what tools masons worked with in the 13th century and reconstruct the technical equipment (set of tools) of the construction artel that worked at the castle of King Danylo.

Instrumental research methods were used only to analyse the microscopic structure of stones (Fig. 1). The research methodology was based on visual inspection of the remains of stone walls to identify the masonry technology, and subsequently on a visual inspection of stone building blocks, architectural details and elements to identify the techniques of their cutting and processing. Lists were compiled of those blocks that had detectable surface texture with traces of processing, including the lists of all architectural details found.

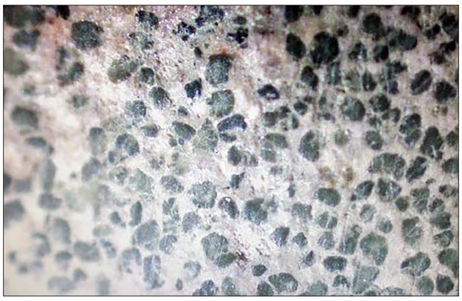


Figure 1. Surface of glauconite stone when magnified under a microscope
Source: photo by M. Bevz

Since the castle buildings were preserved only in archaeological form, the first surveys took place during archaeological excavations. This survey was carried out in the context of archaeological excavations "in situ", when foundations or walls were discovered archaeologically and documented. Visual inspection made it possible to identify those structural elements on which traces of finishing were well preserved. From these elements, a working list was formed for further surveys and recordings. The next stage of work was to photograph these analysed stone blocks or parts from the prepared list. If such blocks or parts were found not in the body of the wall structure, but in the collapse, they were removed, inventoried, and transferred for storage to the repository of the archaeological expedition. This helped to measure them later and take detailed photographs in the studio. Photographs of blocks and parts for surface texture analysis were taken in appropriate daylight or using artificial illumination of samples to reveal the texture. The results of photo recordings and measurements were part of the annual reports. Therefore, in addition to the authors' own photographs of the samples in the field, materials from descriptions and photographs from other reports were also used. Thus, the study analysed several dozen stone blocks and parts from different periods of the expedition, which lasted a total of 10 years. A special experimental part of the study was the selection of those samples of stone materials that belonged to the first phase of the construction of castle buildings. In this case, the authors relied on the interpretations of building substances by A. Buko (2019) and T. Dzieńkowski (2019). Papers by P. Rappoport (1954; 1994), which highlight stone details found during excavations in 1911, were used in the study only to compare the details found during new excavations with those found in the early 20th century. Publication of several photographs from the 1911 excavations by P. Rappoport showed these details in a low-quality image and on a small scale, which made it impossible to use this material for analysis.

The final part of the study was to investigate the processing methods of selected stone materials, blocks, or parts. First of all, the study of literary sources was carried out to identify the tools used by masons and construction artels in the Middle Ages. The scientific literature on this issue is not very extensive. There were no studies in Ukraine that would fully cover this issue, with the exception of isolated local studies (Ivanchyshen, 2017). Therefore, the authors used the synthesising studies by H.J. McKee (1973) and R. Jundrowsky (2015). Based on these studies, an orientation list of typical masonry tools characteristic of the period of the 13th century was compiled. The final stage of the study consisted in a detailed analysis and systematisation of traces on the surfaces of stones from the buildings of the castle of Danylo Romanovych. Comparison and interpretation of these traces, and their relation to the use of various types of tools, formed the final part of the study and allowed highlighting the picture of the "construction and instrumental support" for the building of King Danylo's castle in Kholm. Studies of structural glauconitite and limestone blocks were carried out both on the remains of walls "in situ" in archaeological excavations, and with specimens preserved in the museum collection of the Kholm archaeological expedition.

RESULTS

The walls of the structures at the first stage of the castle's development are made of stone using two technologies – "opus emplectum" and "opus quadratum". Most of the sections of the walls were built using the first technology (Fig. 2). However, the glauconitite blocks at the corners of the perimeter defence wall and entrance gate were very carefully processed and perfectly matched, which allowed these objects to be made using the second technology.

Figure 2. Fragment of the wall of an unidentified castle building; a wall made of glauconitite was erected using the "opus emplectum" technology, excavations in 2015
Source: photo by M. Bevz

The buildings of the second stage of the castle's development were made of other materials and using different construction technologies and masonry techniques. In the foundations of these objects, the secondary use of high-quality architectural details and rectangular blocks of glauconitite is documented. That is, the second construction period came after some kind of disaster, when previous buildings were destroyed and their material was reused in new buildings. Refusal to use glauconite stone at the second stage of construction can also be a consequence of the complete depletion of resources of this raw material or a negative experience of using this stone, which turned out to be unstable to atmospheric influences (Gazda, 2017) or exposure to high temperatures in case of fire.

The wall construction technology "opus emplectum" involves careful masonry of the front parts of the walls from rectangular hewn blocks (Fig. 3). But the interior of the walls is filled with broken stone of irregular shapes and filled ordinarily with mortar. This type of wall is built quite quickly and has sufficient strength, but it requires a fairly large amount of lime mortar of very good quality. Glauconitite blocks, well-matched in height in a horizontal string of rows, were used in the cladding parts of the walls of King Danylo's residence, both internal and external.

The stone blocks had different sizes, dominated by three types: 40×25×20 (length x width x height), 33×34×23, or 37×23×22. A special feature of the walls was that the average height of blocks in one row of walls was always the same (the principle of Romanesque architecture), which ranged from 20 to 23 cm (Fig. 4). These are rather small block sizes, so a logical question arises – what is the reason for such dimensions. This height of the blocks may correspond to the approximate thickness of the horizontal productive formation in the quarry. In particular, it is known about a glauconite cloak over the continental chalk layer in the castle section of Kholm (Gazda & Bevz, 2020). That is, the building material was even at hand at the construction site of the residence facilities.

Figure 3. Fragment of the wall cornerstone made of rectangular hewn blocks of glauconitite
Notes: traces of various hewing methods can be seen on the surfaces of the blocks
Source: photo by S. Gołub (2018)

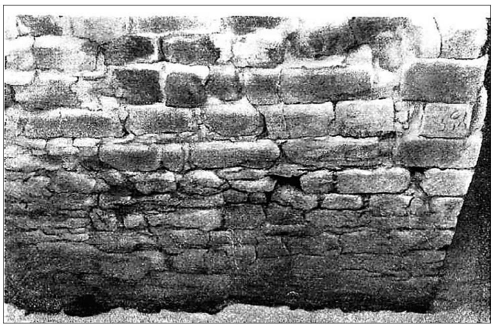


Figure 4. Photo of the North-Western part of the castle wall; excavations by P. Pokryshkin, 1912
Notes: two ways of building a wall can be easily distinguished: 1 – the lower layer is conscientiously and efficiently constructed, 2 – the upper part (the top two rows) is constructed not as carefully. There are also two types of stone blocks – a) of a clear cubic shape and b) when only the front surface and the bottom and top planes of the blocks are quilted evenly, and the two side planes have a broken irregular shape
Source: P. Rappoport (1954)

The walls in the Southern part of the castle hill have been preserved to a height of 1.5-2.0 m. The outer two-metre-thick wall is made of stone in such a way that the sole of the wall in cross-section is not horizontal, but stepped down the slope. The difference between the internal and external levels of the lower part of the wall can be more than 1 m. Therefore, the external preserved part of the wall has a height of more than 3 m. An important result of recent research was also that the wall was not built strictly vertically, but with a slope towards the middle on the outside (Buko, 2019). White and green stone paving on lime mortar was found on the inside of the wall. Research in 1911 revealed an underlying layer of rubble stone filled with lime mortar under the paving. Such a design may indicate that it was not a paving of the yard, but a floor structure. An additional argument for this interpretation is the information that lime mortar also penetrated the wall thickness (Rappoport, 1954).

Outside the castle wall, 3 m below the hillside, another glauconitite wall was discovered in the Southern part of the hill, which consists of several rows of large stones. It was also mentioned and described in general terms by Pokryshkin. He interpreted it as the former foundation of the mountainside (Rappoport, 1954). This interpretation cannot be accepted due to the fragmentation of the studied area. So far, there is no confirmation of the existence of this "foundation" around the entire perimeter of the mountain. In the South-Eastern part of the castle, behind a two-metre defensive wall, the remains of wooden log structures were found (well below the base of the two-metre wall). It is this type of structure that was most often used in medieval Rus' for the construction of ramparts and for strengthening artificial platforms of fortification objects. Most likely, these remains are traces of crates that served as the binding structure of the hillside and may have encircled the entire hill. However, there is also the assumption of A. Buko (2019) that it could have been the wooden remains of a shaft built in the later, second period of the castle's functioning.

Excavations in 1911-1912 revealed the remains of a structure made of glauconite stone, which Pokryshkin called a "tower or well" (Rappoport, 1954). New research on the object proved that it was built using the "opus emplectum" technology. Along the perimeter, the foundation walls of the building had an approximate shape of a square measuring 5×5 m and a round inner part with a diameter of 2 m. The walls are made of not very carefully hewn blocks and slabs of glyconite on a white lime mortar with a small sand content. The repair section of the exterior of the walls using Sarmatian sandstone was traced (Dziekowski, 2019). A similar tower in the plan of the 13th century was preserved in Stolpie near the Kholm. Its dimensions in the plan are also 5×5 m and the diameter of the inner part is 3 m. This object was examined in detail by A. Buko (2016). Its walls, however, are built of quartz sandstone, and not of glauconitite.

An important addition to the discovered technology for the construction of walls "opus emplectum" was the opening in the Northern part of the castle hill. The remains of the so-called building "D" demonstrated the combination of a stone wall with wooden reinforcement. The stone structure in the lower part is made of glauconite stone on a light cream mortar. The walls of the building in the lower part were built with powerful wooden beams measuring 20×35 cm embedded in the body of the wall. The bars were laid in the middle along the axis of the wall at the same height and probably intersected with the cuttings in the corners (Fig. 5). The wall thickness averaged 80 cm. Thus, another innovative technique (reinforcement of the wall structure) can be noted in the castle construction in Kholm. Perhaps this technique was used in other buildings of the residence, but their preservation only in the foundation form does not allow confirming this with sufficient confidence.

Figure 5. Fragment of the wall (OBD) of the stone wall of building "D", built of glauconitite blocks in the "opus emplectum" technique and reinforced with wooden beams
Notes: the photo shows a hole in the wall body left by a wooden beam. The property is located in the Northern part of castle hill
Source: photo by M. Bevz

Hewn blocks of glauconitite for wall construction and carved architectural details that appear as archaeological relics on Vysoka Hirka demonstrate examples of extremely high structural and artistic performance. The quality of the hewing of conventional wall blocks is very thorough and precise. Some of the best-preserved authentic wall fragments and carved details show perfectly hewn and even smoothed flat surfaces of blocks or profiled elements of architectural forms (Gazda & Bevz, 2020).

Compared to other types of sandstone, glauconitite is characterised by relatively soft grains with similar binding properties. Grains, apart from soft fragments and bioclasts of Cretaceous rocks, are 80% composed of the clay mineral glauconite, formed into spherical shapes (Fig. 1), with a characteristic aggregate internal structure (Gazda & Bevz, 2020). When hewing or cutting glauconitite blocks or parts, its structure makes it easy to separate the bonds between the grains, rather than, as is the case with quartz sandstones, breaking them by force in the processing plane. As a result, this material behaves more plastically, but with strength parameters close to most sandstones. This structure has an important aspect for research – the surfaces of the 13th-century Kholm glyconite blocks and details show clearly visible traces of processing. In some cases, these traces are traceologically consistent with the stone tools found in the excavations (Gołub, 2018).

The presence of carved architectural details and fragments of artistic stone decoration in the castle ruins can be a clear confirmation of the records of the Halych-Volhynian Cronicle about the skilled craftsman Avdii, who worked and carved stone for the artistic decoration of buildings (Makhnovec, 1989). The repeatability of the masonry methods and techniques of processing the building stone used in the construction of the walls in the form of well-carved parallelepiped blocks may be evidence of the work of a highly professional building and masonry artel. This artel was well acquainted with the technologies of building buildings in the Romanesque architectural tradition (Gazda & Bevz, 2020).

Analysis of the building and decorative elements suggests that the Kholm craftsmen used a standard scheme for the execution of architectural details in stone. At the first stage, the quarry chipped off the rock in layers of more or less standard height stone blocks of close to rectangular shapes. For the first operation, the quarry used rough hammers and baffles. Visual analysis of stone glauconitite blocks revealed the use of wide toothed baffles. Such a tool was driven with a hammer along a drawn line on the surface in two places, tearing off the stone mass of a more or less regular shape. Such a stone block should have been chipped off due to the thickness of the productive layer of stone. According to archaeological studies of Vysoka Hirka, the thickness of the glyconite layer there was 60-100 cm (Gazda, 2017). It was possible to break off part of it in a vertical chip, breaking off part in the desired direction. Traces of using this chipping method were found on several blocks (Fig. 6). Subsequently, the block obtained by chipping off a rough, often irregular shape was pressed to the desired shape on the construction site. To obtain blocks of the desired size and rectangular shape, their surfaces were worked out in more detail by cutting. In particular, the front surfaces of many blocks were hewn with a 2-centimetre flat mason's hammer (Fig. 5). The photo shows clear traces of such a tool – diagonal stripes on the left side. The surface of this block also shows traces of light adjustment with a trowel or a toothed mason's hammer. This last operation is indicated by small vertical stripes in certain places on the surface.

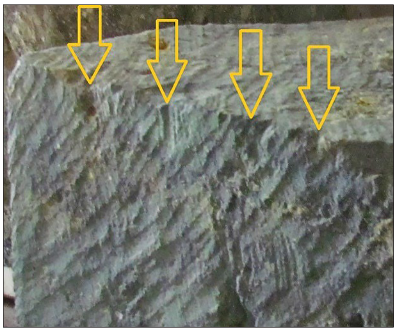


Figure 6. Traces of block splitting with a four-tooth baffle
Source: photo by M. Bevz

Getting smooth surfaces of the stone block required chipping the excess mass of stone around the entire perimeter of the block. Excess parts of the stone were chipped in the right places, first with comb cleavers, then with ax-hammers or toothax-hammers and mason's hammers (also toothed or flat). No traces of sawing stones were found, so the use of saws to form glauconitite blocks was probably not practiced. On the surfaces of the blocks, there are sometimes traces of hewing with a wider hammer with strips of 40-50 mm (a toothax-hammer is a tool similar to a small double-sided axe). There are examples when the excess protrusion formed after breaking off blocks at the first stage was roughly removed with a comb chipper, and then pressed down with a flat one (Fig. 7) or the toothed end of the mason's hammer. This final phase of finishing with a flat or toothed mason's hammer or toothax-hammer is carried out until the surfaces are smooth.

Figure 7. Image of two stages of surface treatment of a stone block
Source: photo by M. Bevz

A flat plane of the walls of blocks or architectural details was obtained in stages: at the first stage, pointed cleavers were used for glauconitite or limestone stone – for the primary removal of stone mass (Fig. 7, bottom of the block), and at the second stage, hewing with a flat or toothax-hammer or mason's hammer with a width of approximately 40 mm was used (Fig. 7, top of the block). The photo clearly shows these two phases of surface treatment of the block, left in the form of traces: at the bottom of the block – a roughly hewn plane with traces from the comb chipper; at the top – a plane smoothly hewn in the second phase with a small flat mason's hammer.

A special invention of the Kholm stonemasons is the production of a certain number of blocks "with a hook" (Fig. 8). Such a block played an important role for more perfect binding of stones in masonry. Especially useful was its use in the corner parts of the walls of buildings. It provided reliable strength of the wall corner, which has always been a weak point in masonry technology when conventional rectangular blocks were used.

Figure 8. An example of a profiled glauconitite block "with a hook" – a protrusion in the rear inner part for better binding and "hooking" the block in the wall
Source: photo by M. Bevz

This technique testifies to the high professionalism of the masons. In Romanesque building practice, it is not very common to find a technique where corner blocks have a protrusion in the back along the entire height for better fastening and "hooking" the block into the wall thickness. This formal decision is very important for the masons who build the structure. The fact of its use indicates a well-thought-out masonry technology and purposeful management of all stages of construction of structures on Velyka Hirka during the construction of the Danylo's residence (Fig. 9). The products of the stone workshop and the likely guidance of the carver Avdii (Kotliar, 2002) over the production of decorative elements prove that they were not only artistically well executed, but also competently designed technologically for their further use in the construction of walls and as decorative elements of buildings.

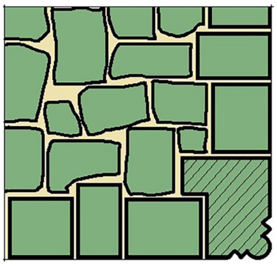


Figure 9. Application of a stone block "with a hook" in the construction of the cornerstone of the wall of the Kholm castle
Source: developed by M. Bevz

The analysis materials showed the use of several methods of cutting stone and the use of several types of tools. Based on the results of the analysis of stone building material, it can be confirmed that three types of hewn blocks were used in the castle buildings. The first was used for laying foundations and exterior walls (with a rougher wall texture), the second – for interior walls with a well-patterned, flat surface of the block faces, and the third – for interior or exterior walls with profiled elements or carved decor. The third type of blocks required the most careful execution, more operations and tools. The blocks of the third type were even polished. A separate group consists of delicately carved elements made of white limestone – a fragment of the capital with an acanthus leaf and a block of the faceted nervure base. Even in the first type of blocks for wall construction, the face and side joint surfaces were very carefully made with flat planes. Most often, masons at the Kholm castle used a double-sided mason's hammer for trimming building blocks – flat pointed at one end and toothed at the other, or flat pointed on both sides. During archaeological research of the castle, two such tools of different sizes were found (Fig. 10).

In the walls of castle buildings, there are often blocks with traces of hewing with a mason's hammer with a single sharp tooth (Fig. 11). This trace is obtained from the most common type of mason's hammer – when this tool has a sharp tooth at one end and a flat blade (or hammer) at the other. Sometimes such an instrument is called a kilof (McKee, 1973). In some regions of Ukraine, mason's hammer is also known as "pickaxe" (Ivanchyshen, 2017). There are a number of blocks where the sharp part of such a tool was used to roughly chisel off the excess mass of stone and then to level the end and face surfaces of the block with the flat part.

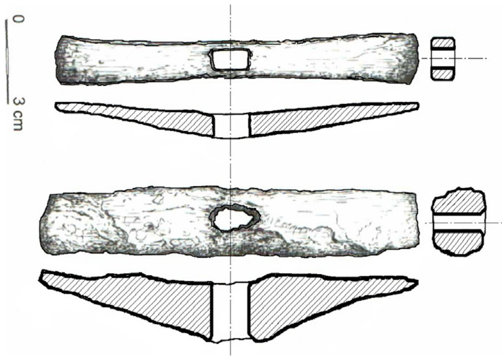


Figure 10. Illustrations of two tools: a narrower and a wider straight mason's hammer with two straight edges, found in excavations in 2013 and 2016
Source: developed by E. Hander and M. Bevz

Figure 11. Example of cutting and processing a glauconitite block
Notes: the side surface has traces of hewing (in different directions) with a sharp-edged mason's hammer; the front surface is perfectly flat and polished. The cornerstones of the block are levelled with a fine-toothed chisel or skarpel to a width of 15 mm
Source: photo by M. Bevz

One interesting technological pattern is observed: the front surfaces of blocks hewn with a mason's hammer or chisel, as a rule, have a diagonal direction of hewing in relation to the rectangular surface. It can be assumed that the use of this technique was conditioned by the desire not to cut the edge of the stone surface at right angles. When cutting perpendicular to the edge of the stone block, it would be more difficult to get a straight line of the cornerstone edge. Such diagonal cutting resulted in the final flat "working" surface of the block. Small traces of diagonal hewing with a mason's hammer are found on many glauconitite blocks (Figs. 6, 11).

The use of certain tools by the construction workforce is supported by archaeological finds of the tools themselves. The metal parts of two more masonry tools were found in the Southern part of the castle during archaeological research in 2011 and 2016 (Fig. 12). These were two different types of chisels and two types of mason's hammers with flat ends. The use of each of these two tools provided a different surface texture. When processing the surface of the stone with a chisel, the bricklayer also used a wooden hammer (mallet). The chisels always leave long, very distinct, even-width grooves on the surface of the stone that correspond to the width of the blade.

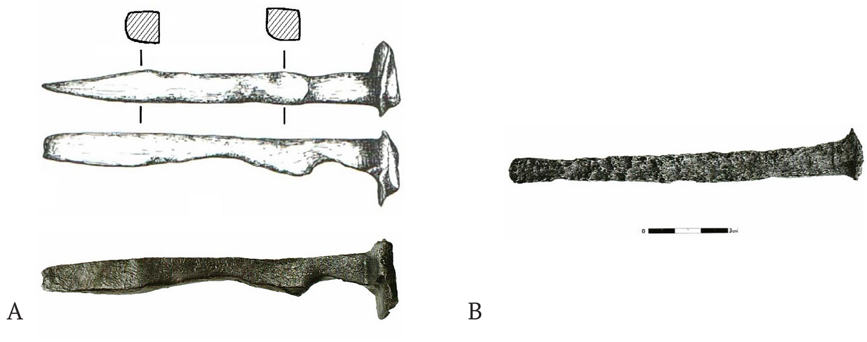


Figure 12. Photos of two types of iron chisels found during archaeological excavations in Kholm
Notes: A – in 2011 in the Southern part of castle hill; B – during the excavations of the Church of the Virgin Mary in 2013
Source: photo by G. Zablocki

Cutting with a mason's hammer is characterised by short traces of "cleaves". The width of the hewing edge depended on the width of the blade. Two widths of the hews were recorded: 20 mm and 30 mm, which corresponds to the tools found in the excavations. On the walls of the stone blocks, traces of such hewing were usually in the form of parallel rows (Fig. 13).

Figure 13. External surface of the wall block made of glauconitite, hewn with a flat mason's hammer
Notes: thick traces of short hews are visible
Source: photo by M. Bevz

Sometimes, among the museified glauconitite blocks in Kholm, there are traces of hewing with a chisel rather than a mason's hammer. In this case, the notch on the body of the stone will be long rather than short. When using the chisel, stonemasons struck them with a wooden mallet (a hammer with a round head) (Discover the secrets..., 2023). The mallet with such cutting was a convenient light tool that allowed not to hit, but as if to push the chisel, extending its course. As a result of this operation, the use of a chisel tended to produce longer, parallel "hew marks" that ran in the same direction on the surface of the block (Fig. 14).

Figure 14. Example of hewing the side surface of a glauconitite block with a flat chisel with a blade width of 12-15 mm in two directions
Source: photo by M. Bevz

Hill craftsmen also used toothed chisels of different widths and sizes of teeth. All glauconitite or white stone blocks, which were elements of architectural decoration, had perfectly straightened block faces or fractures in their shapes. This kind of preload has characteristic traces-stripes from the use of a fine-toothed chisel (Figs. 8, 11, 15).

It should be noted that various types of mason's hammers have been recorded for cutting blocks. In particular, smooth surfaces of blocks were obtained using a mason's hammer with a three-pronged blade (Figs. 16, 17). Judging by the tracks, it was a tool with a sharp toothed blade with a tooth pitch of 7-6-5 mm. The interval between the teeth was 1 mm. Traces of this type of hewn surface have been found on many glauconitite blocks in the Southern part of the castle. As noted, traces of cutting with a mason's hammer are easy to identify, since they have the character of short cutting-notches. Depending on the type of blade of the mason's hammer – toothed or flat, the corresponding profiles of the ditches appear on the surface of the stone as traces of cutting.

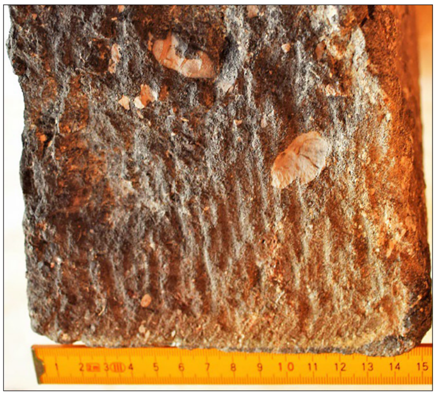


Figure 15. An example of a surface hewing with a fine-toothed comb chipper (clearly parallel ditches of equal depth)
Notes: the bottom edge of the block is trimmed with a fine-toothed chisel – 15 mm wide strip
Source: photo by M. Bevz

Figure 16. Surface of a glauconitite block with traces of cutting with a three-pronged flat mason's hammer
Notes: repeated marks of the three teeth of the tool are specially marked, indicating the direction and density of chiselling
Source: developed by M. Bevz

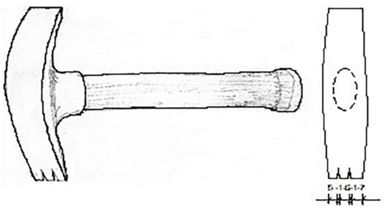


Figure 17. Hypothetical drawing of a three-pronged flat mason's hammer used by a stonemason's artel in the 13th century
Notes: dimensions of the toothed blade: 5-1-6-1-7 mm
Source: developed by M. Bevz

The marks recorded in Figures 15 and 16 from cutting with a toothed mason's hammer indicate the use of a 3 cm wide blade. The blade of this tool is asymmetrical – the teeth are different in width (Fig. 17). The direction of hewing is diagonal to the rectangle of the block surface. The edges of the surface are also trimmed with a toothed chisel in a beveled direction towards the edge of the block. This has its own explanation – it would be difficult to get a flat corner of the block with the perpendicular movement of the chisel. If the chisel is used to cut the edge at an angle, the part of the chisel always remains on the surface of the block, allowing for continuous cutting movements by moving the tool along the edge. The surface of this block (Fig. 16) also demonstrates the fact that when cutting with a mason's hammer, the corner of the block did not turn out to be of high quality. This effect of using a mason's hammer differs from working with a chisel. With the help of a chisel, it was possible to delicately press the cornerstones of the block with diagonal movements. This could even be done manually, without using a mallet. In the same illustration, a closer look reveals that the right and upper edges of the block surface are not hewn with a mason's hammer, but are trimmed with a delicately toothed chisel.

On the surfaces of individual glauconitite blocks, a different size of mason's pick was also used (Fig. 18). It has a wider blade of 4 cm and more worn rounded three teeth. Traces of hewing with this wider-toothed mason's hammer were recorded on glauconitite blocks that may belong to the shrine of St. John Chrysostom, the castle chapel of King Danylo Romanovych, whose construction in majestic, perfect forms was a special intention of the founder (Voytovych, 2016). These blocks, as proven by research, are decorative elements of the entrance portal to the shrine (Bevz, 2019). The front sides of these blocks have a smooth polished character, and only the surfaces of the sole and upper of the block have a smooth surface hewn with a mason's pick. These surfaces connected the blocks to each with mortar, creating a complete architectural form of the portal. This shows a very skilful hewing of the surfaces with a toothed mason's hammer, which were later to create an invisible seam when the blocks were joined. The resulting horizontal surfaces of the blocks turned out to be perfectly smooth and convenient for connecting to each other through a thin seam of mortar.

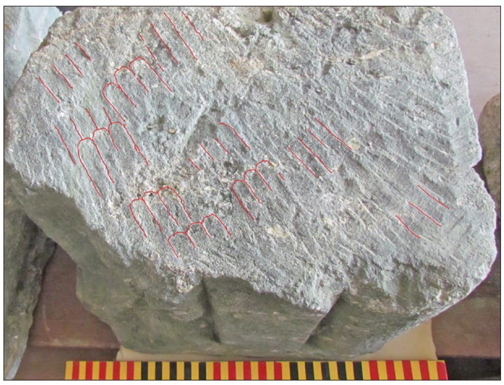


Figure 18. Lower profiled block of the left portal
Notes: traces of hewing with a trident claw with a three-pronged mason's hammer with a blade width of 4 cm on the upper plane of the profiled glauconitite block
Source: processing and photo by M. Bevz

To obtain smooth face surfaces in stone blocks, which were made as decorative elements, Kholm craftsmen used various techniques of their final finishing. In particular, grinding or surface treatment with a chisel or scraping was used to finish the hewn surface. For polishing, stonemasons usually used blocks of hard stone with a grid of notches. Another method of obtaining a flat surface was to use wide flat chisels and skarpels. The essence of this method was to treat the surface with a dense network of perpendicular impacts with a sharp flat skarpel blade or chisel. As a result, it was possible to remove uneven bumpy areas from the surface of the stone and get a densely split flat surface, with the appropriate texture. The textured pattern of the surface depended on the master's plan. It could give it the character of thick parallel notches (Fig. 19) or a grid of perpendicular lines, etc. This type of surface was made in those blocks that were used in the interiors of the building or for decorative elements on the facades.

Figure 19. Rounded surface of the half-column with the texture of a vertical grooved character, obtained by thick blows with skarpel perpendicular to the surface of the part
Source: photo by M. Bevz

Two types of flat iron chisels were found in archaeological excavations at Kholm castle (Fig. 12). They differ only in the shape of the head. Their working blades are similar and have a width of about 2 cm. Instead, the use of notched chisels is only confirmed in the form of specific marks on stone blocks. That is, the use of both flat and toothed chisels was common. As a rule, they were used in the manufacture of profiled and carved parts. But their use was also recorded for levelling the front surface in building wall blocks. On the front walls of blocks and architectural elements from castle buildings, traces of jagged chisels are most often found. The use of such toothed chisels of two types was recorded – with small thick teeth on the blade, as well as with three wider teeth (the so-called "trayanka").

At Kholm castle, operations were also performed to cut flat surfaces of stone blocks using skarpels – a tool similar to a chisel, but with a wider blade. Skarpels, like chisels, are found with a flat or toothed blade. The use of both flat and toothed skarpels has been confirmed. Flat ones were often used to cut off excess parts of the block, for example, if necessary, to get grooves-fluting or the shape of rectangular profiles. An interesting feature is the use of skarpels to create a smooth but textured surface of the block. In particular, in this way, skarpels were used to produce smooth surfaces, and then to give the texture a grooved character by thick strokes of skarpels perpendicular to the surface on the front part. The study showed that even the surfaces of rounded half-columns were treated in this way. An example of this finishing technique is clearly visible on the body of a half-column in the corner blocks of door frames (Fig. 20). The plane aligned with the toothed wide skarpel is also fixed on the upper surface of the profiled glauconitite block with the guilloche (Fig. 21).

Figure 20. Marking with a spike or nail of a modular grid (guilloche) on the upper surface of a profiled glauconitite block
Notes: the engraved lines are drawn in yellow. The centre trace from the compass is also marked with a cross when measuring the half-column
Source: processing and photo by M. Bevz

Figure 21. Reconstruction of the scheme of using compasses and a ruler for measuring and constructing profiling on the following blocks based on the use of a template – a modular drawing on stone with guilloche
Source: processing and photo by M. Bevz

A very specific tool was also used in Kholm to create smooth face surfaces on glauconitite and limestone blocks – a drawknife. The drawknife consists of a wooden handle with several fine-toothed steel blades attached to it. Two types of such tools are known: the first, when metal-toothed plates are embedded in thick parallel strips in the slots of a wooden bar; the second, when a specially made metal stretchable strip is embedded in the bar in two directions. Often, the toothed blades of fine saws were used to make drawknife. This tool was used to perform the final alignment of the block surface. The toothed blades left shallow parallel small grooves on the body of the stone (Fig. 22).

Figure 22. Example of final treatment of the front surface of a glauconitite block
Notes: the surface of the block is perfectly flat, which indicates the use of a drawknife; small parallel lines from the teeth also indicate the use of this tool; after hewing, the edges of the block are delicately cut and levelled with a fine-toothed skarpel or chisel – a strip along three edges 10-15 mm wide
Source: photo by M. Bevz

The stonemasons used not only percussion tools, such as toothax-hammers, mason's hammers, and partially skarpels. The initial important part of the process of making decorative elements was to apply drawings on stone blocks for their subsequent processing to obtain profiled or other, in particular, carved parts. A compass and a so-called spike (a sharp pencil-shaped metal tool) were used to draw the required profiles on the stone. Shpichak had a dual function: it served to make drawings, lines, profiles on the surface, but it also served to drive a stone into the body, if necessary, break off part of it, or to create a depression (McKee, 1973). For example, such depressions and protrusions were specially knocked out on the two surfaces with which the blocks were joined, for better adhesion. If it is necessary to obtain a profiled side of the block or some carved contour, the desired contour was applied to the pre-treated flat surface of the block with a sharp metal "spike". On several glauconitite blocks, lines were found applied to the levelled smooth surface-marks for removing unnecessary parts and marking places where blocks can be bound.

On one of the blocks there is a unique pattern cut out with a spike or nail. A template (guilloche) was drawn on the wide surface of the block for drawing and carving subsequent decorative blocks of this type. In this case, this refers to a type of block with an angular carved half-column and a double strip of fluting (Figs. 20, 21). A separate illustration shows a reconstruction of the measurement scheme and constructions using compasses and a ruler of the process of finding and drawing the profile of a half-column and fluting. After such a drawing of the desired contour on the upper surface of the block, the excess part of the stone was cut off. It can be concluded that the guilloche block was made first, and later served as a reference for measuring and transferring the circuit to subsequent blocks of such profiling. In total, more than 10 corner blocks with such profiled decor were found in excavations in recent years and in excavations from 1911-1912. Rectangular profiling of blocks made of arched or other curved elements was performed with chisels (Fig. 23).

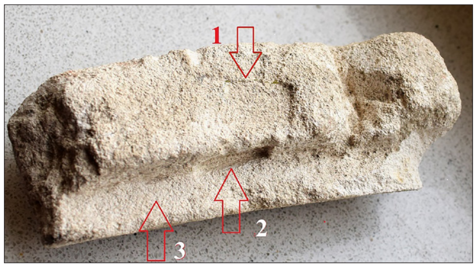


Figure 23. Fragment of a white stone curved profiled part with traces of surface treatment with a chiselk
Notes: 1 – trace from the use of a flat chisel with a width of 20 mm for horizontal chipping of the surface; 2 – trace from a flat chisel with a width of 20 mm and a thickness of 1.5 mm for profiling, cutting off part of the stone; 3 – very thin diagonal traces from removing part of the stone with a fine-toothed chisel or skarpel to obtain a flat surface and a rectangular profile of the part
Source: photo and designation by M. Bevz

The rounded shapes of architectural details and carved elements of a more complex nature were polished with a fine-grained rounded wheel or a specially made stencil made of harder stone. Although it should not be excluded that a small thick notch with vertical stripes may indicate the use of skarpel for chipping excess parts of the stone mass. The surface of a vertical half-column with a carved grid of furrow marks forms a perfectly rounded shape with small regular tool marks (Fig. 21). Perhaps, to get such a correct shape, masons also used a convex template, which constantly checked the correctness of the hewn shape of the half-column. For carving rounded surfaces, rounded chisels were used – the curve chisel (Fig. 24). Curve chisel, like other chisels, could be of different sizes (widths) and different curvatures. The front surfaces of the blocks could be sanded. This is demonstrated by the front, very flat polished surface of the block found in an excavation site in the Northern part of Kholm. The fact that the grinding operation itself took place is indicated by curved furrows from circular movements on the surface (Fig. 24).

Analysis of profiled stone parts shows that the edges-cornerstones of semicircular or other convex shapes in architectural profiles were finally delicately cut at an angle of 45 degrees with a fine-toothed chisel (Figs. 20, 21). This pattern of cutting the cornerstone was performed by a special operation, when the chisel was placed perpendicular to the line of the cornerstone, but moved to cut at an angle of 45 degrees. After such a delicate cutting of the corner of the block, its sides were pressed in accordance with the level of the strip of the corner. Over time, their surfaces could also be sanded. For carving more complex architectural forms, various widths of chisels, skarpels, curve chisels, and drills were used.

Figure 24. Example of a glauconitite block with angular vertical half-columns and fluting
Notes: two shallow fluting grooves were made according to the prepared pattern by cutting with a wide skarpel and then levelling with a fine-toothed chisel with the movement of its blade at an angle of 45 degrees. The body of the half-column has vertical traces from sanding or delicate processing with skarpel. The front surface of the block is also smoothly sanded in different directions
Source: photo by M. Bevz

In addition to a large number of ordinary rectangular wall hewn blocks, excavations on Vysoka Hirka revealed a certain number of architectural details or fragments made of glauconitite and limestone, which had a carved decor. An example of a highly artistic design of such a detail is a fragment of a limestone stone capital (Fig. 25). The part is polished and very delicately carved. The nature of the carving and style of acanthus leaves are very similar to the products of the Galician school (Gazda & Bevz, 2020). The unique feature of this piece is the use of intarsia – glauconitite "eyes" are inserted in the drilled acanthus curls.

Figure 25. Fragment of a carved capital corner with an acanthus leaf
Source: photo by M. Bevz

The summary Table 1 presents the results of a comparative analysis of the use of various tools and, accordingly, different techniques for cutting and processing structural stone blocks or architectural details. The results demonstrate the use of traditional medieval tools and techniques. For a better understanding of the use of a particular stone cutting technique, along with a photo of the stone surface, an image of the tool that was used for the technological operation is presented.

Table 1. Techniques for processing and carving stone in buildings of the 13th century on Vysoka Hirka in Kholm with identification of appropriate tools

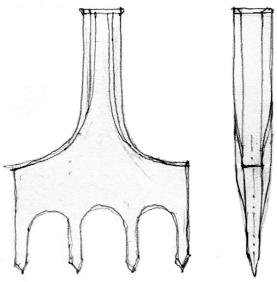
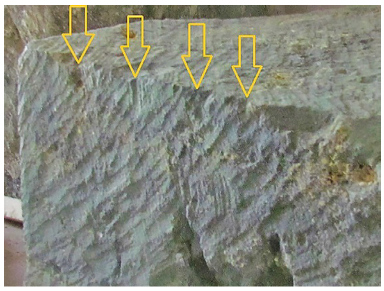
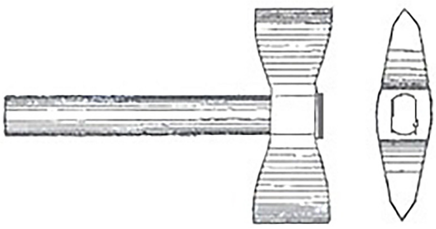
No.	Tools, name	Photo of the treated stone surface
1	 Baffle	
2	 Ax-hammer	

Table 1. Continued

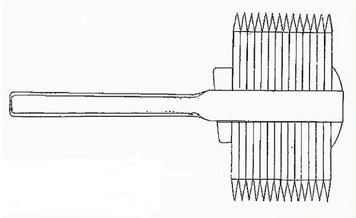
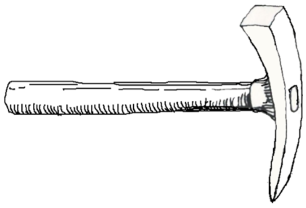
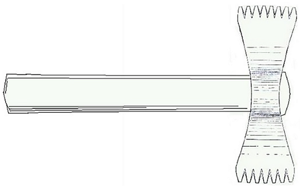
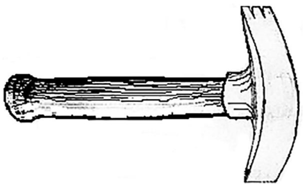
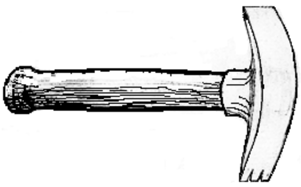
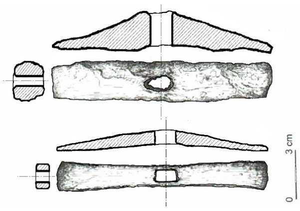
No.	Tools, name	Photo of the treated stone surface
3	 Crandall hammer	
4	 Mason's pick with hammer and point end	
5	 Toothax-hammer (made with teeth of the desired size – small or large)	
6	 Mason's hammer with combined blades – flat and toothed (hewing with the flat side)	
7	 Mason's hammer with combined blades – flat and toothed (hewing with the toothed side)	
8	 Mason's hammer with two flat edges (the edges of the blade are slightly rounded due to grinding)	
9	 Fine tooth chisel (alignment of block edges)	

Table 1. Continued

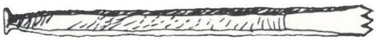
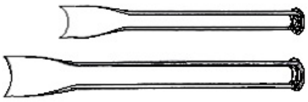
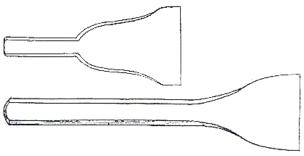
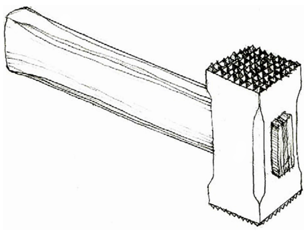
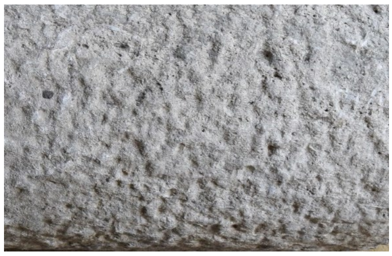
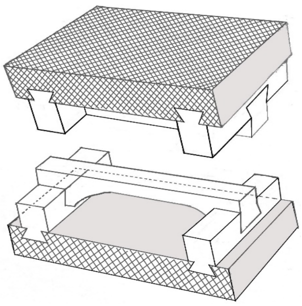
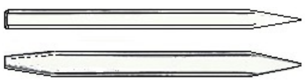
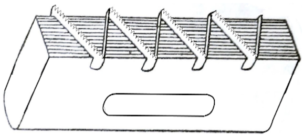
No.	Tools, name	Photo of the treated stone surface
10	 Trident tooth chisel	
11	 13th century narrow chisels found on Vysoka Hirka	
12	 Curve chisel	
13	 Skarpel	
14		
15	 Grinding stone	
16	 Spikes (thin and coarse)	

Table 1. Continued

No.	Tools, name	Photo of the treated stone surface
17	 Drawknife (adze)	

Source: developed by M. Bevz

The results of the study do not provide grounds for accurate dating of the processing methods used (since the blocks could be reused and further processed). However, no other methods of stone processing were found, even in cases where repeated use of blocks was suspected. Most carved and hewn limestone and glauconitite blocks or parts, according to their formal characteristics, belong to the same construction period. Although they have been found in various excavations in different parts of the Vysoka Hirka, the similarity of their processing is beyond doubt. The results of the study, on the one hand, demonstrate the complete tools of the construction artel and, on the other, show the relative conservatism of the development of construction technologies in the 13th century in Kholm. This is evidenced by the absence of traces of the use of saws and mechanised operations.

DISCUSSION

The list of researchers who have considered the architectural and construction aspects of King Danylo's castle in Kholm is very narrow. These are usually participants of an architectural and archaeological expedition working on Vysoka Hirka since 2010. All of them are listed above. Therefore, their assessment of the accuracy of interpretations should be relied upon. The discussion element of the presented study is the correct interpretation of: a) technologies for building walls; b) techniques for processing building blocks and architectural decorative details. If the discussion on the first issue is hardly possible, since the nature of the two types of masonry is clearly recorded in the reports, documents, and drawings of the expedition and is beyond doubt, then on the second issue (interpretation of the tools for cutting blocks and parts by the masonry artel), hypotheses are expressed for the first time and a discussion and critical remarks can be expected.

Regarding the first aspect of the study – technologies for building walls, it should be noted that the first researcher who highlighted this issue was P. Rappaport (1954). Based on the analysis of reports and notes of archaeological research by P. Pokryshkin since 1912, P. Rappaport (1954) first revealed the technological features of the construction of walls in the castle of Danylo Romanovych. However, its descriptions are directed only to objects in the Southern part of Vysoka Hirka. Repeated excavations in 2017-2020 in this part of the castle fully confirmed the results of the first expedition (Buko, 2019). Excavations revealed a rectangle of walls in the Southern part of Kholm (measuring 33×22.5 m), surrounded by a defensive wall about 2 m thick. The wall is made of stone in the "opus emplectum" technology. Pokryshkin's notes indicated that the wall was dominated by green glauconitite and white limestone. The yellowish and reddish stones mentioned in the notes turned out to be glauconitite blocks that changed colour due to high temperature (the fire of 1256) (Gazda, 2017). The outer face of the wall is made up of larger stones, while the inner face is made up of smaller stones. On the corners, an exclusively green stone was used, in the form of better-processed, rectangular blocks. Occasionally, there are 20×25 cm nests in the wall. P. Rappaport (1954) interpreted them as remnants of scaffolding. The correctness of this interpretation should be verified by additional studies. Nests of this size were probably intended not for scaffolding, but for structures. Horizontal rows and layers of stone in ants were carefully stacked from blocks of a certain equal height in each row, but the rules for tying blocks together were not strictly observed (Dzieńkowski & Gołub, 2018). An important and interesting conclusion from the research of 1910-1912 is contained in the notebooks of P. Pokryshkin, where he notes that the outer side of the wall was probably plastered or had a wide grout: there are traces of grey lime mortar on the wall, but the mortar in the masonry and joints is slightly whiter (Rappaport, 1954). The researcher also did not rule out possible lime painting of the walls.

Research of the expedition led by A. Buko (2019) in 2010-2018, in addition to re-opening the remains of the castle in the Southern part, also carried out several excavations in the Northern part of Vysoka Hirka. A total of 32 excavations were completed. Regarding the second aspect of the study – techniques for processing building blocks and architectural decorative details – this issue has been ignored by Kholm researchers until recently. Published materials from P. Pokryshkin's research mention about 30 architectural details found, but only a few details were described, paying attention only to their shape and size. That is, they are not put into scientific circulation, and the published materials do not cover the issues of their manufacturing technology. The results of new research under the guidance of A. Buko (2019) allow supplementing this collection with new carved elements of approximately the same number, but they also did not become the subject of a separate publication. The need to generalise and systematise the results of long-term research of the Kholm residence in the construction and technological aspect was emphasised by S. Gołub (2018). In the study of stone processing techniques, the analysis covers only the latest architectural elements found (from excavations in 2010-2018), so to a certain extent this study is not complete and it is expected to be supplemented with more details. However, even in this format, the technical means and technological features of the local Kholm stonemasonry school are fully described.

For the first time in the scientific literature on construction in 13th-century Ukraine-Rus', the technological and technical aspects of the process of constructing a stone building are described in detail: materials, stone processing techniques, tools used for this purpose, features of masonry, methods of making decorative elements, and various types of decorative surfaces in stone blocks. Although previous researchers declared that they had covered this topic, they merely listed the types of stone and stated that manual methods of processing were used without disclosing detailed characteristics of the types of work and tools. Such an example is the study by P. Rappoport (1994). In addition, the above study incorrectly classified the buildings of Kyivan Rus' as Russian. Another part of the researchers (Jundrowsky, 2015) tried to describe the development of the stonemason craft during a certain historical period. These studies contain lists of typical tools that were used in certain historical periods, but often there is no specific data on the relationship between the construction of a building and the nature of masonry operations, their technological sequence. Especially when it comes to the older medieval period. There are also papers containing the analysis of the stone material itself, but without conclusions about its processing technologies (Hutzuliak & Shevchenko, 2016). As a result, the analysis presented in this study is implemented, since the Kholm castle is in the form of an archaeological ruin, as if in a "disassembled form", which allows exploring many things that could not be done on fully preserved buildings.

CONCLUSIONS

Archaeological research has shown that the oldest part of the Kholm castle was built of two types of stone – local green glauconitite and white limestone (probably imported, which protrudes in much smaller quantities compared to glauconitite). The use of glauconite stone in the construction of architectural buildings of the 13th century should be considered a unique construction phenomenon on the territory of Kyivan Rus' and Poland.

The study revealed a wide variety of techniques for hewing, carving, and surface treatment of stone blocks and parts. Since all of them are used for processing glauconitite, masons used them in the 13th century, because only during this period the construction of the residence of King Danylo Romanovych took place from this material. The results of the comparative analysis demonstrate the use of traditional medieval tools and techniques.

The technological features of the local Kholm stonemasonry school of the 13th century highlight the construction and architectural means, tools and techniques typical of the construction team of the chronicle artist-carver Avdii. The revealed methods of working with the stone indicate that a highly qualified team of masons worked at the Kholm castle, but no evidence was found that it was specialists brought from abroad. Instead, the presence of a chronicle mention of the master Avdii proves that these were performers of the local, Kholm or Galician school. Belonging to the Romanesque technique of building walls and the Romanesque style of decorative elements cannot be a convincing argument about the foreign origin of masons. The study is yet another evidence of a mature and long-lasting tradition of Romanesque Ukrainian architecture with centres in Peremyshl, Halych, Volodymyr, and Kholm in the 13th century.

The construction of stone walls in Kholm takes the form of masonry technology "opus emplectum", which was a characteristic feature of the construction of buildings of the Romanesque architectural style of the 12th-13th centuries. The construction of the walls in Kholm is characterised by the use of blocks with a protrusion in the cornerstones. This technique testifies to the high professionalism of the masons.

In general, the presented material is an addition to the picture of architectural and construction craft in Ukraine-Rus' in the 13th century. The results can be used to build hypotheses about the quantitative composition of the construction artel, the distribution of professional responsibilities among its members, and the direction for further research can be compared with construction techniques and technologies of other schools of the 13th century – in Halych, Sandomierz, Krakow, Buda, Esztergom, Poznan, etc.

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None.

CONFLICT OF INTEREST

None.

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Технологія мурування стін і обробки кам'яних матеріалів у будівлях замку XIII століття короля Данила Романовича в Холмі

Анотація. Актуальність дослідження зумовлена великим культурним значенням замку короля Данила, одного з незвичайних архітектурних об'єктів XIII ст. Русі. Мета дослідження – розкрити будівельні технології, техніки обробки і різьблення архітектурних деталей з каменю, що їх застосовано при зведенні замкових об'єктів. Методика дослідження базується на детальному аналізі залишків будівель та окремих будівельних чи архітектурних деталей, які відкриті в результаті архітектурно-археологічних досліджень. У статті проаналізовано характеристики застосованих природних каменів. Археологічні залишки оборонної стіни, веж, фундаментів та стін кількох будівель, призначення яких ще не вияснено, презентують об'єкти створені висококопрофесійною будівельною майстернею. Розкопки виявили велику кількість різьблених декоративних архітектурних деталей з глауконіту та вапняку, використання яких свідчить про багатство архітектури та презентує конкретні архітектурні форми романського стилю. Замок на першому етапі будувався лише з каменю, на другому – застосовувалася також цегла. Найстаріші споруди були зроблені з натурального каменю-глауконітиту. Крім місцевого зеленого глауконітиту, застосовано також пісковик, вапняк та скам'яніла крейда. Цікавою особливістю замку є застосування типової романської технології мурування стін, технік тесання кам'яних блоків та різьблення декоративних кам'яних деталей. За результатами досліджень можна ствердити, що тут застосовувався стандартний для того часу набір ручних інструментів. Залишки різьблених кам'яних деталей показують багатий пластичний вистрій фасадів та інтер'єрів замку. Подібні вироби та технології не зустрічаються в інших тогочасних замках Русі. Знахідки каменярських інструментів у замкових руїнах дозволяють припустити, що більша частина технологічного процесу обробки каменю відбувалася тут же – на замковому дворі. Результати дослідження дозволяють вперше представити детальну характеристику каменярської артілі «Майстра Авдія» – персонажа літописних рядків про будівництво замку в Холмі

Ключові слова: будівельні матеріали; архітектурні деталі; камінь; техніка обробки; каменярські інструменти

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Principles of barrier-free formation of "green" architecture in the contemporary spatial-object environment

Abstract. The relevance of the chosen topic lies in the necessity of developing barrier-free architecture that incorporates the principles of inclusivity. This study examined the trends in leading architectural and urban planning areas, specifically "green" architecture, through the lens of addressing the needs of all population groups, including those with limited mobility. The purpose of this study was to analyse the key trends in barrier-free "green" architecture and to determine their role in shaping modern accessible urban environments. In conducting this study, the philosophical level included principles of objectivity, a holistic approach, and the consideration of processes in development and interaction with other systems. The study employed general scientific methods such as the comparative-historical method, modelling, and a systemic approach. The special scientific methods involved a structural-functional approach. Each of these methods was implemented through distinct approaches, methods, and tools. The study found the key issues and prospects for developing the barrier-free "green" architecture concept. In identifying the main issues, the relevance of the study in the contemporary

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spatial-object environment was determined. Through an in-depth analysis of the current state of barrier-free "green" architecture formation, it was found that the barrier-free "green" architecture is multifaceted and encompasses inclusive energy-efficient, ecological, and economic aspects with minimal impact on the environment. The principal trends in developing barrier-free "green" architecture were identified, which helped to determine their role in shaping the modern accessible urban environment not only in terms of sustainable development but also in modern aspects of accessibility and inclusion. Based on the conducted research, the key principles of barrier-free "green" architecture were determined – the principle of energy efficiency, the principle of solar orientation, the principle of inclusivity, the principle of ecological sustainability, and the principle of autonomy. The practical value of this study lies in the systematisation of the "green" architecture developing process, wherein principles of accessibility and inclusion are applied at all stages of its formation

Keywords: inclusion; "green" roof; energy efficiency; solar energy; vertical greening; "green" surfaces

INTRODUCTION

As the 20th century drew to a close, many nations began to focus on issues concerning environmental preservation and sustainable development. Accessibility and inclusion, as leading trends in the architecture and urban planning development, are increasingly being integrated into global practices. "Green" architecture and the specifics of its implementation necessitate investigating it through the lenses of safety, accessibility, and inclusion, among other factors.

Many researchers have explored the concepts of sustainable development and building energy efficiency. S.E. Bibri & J. Krogstie (2020) found that smart technologies are pivotal in shaping the development of sustainable cities. Z. Sun *et al*. (2023) concluded that the impact of advancing "green" technologies is rapidly expanding, increasingly becoming a critical determinant of energy efficiency. The advent of the "sustainable development" concept signified not a mere re-evaluation of the interplay between the anthropogenic and natural milieus, but the evolution and deepening of contemporary ecological paradigms within a cultural context. I. Ryzhova & O. Pavliuk (2023) noted a pronounced emphasis on orienting "sustainable development towards protracted temporal horizons, a departure from analogous environmental trajectories in antecedent epochs". As of 2024, "green" architecture, as a facet of "sustainable development", delineates equilibrium between human activities and ecological systems as a foundational tenet for advancement, construing urbanised zones as integral components of natural landscapes. This engenders a re-evaluation among architects and urban planners, compelling them to adeptly integrate their practices within the extant environmental frameworks.

O. Filonenko *et al*. (2022) also deliberated on the concepts of sustainable development and building energy efficiency, while investigating solar architecture as an alternative to mitigating greenhouse gas emissions. However, within this paradigm, yet another imperative emerges – environmental settings must not solely be ecologically sound but also universally accessible across the demographic strata. Moreover, most developed nations are actively engaged in the pursuit of establishing a secure, comfortable, convenient, and information-rich environment. Z. Al Taweel *et al*. (2020) emphasised the significance of considering and analysing architecture in terms of the safety and accessibility requirements of urban infrastructure. The use of smart parking spaces in the city's infrastructure increases the accessibility of low-mobility population groups to basic city services. The significance of incorporating principles of accessibility and inclusion in architectural and urban planning projects is also discussed in the studies of researchers in this field. M. Ward & J. Bringolf (2018) and T. Pavlenko *et al*. (2024) underscore the importance of integrating the needs of individuals with limited mobility at every stage of building design and implementation.

Consequently, the purpose of this study was to analyse the key trends in the development of barrier-free "green" architecture, focusing on identifying the core principles of its formation within the contemporary spatial-object environment and to assess the significance of these principles in shaping a modern, accessible urban environment.

MATERIALS AND METHODS

The methodology comprised the following structure: philosophical level, general scientific level, and special scientific level, each implemented through its specific approaches, methods, and tools. The methodology was defined by fundamental (philosophical) and general scientific principles of scientific cognition. Special scientific principles are inherent to concrete disciplines or scientific fields. A system of special methods and tools was used to address particular objectives of this study.

The philosophical level of the methodology for investigating barrier-free "green" architecture included the general principles of cognition as follows:

- Objectivity and the formation of barrier-free "green" architecture under specific conditions, factors, and causes.
- A holistic approach to investigating the phenomena and processes in the formation of barrier-free "green" architecture.
- Examining the formation of barrier-free "green" architecture in its connections and interactions with other phenomena.
- Studying the organisation of barrier-free "green" architecture in its development.

Accordingly, the relevant methodological principles ensured the systematic direction of this scientific research and practical understanding of barrier-free "green" architecture – the general scientific level of investigating barrier-free "green" architecture included methods such as the comparative-historical method, modelling method, and systemic approach. The patterns of the functional and planning organisation of barrier-free "green" architecture were determined by applying a unified approach to the research object and analysing its spatial transformations over time, which involved the comparative-historical method. This method helped to identify the features of dynamic development in chronological order, discern similarities and differences among research objects, and determine the general and specific aspects of dynamic development. The study employed this method to investigate the theoretical experience and analyse the chronology of scientific thought in barrier-free "green" architecture.

The modelling method was an indirect and mediated method of scientific research on barrier-free "green" architecture based on using a model as a research tool. The essence of the modelling process involved replacing the research object with another specifically created for this purpose. Either conceptual or materially implemented, the model represents the barrier-free "green" architecture system. It mirrors the research object, making the model itself a source of information about the barrier-free "green" architecture. The graphical drawings of barrier-free "green" architecture considered in this study were created using this method.

Systemic approach was applied to the study of barrier-free "green" architecture. This approach involved investigating barrier-free "green" architecture as a system – a coherent whole where all components and elements function harmoniously. Analysing barrier-free "green" architecture as a system involved methods resulting from the research of many leading researchers in this field. For instance, T. Mukha *et al*. (2016) and T. Pavlenko *et al*. (2022) addressed the issues related to creating effective research methods and optimising the agro-recreational eco-complexes. The concept of urban planning was reinterpreted – not merely as an environment for human activity but as a demo-ecosystem, a system of interrelations and interactions between the population and its living environment. The urban planning level (special scientific methodology) encompassed a set of special methods of scientific cognition on urban planning, forming the basis for addressing the research problem of forming barrier-free "green" architecture (BREEAM certification..., n.d.; LEED rating system, n.d.). These were the scientific concepts that the study relied on.

RESULTS AND DISCUSSION

As of 2024, the prevalent ecological issues exert a significant impact on the environment globally. Urbanised areas warrant considerable attention in particular, serving as primary zones for the active utilisation of natural resources such as land, materials, water, and energy, while concurrently acting as sources of noise, waste, and environmental pollution. Inefficient energy and water usage rank among the most pressing eco-economic challenges due to the operational characteristics of buildings and infrastructure (Dolinsky *et al*., 2020).

The distinct adverse effects of urbanised areas on the environment are identified in the implementation of sustainable development and barrier-free concepts. According to some experts (Asfaw *et al*., 2016; Ryzhova & Pavliuk, 2023), this constitutes the primary challenge of urban areas' inaccessibility, which increasingly confront limited capabilities to fulfil their core functions without significant adverse effects on the natural environment. Other professionals (Gamache *et al*., 2018; Bibri & Krogstie, 2020) add that implementing environmental oversight over architectural and urban planning activities is a crucial necessity for effective economic levers of development in the 21st century's architectural sector. Consequently, new concepts and methodologies emerge in industrialised nations to achieve the set objectives. A field termed "sustainable architecture", or "green architecture", emerges, reflecting architectural and urban development trends intertwined with economic and ecological aspects (reduced energy consumption, optimised use of natural resources, and effective solutions for renewable energy sources).

Sustainable architecture is an eco-oriented high-tech architectural approach that aims to minimise the adverse environmental impacts through the efficient and rational use of modern materials, energy, and space within the ecosystem of urbanised areas. The design and implementation of sustainable architecture are based on energy conservation and environmental protection principles (Dolinsky *et al*., 2020; Filonenko *et al*., 2022; Vilinska *et al*., 2023). The development of "green" architecture is quite multifaceted. In the 1970s, ecological thought rapidly evolved, driven by the intensive construction of high-rise buildings – skyscrapers in the United States. The increase in energy production and consumption led to problems in the use of natural resources, especially minerals, triggering an oil crisis (Bibri & Krogstie, 2020). This crisis spurred the development of ecological activities aimed at preserving the environment.

The creations of Frank Lloyd Wright are considered the first examples of "green" architecture. His projects are organically integrated into the landscape environment. One notable example of the successful interaction between the natural and built environments is the "Fallingwater" house, where the architectural object is harmoniously integrated into its natural surroundings. Wright's projects and landscapes are unified through the use of natural materials, which creates an inseparable connection between the building, viewed as part of a system, and the exterior, contrasting with the functionalist architectural approach that was also developing at the time. Architectural harmony in Wright's work is associated more with "naturalness" than with "bionic" forms, which are characterised by geometric shapes, unlike the projects of the German architect Hugo Häring. "Green" architecture and organic architecture as concepts have become popular among European architects, each with distinct characteristics depending on the region. An example of the interaction between functionalism and organic architecture is the work of the Finnish architect Alvar Aalto. The eclectic and polymorphic compositional structure of his projects blends with the surrounding environment.

In the 1990s, international "green" standards were implemented: Energy Star in the United States and BREEAM (Building Research Establishment Environmental Assessment Method) in the United Kingdom, along with the LEED (Leadership in Energy and Environmental Design) rating system. The BREEAM standard was proposed in 1990 by the British Building Research Establishment (BRE), a multidisciplinary research organisation in the field of construction. BREEAM is the oldest "green" standard for the environmental assessment of buildings of any purpose. As of 2024, it is adopted by companies in more than 80 countries. BREEAM's assessment criteria have served as the foundation for the development of other certification systems for environmentally friendly buildings, including LEED. LEED standards aim to create a more environmentally friendly environment and increase building efficiency with greater economic benefits. These standards are provided to architects, engineers, developers, and investors. They consist of a straightforward list of criteria that evaluate a building's compliance with environmental requirements.

The formation of the "naturalness" of "green" architecture has taken on an urban, industrial nature, aimed at creating buildings and structures that cause minimal harm to the environment. An example of this is the "House in the Hill" (architect Arthur Quarmby, United Kingdom), where the unity of lines and forms of the project with the environment, the organic blending of the building's silhouette with the morphology of the landscape, and the use of local ecological materials create harmony between the architectural complex and the environment. In industrially developed countries, many large buildings embody the concept of sustainable "green" architecture, which reduces environmental impact, including the Conde Nast Tower (48 floors) in Times Square, New York. This tower is one of the earliest instances of applying sustainable "green" architecture principles, utilising the latest technologies of its time to maximise energy savings (Daradkeh *et al.*, 2021). However, in most cases, "green" architecture does not address the issues of inclusivity, and thus does not fully meet all accessibility requirements, resulting in the creation of uncomfortable and inefficient urban environments.

Analysis shows that barrier-free "green" architecture is multi-faceted. This approach encompasses inclusive, energy-efficient, ecological, and economic aspects while minimising the environmental impact. Identification of the main trends in barrier-free "green" architecture (Pollo *et al.*, 2021) allows determining their role in shaping a modern, accessible urban environment in the following aspects: improving the energy efficiency of buildings; employing alternative energy sources, "green" technologies, and innovative materials while considering the barrier-free aspect.

1) Improving building energy efficiency. This aspect encompasses rational energy consumption and energy saving. Applying various design standards and/or retrofitting buildings (low-energy buildings, "passive houses", "zero-energy buildings", "positive-energy buildings") significantly enhances the energy efficiency of both new and existing architectural structures. Here, the concept of energy efficiency is intricately linked to alternative energy sources: wind, tidal, geothermal, and solar energy (solar power), among others. Solar power, specifically, has the closest interaction with "green" construction.

2) Solar energy. The 1950s saw the emergence of the first solar panels, and by the 1970s and 1980s, they were being used in residential construction (Sikora & Nazarenko, 2018). The eco-settlement "Iliako-Horio", created by Alexandros Tombazis and called the Solar Village, was built using various sources of solar energy. In the early 21st century, skyscrapers, stadiums, public, and residential buildings began to be equipped with solar panels (e.g., Conde Nast Building in New York, National Stadium of the World Games in Kaohsiung, HELIOS, and the headquarters of the National Institute of Solar Energy in Savoy, designed by Michel Remon and Frédéric Nicolas).

3) "Green" technologies. This area of "green" architecture is often used in urban planning solutions. Key types of implementation include creating additional accessible "green" spaces for primary and special purposes and establishing additional accessible functional spaces (Fig. 1).

Based on maintenance needs, "green" roofs come in two types: extensive (a multi-layered cover with hardy, lightweight, low-maintenance grass plants) and intensive (requires proper maintenance with the planting of flowers, shrubs, trees, etc). Examples include the rooftop garden of Villa Savoye, designed in 1929 by French architect Le Corbusier, and the "green" roofs of the Big House residential complex in Copenhagen. "Green" roofs offer several advantages: improving the local environment; providing additional accessible space for human activities; enhanced thermal insulation; high sound insulation; and solving rainwater drainage issues. The technology for constructing "green" roofs (Mukha *et al.*, 2016; Sun *et al.*, 2023) is quite complex. Such roofing includes multiple layers: structural decking, vapor barrier, insulation, waterproofing, protective layer, drainage layer, filter, soil, and vegetation. Modern technologies reduce the weight of the roofing structure by using high-strength waterproofing layers. Thus, "green" roofs are aesthetically pleasing and environmentally friendly.

"Green" surfaces, both vertical and horizontal, can be directly integrated into building structures, encompassing balconies, walkways, and even entire floors. These technologies are rapidly advancing and being implemented in many countries. Notable examples of this trend include the high-rise Oasia Hotel Downtown in Singapore, the multifunctional complex One Central Park in Sydney, the residential skyscraper Bosco Verticale in Milan, the Agora Garden Tower in Taiwan, which boasts a LEED Gold+ certification, the Japanese office centre Pasona Group, and the Athenaeum Hotel in England, which features an eight-storey "green" wall by Patrick Blanc's Vertical Garden System.

Among the examined examples, the main types of vertical greening were identified as follows (Fig. 2): vertical gardens, energy-efficient "green" walls, and the use of decorative ivy.

TITLE	NOTE	IMAGE
ADDITIONAL ACCESSIBLE "GREEN" SPACE	"Green" roofs as additional accessible green spaces enhance aesthetic qualities and increase green area coverage while addressing roof maintenance issues.	
ADDITIONAL ACCESSIBLE FUNCTIONAL SPACE	"Green" roofs as additional accessible functional spaces (public, children's, sports, recreational areas).	
ACCESSIBLE "GREEN" SPACE FOR SPECIAL PURPOSES	"Green" roofs as accessible spaces for growing plants that serve specific functions (plants for various species of butterflies, insects, birds, etc.).	

Figure 1. Types of accessible "green" roof space formation
Source: developed by the authors of this study

TITLE	NOTE	IMAGE
VERTICAL GARDENS	Tropical plants that grow at any slope and require minimal sunlight and water. These plants can grow on vertical surfaces without soil, using only a circulating nutrient solution.	
ENERGY-EFFICIENT "GREEN" WALLS	Surfaces heat less in summer and reduce heat loss in winter. They lower noise, dust, and gas pollution levels, and enrich the surrounding area with oxygen.	
DECORATIVE IVY	Ivy canopy acts as a thermal shield, protecting walls from extreme temperature fluctuations. Ivy makes walls more resilient to weather changes and pollutants.	

Figure 2. Main types of vertical greening
Source: developed by the authors of this study

Advantages of vertical facade greening include aesthetic appeal, durability, thermal regulation, ecological benefits, maintenance of the building's microclimate, sound insulation, and energy efficiency. Additionally, the main types of vertical greening were identified. Felt type (hydroponic) – this is one of the most popular types of vertical greening. The main structure consists of a metal frame with attached felt pockets, fixed to the facade of the architectural object. This setup allows for the installation of a drainage system with automated drip irrigation. Modular type – this relatively new method involves the installation of vertical structures on a special facade frame, where modules with greening elements are fixed. This type enables the integration of essential greening systems into the structure of any shape. Container type – this is one of the most used types for forming "green" facades. The construction consists of a large network of hollow pipes for irrigation combined with containers for various greening elements. This type also includes its own lighting, water supply, and drainage systems.

A comprehensive examination of the subject matter addressed in this study necessitates an analysis of the micro-level components of the barrier-free "green" architecture system, particularly focusing on eco-friendly building materials. ETFE membranes (ethylene tetrafluoroethylene) are an innovative building material that is significantly lighter than glass, has insulating properties, and is comparable in quality to other building enclosures. ETFE membranes can be used as solar energy accumulators to reduce the energy consumption of a building. The advantages of ETFE membranes include light weight; high strength; low flammability; resistance to hot temperatures; resistance to ultraviolet radiation; self-cleaning ability; and a wide range of material sizes (Sun *et al*., 2023). Wooden hollow blocks (WHB) are a new type of building material made from wood, which helps save timber and reduce deforestation. WHB elements create a vacuum layer in the walls of a building, significantly reducing heat loss. The benefits of wooden hollow blocks include high thermal retention; timber savings; lightweight elements; material eco-friendliness; reduced structural shrinkage; the ability to combine with other building materials and technologies; high readiness of the material during manufacturing; and energy savings on heating. Wood-polymer composite (or liquid wood) has similar characteristics to regular wood but with enhanced mechanical properties. It is often used for wall cladding, balconies, flooring, and the production of paints that mimic real wood. The advantages of wood-polymer composite include eco-friendliness; high moisture resistance and resistance to biological impact; surface uniformity; high plasticity and strength; durability; ease of installation. Aerogel, also known as "frozen air", is an innovative material with the highest insulation performance among all materials. It has been recognised in the Guinness Book of Records for its exceptional properties. Structurally, aerogel consists of nano-cells that are indistinguishable even under a microscope. The advantages of aerogel are as follows: eco-friendly, being composed of over 95% air; durability; fully recyclability; economical; high strength, water repellence, and sound insulation; low flammability (extinguishes quickly when ignited); lightweight, making it easy to transport. The principles of barrier-free "green" architecture are ensured through the integration of natural environmental components into the architectural and urban planning structure, accommodating the needs of all population groups (Fig. 3).

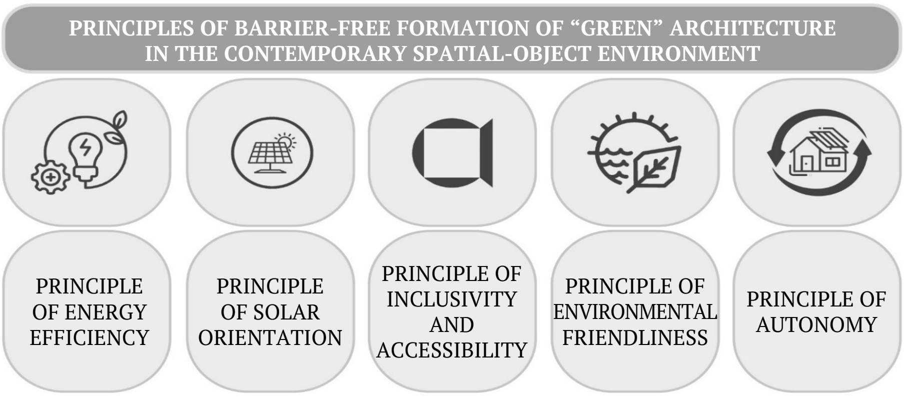

Figure 3. Principles of barrier-free formation of "green" architecture in the contemporary spatial-object environment
Source: developed by the authors of this study

The principle of energy efficiency is achieved through measures that minimise heat loss upon heating and cooling; the application of low-energy consumption building standards (during reconstruction), "passive buildings", "zero-energy buildings" and "plus-energy buildings"; compliance with BREEAM and LEED standards allows for the creation of a more environmentally friendly environment and increases building efficiency with greater cost-effectiveness (Vilinska *et al*., 2023). The principle of solar orientation is ensured through the generation of light and heat using solar energy. In the design of solar-oriented architecture, both active and passive solar design techniques are used. This includes the orientation of buildings according to the position of the sun during the day, the selection of materials with favourable thermal mass and light diffusion properties, and the planning of the surrounding space. The use of solar panels involves the integration of photovoltaic converters (photovoltaic cells) – semiconductor devices that directly convert solar energy into direct current electricity, unlike solar collectors that produce heat by warming a material – typically a heat-transfer fluid. The use of solar concentrators focuses on the practical application of these devices, which gather solar radiation from the sun and concentrate it into a single point. This approach, described by K. Sikora & O. Nazarenko (2018), leverages fully accessible and renewable energy sources to enhance energy efficiency and sustainability.

The principle of inclusivity and accessibility involves designing urban environments to be comfortable for people from all population groups. Means of accessibility for the exterior space elements of barrier-free "green" architecture are as follows: external ramp; ramp descent; elevated pedestrian crossing; lifting device; accessible external stairs; parking space for individuals with disabilities. Means of accessibility for the interior space elements of barrier-free "green" architecture include internal ramp; accessible internal stairs; lift; internal lifting device; escalator; lavatory for people with disabilities. Means of universal (inclusive) design for elements of both exterior and interior spaces of barrier-free "green" architecture: tactile accessibility elements (TAE); visual accessibility elements (VAE); auditory accessibility elements (AAE) (Pavlenko *et al.*, 2024).

The principle of environmental friendliness focuses on minimising harmful impacts when integrating urbanised and natural environments by using energy-efficient technologies; eco-friendly materials (local building materials, environmentally clean building materials); application of high-tech, innovative materials (ETFE membranes, wooden hollow blocks, wood-polymer composite or liquid wood, aerogel or frozen air); adoption of ecological mobility strategies (reducing the need for cars, promoting alternative modes of transport); ecological planning techniques (reducing building heights, integrating greenery into various building planes); resource conservation practices (preservation and development of "green" spaces); minimisation of non-renewable resource consumption; minimisation of waste production; implementation of "green" technologies ("green" roofs, "green" surfaces, vertical greening). The principle of autonomy refers to the ability of architectural and urban planning objects to function independently in critical situations. Ensuring buildings with alternative power sources entails incorporation of solar panels, rainwater harvesting systems, recycling and filtration of greywater, heat recovery ventilation systems, ground heat exchangers, inverters, batteries, generators, and other alternative power solutions.

Over its course, this study identified the following key discussion points: integration of the fundamental principles of "green" architecture with the requirements of barrier-free accessibility and inclusion; and definition of the primary principles of barrier-free formation of "green" architecture in the contemporary spatial-object environment. The term "barrier-free environment" is most often used in reference to people with physical disabilities. Barrier-free accessibility typically includes the presence of standard ramps and pathways with suitable surfaces, paths and passageways of sufficient width, doors, and other elements of the built environment to facilitate the movement of people with limited mobility. However, M. Ward & J. Bringolf (2018) examined similar assertions within the context of residential construction. These assertions should be applied to all types of development based on the principle of isomorphism in the systemic approach. For these groups, the presence of a barrier-free environment significantly affects their quality of life.

G.W. Bascom & K.M. Christensen (2017) note that a sufficient level of mobility ensures a comfortable barrier-free environment. According to K. Carr *et al.* (2013), at any given time, up to a quarter to a third of the population uses elements of the barrier-free environment. The accessibility of "green" architecture should ensure unobstructed movement within spaces and the ability to enjoy communal resources and amenities. Many countries have reviewed best practices and developed accessibility standards (Gamache *et al.*, 2020). Consequently, the unified standards developed and refined by civilised nations should be actively introduced in the design and implementation of urbanised environments, specifically for "green" architecture projects. Barrier-free "green" architecture, barrier-free "green" construction, and barrier-free ecological design are integral components of the primary ecological approach to barrier-free planning and construction.

Thus, the conducted study focused on the core principles of "sustainable development" over the long term. Barrier-free "green" architecture, as a branch of "sustainable development", embodies the intelligent integration of the built and natural environments while considering the requirements of accessibility and inclusivity.

CONCLUSIONS

This study identified the primary issues and future prospects of the barrier-free "green" architecture concept by combining the fundamental principles of "green" architecture with the requirements of accessibility and inclusivity. A thorough analysis of available research on the subject matter was conducted, focusing on key areas such as the formation of "green" architecture, trends in solar architecture, environmental preservation and sustainable progress, and the safety and accessibility requirements of urban infrastructure. The principles of accessibility and inclusivity in architectural and urban planning were also considered.

Using a comprehensive methodological approach, the study identified the principal vectors in the formation of barrier-free "green" architecture, namely: inclusivity, energy efficiency, environmental sustainability, and cost-effectiveness. Barrier-free "green" development represents a promising avenue for sustainable growth, enhancing environmental protection, conserving natural resources, and mitigating anthropogenic impacts on the natural environment while addressing the needs of all population groups. Barrier-free "green" architecture facilitates the creation of new types of accessible buildings that are integrated into innovative urban planning solutions. Adhering to the principles of barrier-free "green" architecture enables the development of energy-efficient, solar-oriented, inclusive, ecological, and autonomous solutions to contemporary challenges.

The study identified the fundamental principles for the barrier-free development of "green" architecture within the modern spatial and material environment (principle of energy efficiency, principle of solar orientation, principle of inclusivity and accessibility, principle of environmental friendliness, principle of autonomy) provide a foundation for further in-depth exploration of the topic, including the identification and detailed analysis of the main techniques and tools that ensure the implementation of these principles. Additionally, it is crucial to develop a methodology for designing barrier-free "green" architecture within the modern spatial and material environment. Thus, a systemic investigation of ecological and inclusive processes facilitates the development of more sustainable, barrier-free solutions and technologies that safeguard natural resources while addressing social demands for living environments.

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CONFLICT OF INTEREST

None.

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Принципи безбар'єрного формування «зеленої» архітектури в сучасному просторово-предметному середовищі

Анотація. Актуальність обраної теми зумовлена необхідністю розвитку безбар'єрної архітектури з урахуванням принципів інклюзивності. У цьому дослідженні розглянуто тенденції провідних архітектурних та містобудівних напрямків, зокрема «зеленої» архітектури, через призму задоволення потреб усіх груп населення, в тому числі маломобільних. Метою дослідження було проаналізувати ключові тенденції безбар'єрної «зеленої» архітектури та визначити їхню роль у формуванні сучасного доступного міського середовища. Філософський рівень дослідження включав принципи об'єктивності, холістичного підходу, розгляду процесів у розвитку та взаємодії з іншими системами. У дослідженні використано такі загальнонаукові методи як порівняльно-історичний метод, моделювання та системний підхід. Серед спеціальних наукових методів використано структурно-функціональний підхід. Кожен з цих методів був реалізований через окремі підходи, методи та інструменти. В результаті дослідження було виявлено ключові проблеми та перспективи розвитку концепції безбар'єрної «зеленої» архітектури. При визначенні основних питань було визначено актуальність дослідження в сучасному просторово-предметному середовищі. Завдяки поглибленому аналізу сучасного стану формування безбар'єрної «зеленої» архітектури, встановлено, що безбар'єрна «зелена» архітектура є багатогранною та охоплює інклюзивні енергоефективні, екологічні та економічні аспекти з мінімальним впливом на навколишнє середовище. Виявлено основні тенденції розвитку безбар'єрної «зеленої» архітектури, що дозволило визначити її роль у формуванні сучасного доступного міського середовища не тільки з точки зору сталого розвитку, але й сучасних аспектів доступності та інклюзії. На основі проведеного дослідження визначено ключові принципи безбар'єрної «зеленої» архітектури – принцип енергоефективності, принцип сонячної орієнтації, принцип інклюзивності, принцип екологічної сталості та принцип автономності. Практична цінність дослідження полягає в систематизації процесу розвитку «зеленої» архітектури, де принципи доступності та інклюзивності застосовуються на всіх етапах її формування

Ключові слова: інклюзивність; «зелений» дах; енергоефективність; сонячна енергія; вертикальне озеленення; «зелені» поверхні

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Investigation of the uniform distribution of basalt fibre in a foam concrete mixture

Abstract. This research aimed to study the impact of uniform basalt fibre reinforcement on the mechanical properties of foam concrete, such as compressive strength, bending and frost resistance. A comprehensive methodology was used, which included the preparation and testing of foam concrete mixtures containing basalt fibre, and conducting strength and frost resistance tests using specialised equipment. As a result of the conducted research, it was found that the uniform addition of basalt fibre to the foam concrete composition significantly improves its mechanical properties. The compressive strength of reinforced foam concrete has increased by 30-40% compared to conventional foam concrete, especially noticeable in the early stages of hardening. For example, after 28 days of hardening, the compressive strength of reinforced foam concrete was 2.65 MPa, whereas for the non-reinforced analogue, it reached only 1.8 MPa. In addition, reinforced foam concrete has demonstrated a significant improvement in bending strength. After 28 days of hardening, the bending strength was 1.8 MPa, which is 56% higher compared to conventional foam concrete, which had this indicator

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of 1.15 MPa. This suggests that basalt fibre effectively prevents the development of microcracks, increasing the overall durability of the material. In addition, in the course of the study, an improvement in the frost resistance of foam concrete reinforced with basalt fibre was revealed. After 30 cycles of freezing and defrosting, reinforced foam concrete showed a lower weight loss of 1.8% compared to conventional foam concrete, in which this figure reached 3.7%. This indicates the high resistance of the material to cyclic climatic influences, which makes it more suitable for use in extreme climatic conditions. Thus, the results obtained confirm a significant improvement in the mechanical properties of reinforced foam concrete, demonstrating that basalt fibre reinforcement makes it a more reliable and durable material for various construction applications

Keywords: foam concrete; reinforcement; basalt fibre; cement mortar adhesion; compressive strength; bending strength; frost resistance

INTRODUCTION

Foam concrete is a lightweight building material that has gained its popularity due to its excellent thermal insulation properties, low weight, and cost-effectiveness. It is a mixture of cement, water, sand, and a special foam generator that forms air bubbles in the solution. Such bubbles help to reduce the density of the material and improve its thermal insulation qualities. Due to these characteristics, foam concrete is used in various industries, and is in demand in construction technologies. However, despite its advantages, foam concrete has certain limitations in terms of strength and durability, which can be improved with reinforcement. The problem is that the uniform distribution of reinforcing fibres, such as basalt fibre, in a foam concrete mixture is a difficult task. Improper fibre distribution can lead to the appearance of local defects, reducing the strength characteristics and durability of the material (Hezentsvei & Bannikov, 2020). This makes it difficult to achieve optimal performance properties of foam concrete and limits its use in more demanding construction projects. In this regard, studies aimed at the investigation of the uniform distribution of basalt fibre in a foam concrete mixture can significantly improve its operational characteristics. Such studies may determine the most effective methods of integrating basalt fibre into foam concrete to minimise problems with uneven distribution and improve the strength and durability of the material. Ultimately, this will help to improve existing foam concrete reinforcement technologies, offering new solutions to improve its quality and expand its applications in construction.

One of the main factors influencing the effectiveness of reinforcement of foam concrete with basalt fibre are the methods of uniform distribution of fibre and its interaction with other components of the mixture (Kutsenko & Kutsenko, 2022). The study by R. Lukpanov *et al.* (2021) noted the influence of mixing methods on the uniformity of foam concrete, emphasising that the use of different mixing methods allows for different degrees of distribution of components in the mixture. O. Gencel *et al.* (2022) focused on assessing the effect of a certain concentration of basalt fibre on the strength and resilience of foam concrete, showing that increasing the fibre content to a certain level significantly improves the mechanical properties of the material. A. Sagyndykov *et al.* (2023) assessed the impact of basalt fibre on the distribution and structural characteristics of foam concrete, finding that the use of fibre with a certain length and diameter has a noticeable effect on improving compressive strength and crack resistance. Such studies emphasise the need for an integrated approach to the choice of mixing methods, fibre concentration, and its characteristics to ensure maximum efficiency and durability of reinforced foam concrete.

In addition, one of the determining factors of reinforcement of foam concrete with basalt fibre is the quality of interaction of fibre with the matrix of cement mortar. X. Shi *et al.* (2023) reviewed the process of adhesion of basalt fibre to cement mortar, where it was found that pretreatment of fibre with special modifiers significantly improves adhesion to the matrix, contributing to a more uniform distribution and improved mechanical properties of the material. The study by O.Y. Bayraktar *et al.* (2023) analysed the basalt fibre and cement mortar, revealing that optimising the hardening process allows for better properties and structure. M. Khan *et al.* (2022) evaluated the effect of temperature on the fibre integration process, demonstrating that at high temperatures, an increase in the temperature of the mixture can lead to improved fibre distribution, but also requires precise control of conditions to prevent material degradation. Thus, the mentioned studies confirm the importance of investigating the process of interaction of fibre with cement mortar, and the need for further research to fully understand and optimise the technology of reinforcement of foam concrete with basalt fibre.

For the assessment of the effectiveness of basalt fibre in foam concrete, it is important to conduct a comprehensive analysis of the impact on key features of the material, such as compressive strength, bending strength, temperature resistance, and resilience. The study by Q. Fu *et al.* (2022) evaluated changes in the strength of reinforced foam concrete with different concentrations of basalt fibre, showing that the use of fibre improves strength characteristics, providing a significant increase in bending strength. Z. Xue *et al.* (2023) focused on methods for assessing the crack resistance and durability of foam concrete with basalt fibre, finding that basalt fibre reduces the number and width of cracks, contributing to an increase in the durability of the material. In the course of the study, S. Li *et* *al*. (2024) analysed basalt fibre's impact on the qualities of foam concrete, including frost resistance, as a result showing that the uniform distribution of fibre contributes to a better improvement of the studied properties, while uneven distribution can lead to local defects and a decrease in the overall effectiveness of reinforcement. However, despite the results achieved, additional research remains necessary to assess the impact of other mixing methods on the uniformity of fibre distribution and its impact on the long-term performance of foam concrete.

The purpose of this study was to determine the effect of the efficiency of uniform distribution of basalt fibre according to a certain technique on the performance properties of foam concrete. To achieve this goal, tasks were set that included evaluating the effect of fibre on the mechanical properties of reinforced foam concrete, such as compressive strength, bending strength, and frost resistance, compared with conventional foam concrete.

MATERIALS AND METHODS

A comprehensive methodology was applied to evaluate the effect of basalt fibre reinforcement of foam concrete on its mechanical and performance properties. First, two mixtures of foam concrete were prepared, which included ordinary foam concrete and foam concrete reinforced with basalt fibre. Portland cement of CEM 1 42.5 N grade produced by Kant Cement Plant (Kyrgyzstan) was utilised for this purpose, which properties are described in Table 1.

Table 1. Properties of Portland cement CEM 1 42.5 N

Property	Value
Density, kg/m^3	3,100
Specific surface area, cm^2/g	3,500
Beginning of setting, hours	2
End of setting, hours	4
Normal density, %	25

Source: developed by the authors

For reinforced foam concrete, basalt fibres manufactured by Aviapromstal (Kyrgyzstan) were added in an amount of 0.5% of the total volume of the mixture, the characteristics of which are shown in Table 2.

Table 2. Characteristics of basalt fibres

Characteristics	Value
Composition	100% basalt
Fibre diameter, μm	13-20
Fibre length, mm	6-12
Density, g/cm^3	2.63
Tensile strength, MPa	3,000-4,850
Modulus of elasticity, GPa	85-95

Source: developed by the authors

For the preparation of foam concrete mixtures, cement and water were added in the amount of 350 and 200 kg/m^3, respectively. The ratio of cement to water was approximately 0.57. Foam generator PB-2000 (Kyrgyzstan) in the amount of 2 kg/m^3 was used to form a fine-porous structure of foam concrete. Sand, used to increase the density and strength of foam concrete, was added in an amount of 500 kg/m^3. The density of the sand was approximately 1,600 kg/m^3. In addition, during the study, fine gravel of the Gravel-10 brand with a fraction of 5-10 mm was used, which was added in an amount of 150 kg/m^3. The density of gravel was approximately 1,400 kg/m^3. All components were thoroughly mixed according to the diagram shown in Figure 1, until a homogeneous mass was achieved using a BM-125 concrete mixer (Kyrgyzstan).

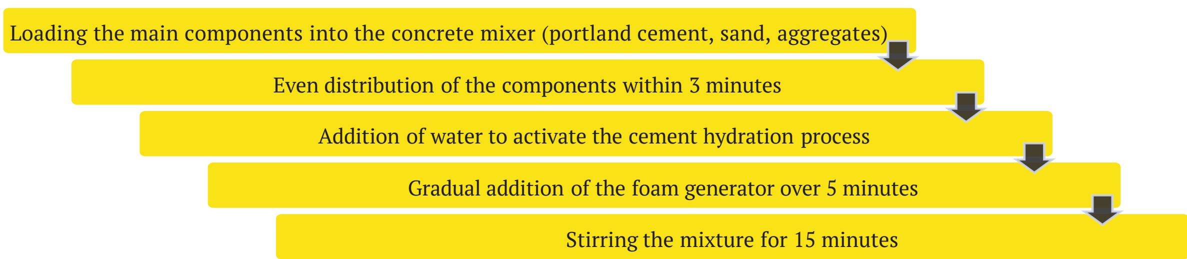

Figure 1. Schematic diagram of mixing technology of foam concrete components
Source: developed by the authors

After preparing the mixtures, they were poured into moulds to form cubes of 100×100×100 mm and prismatic samples of 100×100×400 mm. After pouring the mixture, the moulds were sealed to avoid the appearance of air bubbles, and left to gain initial strength for 24 hours at a temperature of 20°C. The samples were then removed from the moulds and placed in a water bath at 20°C and 95% humidity until the required age for testing was reached. Compressive strength tests were carried out using a small-sized hydraulic press PGM-1500MG4. The samples were tested for compression after 1, 3, 7, and 28 days of hardening. The test procedure consisted of placing the samples on a pressing table, which was gradually loaded until destruction. The maximum load at which the fracture of the sample occurred was recorded and used to calculate the compressive strength. The MII-100 testing machine was employed to assess the bending strength. The prismatic samples were subjected to loading until destruction, after which the result was recorded. During the tests, the maximum values of bending loads were determined, which allowed calculating the bending strength. Additionally, frost resistance tests were carried out, where the samples were subjected to freezing and defrosting cycles. The tests included measuring weight loss after a certain amount (5, 10, 15, 20, 25, and 30) of cycles of freezing and defrosting, which helped to assess the resistance of foam concrete to frosty conditions. The scheme of frost resistance tests is presented in more detail in Figure 2.

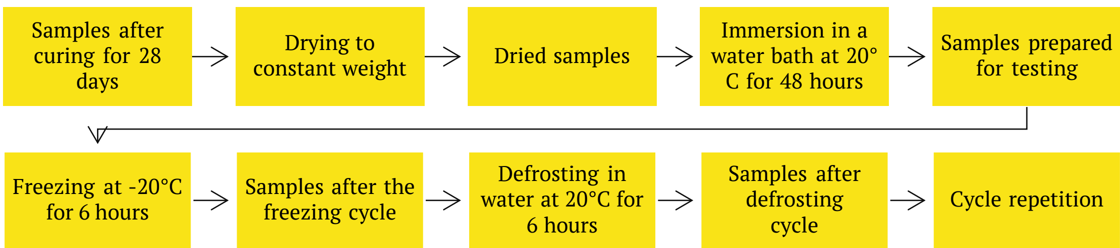

Figure 2. Scheme of frost resistance tests

Source: developed by the authors

Thus, all the stages of the study helped to obtain a complete understanding of the effect of basalt fibre on the strength and performance characteristics of foam concrete, providing reliable and accurate data for further analysis and application.

RESULTS

The uniform distribution of basalt fibre in the foam concrete mixture plays a critical role in ensuring optimal mechanical and operational characteristics of the material. Basalt fibre, because of its strong mechanical characteristics and resilience to aggressive media, is used for reinforcing foam concrete, improving its strength, crack resistance, and durability (Kuznetsova & Ivanova, 2023). To achieve the maximum effect from the addition of fibre, it is necessary to ensure its even dispersion across the whole volume of the mixture. This can avoid local concentrations of fibre, which can lead to uneven material properties and potential defects. Basalt fibre is an effective reinforcing component due to its high tensile strength, resistance to corrosion and chemical influences, and heat resistance. When the fibre is evenly distributed in foam concrete, it forms a complex three-dimensional network that effectively prevents the development and spread of cracks in the material. This can significantly improve the various properties of foam concrete, allowing it to withstand heavy loads and impacts without destruction. In addition, the uniform distribution of fibre can help in enhancing the overall structural integrity of the material, increasing its durability and reliability in operation (Amran, 2020).

One of the main parameters used to assess the foamed concrete's mechanical characteristics, and allowing to evaluate the efficiency of uniform distribution of basalt fibre in it, is its compressive strength. This indicator determines the ability of a material to withstand significant compressive loads without breaking or significant deformation. The foam concrete's compressive strength with basalt fibre directly affects its use in building structures where the material is subjected to constant or variable loads (Salami *et al.*, 2022). Compressive strength tests provide important information about the behaviour of foam concrete under load. This determines the maximum load that the material can withstand before the destruction begins. Such data can be used to assess the quality of foam concrete and compliance of its mechanical characteristics with established standards and to help optimise the mixture's composition of foam concrete. By conducting a strength analysis, it becomes possible to adjust and change the proportions of components, add various modifiers, or change production conditions to achieve better material characteristics. This is especially important when developing new grades of foam concrete for specific applications where special properties such as increased strength, lightness or improved thermal insulation are required. In addition, the compressive strength is closely related to other performance characteristics of foam concrete, such as its durability and resistance to external influences. A material with high compressive strength, as a rule, has better resistance to mechanical damage, moisture, and chemicals (Ahmad *et al.*, 2023). This makes it more reliable and durable, reducing the cost of repair and maintenance of building structures. The results of compressive strength tests conducted with samples of conventional and reinforced foam concrete are shown in Figure 3.

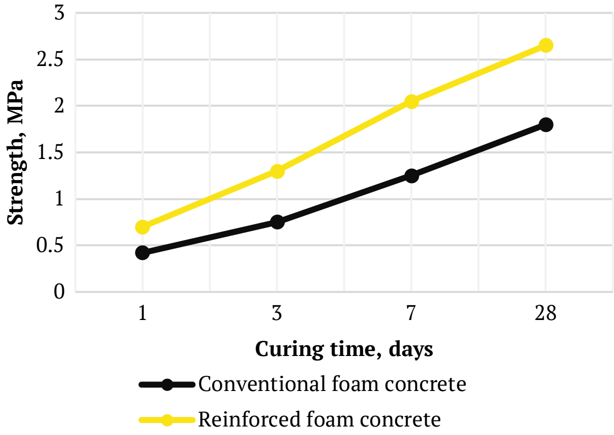

Figure 3. Ultimate compressive strength
Source: developed by the authors

Thus, the results of the tests show that the uniform distribution of basalt fibre in the foam concrete mixture significantly increases the compressive strength of the material at various stages of hardening. After 1 day of hardening, ordinary foam concrete demonstrates a compressive strength of 0.42 MPa, whereas reinforced foam concrete reaches strength of 0.7 MPa. This indicates a significant improvement in strength characteristics due to the addition of basalt fibre. After 3 days of hardening, the compressive strength of ordinary foam concrete increases to 0.75 MPa, and reinforced foam concrete – to 1.3 MPa, confirming a significant improvement in the mechanical properties of foam concrete during reinforcement. After 7 days of hardening, conventional foam concrete reaches a compressive strength of 1.25 MPa, whereas reinforced foam concrete shows a strength of 2.05 MPa. The uniform distribution of the fibre plays a key role in ensuring these properties, as it contributes to the uniform distribution of stresses throughout the entire volume of the material, preventing local stress concentrations and possible foci of destruction. After 28 days of hardening, conventional foam concrete reaches a compressive strength of 1.8 MPa, while reinforced foam concrete reaches 2.65 MPa. This shows that adding the basalt fibre not only accelerates the strength gain in the early stages, but also provides a long-term enhancement of foam concrete's mechanical properties. The graph shown in Figure 4 shows the dynamics of the increase in compressive strength when reinforcing foam concrete with basalt fibre.

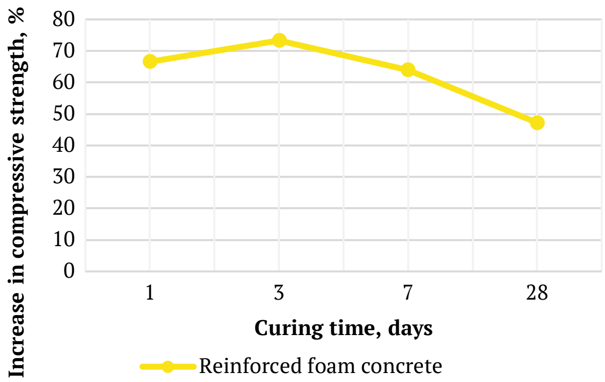

Figure 4. Dynamics of the increase in compressive strength of reinforced foam concrete
Source: developed by the authors

On the first day of hardening, the percentage increase is 66.67%, indicating that reinforcement contributes to the rapid strengthening of the material in the early stages of hardening. This advantage is especially important for structures requiring early formwork removal or rapid strength gain for further construction work. The 3-day period shows an even more pronounced advantage of reinforced foam concrete, which demonstrates a strength increase of 73.33% compared to conventional foam concrete. Such a significant gain in strength is explained by the fact that basalt fibre, evenly distributed throughout the entire volume of the material, forms a mesh structure that efficiently stops the creation and spread of microcracks, thereby increasing the resistance of the material to loads. The percentage increase in strength at the 7-day hardening stage is 64%, which indicates the continued significant influence of basalt fibre on improving the mechanical features of foam concrete. This growth demonstrates that reinforced foam concrete retains its improved characteristics even after some time. In turn, after 28 days, the percentage increase in strength is 47.22%. Although the percentage increase in strength decreases over time, reinforced foam concrete continues to show a significant advantage in compressive strength even at later stages of hardening. One of the main factors contributing to the improvement of compressive strength is the ability of basalt fibre to evenly distribute loads over the entire volume of the material (Yang *et al.*, 2021). As a result, the load is not concentrated in individual areas, but is evenly distributed, which prevents the development of cracks and reduces the likelihood of local damage.

Another factor is that basalt fibre helps to enhance the adhesion between the particles of the cement matrix and aggregates. Since the fibre penetrates into the cement dough and forms strong bonds between its components, this strengthens the material and makes it less susceptible to deformation under the action of compressive forces. Such improved particle-to-particle bonds contribute to a more uniform pressure distribution and an increased ability of the material to withstand high loads, which is especially important for structural elements that experience significant compressive loads (John & Dharmar, 2021). Additionally, it should be emphasised that basalt fibre improves the resistance of foam concrete to internal stress caused by shrinkage and thermal changes. When compressed, internal stresses can lead to cracks, which reduces the strength of the material. Fibre reinforcement helps to neutralise these stresses and reduces the risk of cracking, providing a more stable and reliable structure. This makes reinforced foam concrete more resistant to various operating conditions and increases its durability in construction applications (Yu *et al.*, 2022; Rusho *et al.*, 2024).

Another important characteristic of foam concrete is its flexural strength, which plays a key role in determining its performance properties. Flexural strength characterises the ability of a material to withstand bending forces without breaking and significant deformations. This parameter is especially important for structural elements subject to combined loads, such as floor slabs, wall panels, and other horizontal structures where both vertical and horizontal forces act on the material. It should be noted that increased flexural strength can also assist in enhancing the overall durability of foam concrete. When bending the material, basalt fibre works as microscopic reinforcing rods, taking over part of the load and preventing the development and spread of microcracks. This helps to significantly increase the durability of structures, reduce the need for repairs, and increase the overall reliability of construction sites, making foam concrete with evenly distributed basalt fibre a more effective material for use in construction. The results of bending strength tests conducted with samples of conventional and reinforced foam concrete are shown in Figure 5.

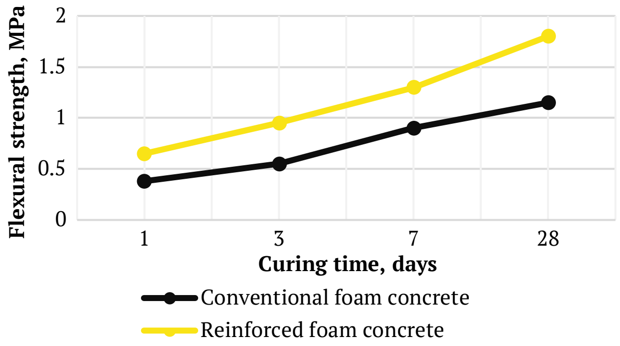

Figure 5. Flexural strength test results
Source: developed by the authors

The results obtained show that after 1 day of hardening, conventional foam concrete demonstrates a bending strength of 0.38 MPa, whereas reinforced foam concrete reaches a strength of 0.65 MPa. This confirms the noticeable strengthening of the strength properties of the material due to the use of basalt fibre. After 3 days of hardening, the bending strength of ordinary foam concrete is 0.55 MPa, while reinforced foam concrete has values up to 0.95 MPa, which shows an increase in the resistance of the material to bending loads with a uniform distribution of basalt fibre. After 7 days of hardening, conventional foam concrete reaches a bending strength of 0.9 MPa, whereas reinforced foam concrete shows indicators reaching a strength of 1.3 MPa. Ultimately, after 28 days of hardening, conventional foam concrete reaches a bending strength of 1.15 MPa, while reinforced foam concrete reaches 1.8 MPa, demonstrating a continued improvement in mechanical properties over its long service life. The graph shown in Figure 6 shows the dynamics of the increase in bending strength when reinforcing foam concrete with basalt fibre.

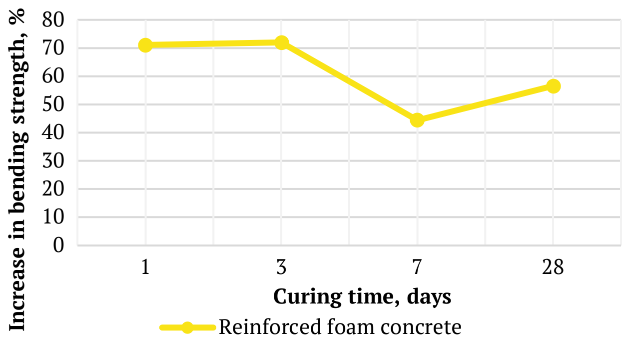

Figure 6. Dynamics of flexural strength gain of reinforced foam concrete
Source: developed by the authors

This graph shows that reinforced foam concrete demonstrates an increase in bending strength by 71.05% compared to conventional foam concrete after 1 day of hardening, which indicates rapid strengthening of the material due to reinforcement in the early stages of hardening. After 3 days, there is also a pronounced advantage of reinforced foam concrete, whose strength gain is 72.73% compared to conventional foam concrete. Such a significant improvement in strength is conditioned by the capacity of basalt fibre to strengthen the connectivity of the foam concrete structure. The percentage increase in strength after 7 days of hardening is 44.44%, which indicates the continued significant influence of basalt fibre on improving the mechanical qualities of foam concrete. Fibre acts as a reinforcing element, distributing loads more evenly and reducing the likelihood of weak points, which helps to increase the overall strength and material's ability to resist bending forces. After 28 days of hardening, the percentage increase in strength is 56.52%. This indicates that, despite the slowdown in strength growth over time, reinforced foam concrete retains a clear advantage in flexural strength even at later stages of hardening.

An important factor is that when bending foam concrete without reinforcement, significant stress concentrations may occur at the sites of microcracks, which can lead to rapid crack development and subsequent destruction of the material. However, when basalt fibre is introduced into the foam concrete, the fibre fibres work as microscopic reinforcements that distribute stresses and prevent the development and spread of microcracks. This, in turn, significantly increases the material's resistance to bending loads (Othman *et al.*, 2020). An additional advantage of the uniform distribution of basalt fibre is the improved adhesion between foam concrete and fibre. When the fibres are evenly distributed throughout the entire volume of the material, each fibre is in close contact with the surrounding foam concrete matrix. This improves the transfer of forces from foam concrete to fibre and vice versa, creating a more durable and uniform structure. As a result, foam concrete with evenly distributed basalt fibre demonstrates higher bending strength compared to non-reinforced foam concrete. In addition, one of the key aspects that allows evaluating the durability and reliability of foam concrete is its frost resistance. This parameter determines the ability of a material to maintain its mechanical properties and structural integrity during multiple cycles of freezing and thawing.

The frost resistance index is especially important for structures that are subject to sudden temperature changes. Low frost resistance can lead to the destruction of the material, deterioration of its strength characteristics and the need for frequent repairs. The foam concrete's resistance to frost demonstrates its ability to withstand cyclical temperature fluctuations without significant loss of strength or cracking. When water freezes in the pores of foam concrete, it expands, which can lead to cracks and disruption of the structure of the material (Zhou & Su, 2023). The results of frost resistance tests conducted with samples of conventional and reinforced foam concrete are shown in Figure 7.

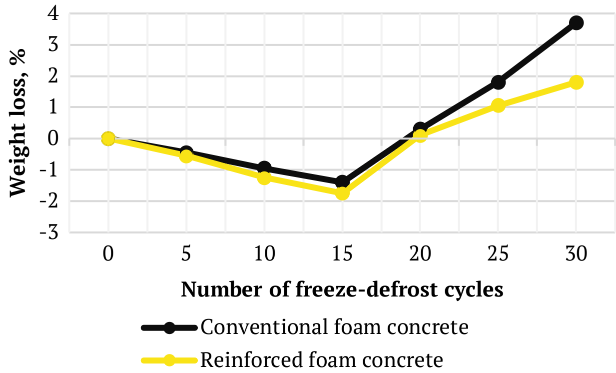

Figure 7. Frost resistance test results
Source: developed by the authors

These results show how the weight loss of foam concrete differs depending on the number of freezing and defrosting cycles. In the initial stages of testing, up to 5 cycles of freezing and defrosting, both types of foam concrete show negative weight loss values. Ordinary foam concrete loses -0.45%, and reinforced concrete loses -0.55%. Negative values indicate that during this period, both materials, on the contrary, gain weight. This may be due to the fact that moisture in the pores of the material freezes and increases its weight, which indicates the initial stage of moisture accumulation in the foam concrete structure. This situation persists on cycles 10 and 15. Conventional foam concrete shows a weight loss of -0.95% on cycle 10 and -1.4% on cycle 15, while reinforced foam concrete loses -1.25 and -1.75%, respectively. These negative values confirm that at these stages both types of foam concrete continue to gain weight, which may be the result of further accumulation of ice and moisture in their pores. However, reinforced foam concrete demonstrates higher weight gain values, which may indicate its more complex interaction with moisture during the freezing process. After 20 cycles, the weight loss becomes positive. Conventional foam concrete loses 0.3%, while reinforced concrete loses 0.1%. This transition from negative to positive values signals that the initial stages of moisture accumulation are replaced by a stage of its loss. This may be due to the destruction of the structure of the material and the release of accumulated ice, which leads to a loss of weight. Reinforced foam concrete shows less weight loss compared to conventional, which indicates its better behaviour in conditions of frost cycles. At cycles 25 and 30, weight losses increase significantly: conventional foam concrete loses 1.8% at cycle 25 and 3.7% at cycle 30, while reinforced concrete loses 1.05 and 1.8%, respectively. These data confirm that reinforced foam concrete demonstrates lower weight loss at all stages of testing, which emphasises its better frost resistance.

Thus, reinforced foam concrete retains its weight and structural integrity better than conventional, even under prolonged exposure to freezing and defrosting cycles. This is conditioned by the fact that the basalt fibre used for reinforcement forms a strong mesh structure inside the material, which effectively distributes loads and prevents the development of cracks. Such cracks may result from water freezing and expanding in the pores of foam concrete, which leads to the destruction of the material. Reinforcement prevents the development and expansion of these cracks, thereby reducing the likelihood of weight loss during freezing and defrosting cycles. Moreover, the uniform distribution of basalt fibre enhances the overall strength of the material, which additionally plays a role in its frost resistance. Fibre strengthens the structure of foam concrete, increasing its ability to withstand internal stresses that occur when water freezes inside the material. This helps to prevent damage and deformation, which reduces weight loss during multiple cycles of freezing and defrosting.

DISCUSSION

A thorough study was conducted of the effect of the basalt fibre mixing technique in a foam concrete mixture with a content of 0.5% of the total volume of the mixture. The main focus was on how the uniform distribution of fibre affects the mechanical qualities of foam concrete. Assessing the impact of the content of basalt fibre in a volume of 0.5%, the study showed that such a number of fibres provides a balance between improving strength and preventing an excessive increase in the viscosity of the mixture, which can make it difficult to process. It was found that the addition of fibre in this concentration leads to an enhancement in the mechanical properties of foam concrete, which makes it more durable and reliable in various climatic conditions. Thus, the uniform distribution of fibre achieved using a special mixing technique confirms the effectiveness of reinforcement of foam concrete with basalt fibre and opens up new opportunities for its use in construction. Y.-F. Li *et al*. (2022) also examined the effectiveness of various concentrations of basalt fibre, as a result revealing that the optimal size and concentration of fibres provides optimal improvement in strength characteristics, while smaller or larger sizes and numbers of fibres lead to a decrease in these effects due to a deterioration in the uniformity of distribution or a rise in the mixture's viscosity. The study by A. Qsymah *et al*. (2023) analysed the durability of reinforced foam concrete under extreme climatic conditions, finally confirming that foam concrete with basalt fibre has the best resistance to temperature and humidity changes. In turn, M. Liu *et al*. (2022) examined the impact of different concentrations of basalt fibre on the microstructure of foam concrete, finding that the optimal concentration of fibre contributed to improving the uniformity of distribution and preventing the development of weak points in the material. Thus, in combination with the findings of the mentioned works, the current study's results emphasise the high efficiency of using basalt fibre at optimal concentrations, which significantly enhances the strength and durability features of foam concrete and expands its potential applications in construction practice.

During the compressive strength tests performed in this study, the characteristics of both conventional foam concrete and foam reinforced with basalt fibre were assessed. For ordinary foam concrete, the compressive strength during the first days of hardening was relatively low, which is typical for this material. At day 1, the compressive strength was 0.42 MPa, which increased to 1.8 MPa after 28 days. In the case of reinforced foam concrete, the results were significantly more impressive. On the first day of hardening, the compressive strength was 0.7 MPa, which is already 66% more than that of conventional foam concrete. The compressive strength of reinforced foam concrete reached 2.65 MPa in 28 days, which is almost 1.5 times higher than that of its non-reinforced counterpart. These results indicate that basalt fibre effectively strengthens foam concrete, increasing its ability to withstand compressive loads. As a result, the reinforcement of foam concrete with basalt fibre significantly expands its possibilities for use in conditions where high strength and durability are required (Sidliarenko, 2023). The study by J. Wang *et al*. (2021) also confirms these findings, showing with their results that the addition of basalt fibre leads to a significant improvement in compressive strength, making the material more suitable for critical structural elements. P.J. Ardhira *et al*. (2023) supplemented these data by discovering during the study that the optimal choice of reinforcing fibres minimises the effect on the viscosity of the mixture and simplifies its processing. H.S. Gökçe *et al*. (2023) revealed that when a certain concentration of various fibres is exceeded, a decrease in compressive strength is observed, which is associated with the formation of excess fibres, which can create local weaknesses in the material. It should be noted that the results of this study, in comparison with the results of the mentioned papers, provide a more detailed understanding of the impact of basalt fibre on the compressive strength of foam concrete, and also emphasise the importance of precise control over the concentration of fibre to achieve maximum performance.

During flexural strength tests, it was discovered that the adding the basalt fibre to foam concrete also significantly improves its characteristics in this indicator. The main test results showed that on the first day of hardening, the bending strength for ordinary foam concrete was 0.38 MPa, while for reinforced foam concrete it reached 0.65 MPa. This represents a 71% increase in bending strength compared to conventional foam concrete, which indicates a significant improvement in resistance to bending loads during the early stages of hardening. After 28 days of hardening, the bending strength of ordinary foam concrete was 1.15 MPa. However, the bending strength of reinforced foam concrete has increased to 1.8 MPa. This is almost 57% more than that of conventional foam concrete, which emphasises the effectiveness of basalt fibre in increasing crack resistance and bending strength. This allows the use of reinforced foam concrete in structures where a combination of high strength and resistance to bending loads is required. D. Falliano *et al*. (2022) studied optimising the concentration of fibres, as a result, setting the optimal amount of basalt fibre to achieve maximum bending strength. In turn, H. Al-Zubaidi & R. Allouzi (2023) analysed the long-term effects of reinforcement on flexural strength, confirming that basalt fibre retains its effectiveness for a long time, preventing cracks and improving the durability of the material. When comparing the results of this study with the one of the mentioned studies, it should be highlighted that the use of basalt fibre in a concentration of 0.5% shows comparable or even better results in bending strength than in similar studies, which confirms its effectiveness for both early and late stages of foam concrete hardening.

In addition, in the course of this study, a frost resistance test was conducted for ordinary foam concrete and basalt fibre-reinforced foam concrete. In the initial stages of testing, that is, after 5 and 10 cycles, both conventional and reinforced foam concrete showed an increase in weight, indicating water absorption and possibly initial swelling of the material. However, starting from 15 cycles, ordinary foam concrete began to lose weight, which indicates the destruction of the structure and loss of strength under the influence of cyclic freezing and defrosting. The weight loss continued and increased to 3.7% by 30 cycles. Meanwhile, reinforced foam concrete, although it showed a similar trend in the early stages, had significantly better resistance to weight loss. The weight loss of reinforced foam concrete was 1.8% after 30 cycles, which is 2% less than that of conventional foam concrete. These results indicate that basalt fibre enhances the frost resistance of foam concrete, reducing internal damage and improving its ability to maintain structural integrity at extreme temperatures. The study by Y. Guo & H. Yokota (2018) found that under the conditions of freezing and defrosting tests, ordinary foam concrete loses weight much faster, confirming the insufficient resistance of this material to frost-resistant conditions. X. Tan *et al*. (2013) demonstrated that the utilisation of various types of reinforcement, such as polypropylene fibres, improves frost resistance, but not to the same extent as basalt fibre. The results of the study by W. Zhang *et al*. (2016) also confirmed that the addition of steel reinforcing fibres helps to reduce weight loss, but without reaching the level of efficiency observed when using basalt fibre. When evaluating the results obtained and comparing it to the findings of the previous studies, it can be concluded that basalt fibre demonstrates the highest efficiency in improving the frost resistance of foam concrete, providing a significant advantage over other types of reinforcing materials.

Thus, research on improving the properties of foam concrete through reinforcement with various fibres plays a key role in improving its performance and expanding the scope of applications in construction. The analysis of the test results for strength, frost resistance, and other mechanical properties determines the most effective reinforcement methods and identifies the optimal concentrations of additives to achieve the required material qualities. Such research contributes to the development of more reliable and durable construction solutions, which improve the safety and durability of structures in general.

CONCLUSIONS

The study found that the uniform reinforcement of foam concrete with basalt fibre has a significant effect on its key mechanical qualities, including compressive strength, bending strength, and frost resistance. Thus, the analysis of compressive strength showed that reinforced foam concrete shows a noticeable improvement compared to conventional foam concrete. At the beginning of hardening, on day 1, the compressive strength of reinforced foam concrete was 0.7 MPa versus 0.42 MPa for the conventional one. This represents an increase of 66% compared to conventional foam concrete. On day 28, the strength of reinforced foam concrete reached 2.65 MPa, which is 47% higher than 1.8 MPa for conventional foam concrete. At all stages of hardening, reinforced foam concrete demonstrated sustained superiority, especially in the early stages, which makes it particularly effective in conditions requiring high compressive strength.

In terms of flexural strength, the results also showed significant improvement. On day 1 of hardening, the bending strength of reinforced foam concrete was 0.65 MPa, which surpasses the standard foam concrete by 71%, which had a strength of 0.38 MPa. On day 28, the bending strength of reinforced foam concrete reached 1.8 MPa, which is 56% higher than 1.15 MPa of conventional foam concrete. These data show that reinforcement is effective both in the early and late stages of hardening, improving bending strength in long-term operation. The frost resistance of reinforced foam concrete is also significantly superior to conventional foam concrete. At the 30th test cycle, reinforced foam concrete demonstrated weight loss rates of 1.8%, whereas conventional foam concrete showed 3.7%. This confirms that reinforced foam concrete is more resistant to the effects of freezing and defrosting cycles, which provides it with greater durability and efficiency of use in difficult climatic conditions.

It is worth noting that this study has a limitation in the form of using only one type of basalt fibre during testing, which may not fully reflect all possible variations in the qualities of foam concrete. For further research, the use of various types of fibres and fillers should be considered, including the examination of the impact of these additions on the durability of the material under extreme operating conditions. Another promising area is the investigation of the effect of various additives on the features of reinforced foam concrete, which can improve other performance characteristics such as water resistance and thermal conductivity, expanding the scope of foam concrete in construction.

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CONFLICT OF INTEREST

None.

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Дослідження рівномірного розподілу базальтової фібри в пінобетонній суміші

Анотація. Метою цього дослідження було вивчення впливу рівномірного армування базальтовою фіброю на механічні властивості пінобетону, такі як міцність на стиск, згин і морозостійкість. Було використано комплексну методику, яка включала приготування та випробування пінобетонних сумішей з базальтовою фіброю, а також проведення випробувань на міцність та морозостійкість з використанням спеціалізованого обладнання. В результаті проведених досліджень було встановлено, що рівномірне додавання базальтової фібри до складу пінобетону значно покращує його механічні властивості. Міцність на стиск армованого пінобетону зросла на 30-40 % у порівнянні зі звичайним пінобетоном, що особливо помітно на ранніх стадіях твердіння. Наприклад, після 28 днів твердіння міцність на стиск армованого пінобетону становила 2,65 МПа, тоді як для неармованого аналога вона досягала лише 1,8 МПа. Крім того, армований пінобетон продемонстрував значне поліпшення міцності на вигин. Після 28 днів твердіння міцність на вигин становила 1,8 МПа, що на 56 % вище в порівнянні зі звичайним пінобетоном, у якого цей показник становив 1,15 МПа. Це свідчить про те, що базальтова фібра ефективно запобігає розвитку мікротріщин, підвищуючи загальну довговічність матеріалу. Крім того, в ході дослідження було виявлено поліпшення морозостійкості пінобетону, армованого базальтовою фіброю. Після 30 циклів заморожування і розморожування армований пінобетон показав меншу втрату ваги на 1,8 % в порівнянні зі звичайним пінобетоном, у якого цей показник досяг 3,7 %. Це свідчить про високу стійкість матеріалу до циклічних кліматичних впливів, що робить його більш придатним для використання в екстремальних кліматичних умовах. Таким чином, отримані результати підтверджують значне поліпшення механічних властивостей армованого пінобетону, демонструючи, що армування базальтовою фіброю робить його більш надійним і довговічним матеріалом для різних будівельних застосувань

Ключові слова: пінобетон; арматура; базальтове волокно; адгезія цементного розчину; міцність на стиск; міцність на вигин; морозостійкість

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The development of fitness centre architecture: Integration of modern trends and conventional approaches

Abstract. This study is concerned with the analysis of fitness centre architecture, with a particular focus on the integration of modern technologies with traditional design approaches. The objective was to examine the impact of contemporary architectural trends and technologies, including Building Information Modeling and artificial intelligence, on spatial solutions, functionality, and sustainability in the context of fitness centres. A comparative analysis was conducted between historical examples of Soviet-era sports complexes, which were imbued with ideological significance, and modern fitness centres, which are oriented towards the comfort and individual needs of users. The findings demonstrate that the process of globalisation has exerted a considerable influence on the standardisation of fitness centre design, frequently resulting in the erosion of national architectural characteristics. However, innovative approaches, such as the use of environmentally friendly materials and the integration of energy-efficient technologies, have been identified as pivotal to the development of modern fitness centres that are aligned with the needs of urban spaces. Based on an analysis of trends in various countries, recommendations were made for the creation of inclusive, eco-friendly, and innovative training spaces that support both social integration and individual goals. This study makes a significant contribution to architectural practice by offering ways to improve the efficiency of fitness centres through the use of modern technologies, the preservation of local cultural features, and the creation of comfortable environments for all visitors

Keywords: standardisation; globalisation; sustainability; energy efficiency; regionalism; typology

INTRODUCTION

Since the beginning of the 21st century, fitness centres have played an important role as places for improving physical health and as social and cultural spaces where people strive to enhance their quality of life. The relevance of this study is driven not only by the rapid development of the fitness industry in various cities but also by the desire to understand how architectural preferences and urban residents' needs are changing. Analysing the architecture of fitness centres allows for an assessment of how global trends and local characteristics are combined in creating urban spaces. In cities worldwide, including major metropolises and cultural centres, fitness centres are becoming embodiments of global trends, reflecting cities' aspirations to integrate into the global community. The analysis of these

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institutions' architecture presents not only architectural interest but also allows for an in-depth examination of the sociocultural changes occurring in the urban environment. This evolutionary path not only reflects general trends in architecture and construction but also reveals unique aspects of the influence of cultural and economic factors on urban infrastructure development.

When examining the development of fitness centre architecture, researchers face several key challenges. Historically, the development of fitness centres has undergone several key stages. Starting from simpler, functional buildings in the past to multifunctional complexes that incorporate the latest technological and architectural innovations. Studies covering this subject have been conducted by D. Blumetti *et al*. (2020) and M. Żychowska *et al*. (2022). It was noted that changes in governmental ideology are reflected in architecture, especially in authoritarian and socialist countries. For instance, the use of styles in courthouse architecture serves as a form of performance that expresses institutional power and adapts to the social context to maintain legitimacy and create a visual representation of justice.

In the context of exploring innovative approaches to the design of fitness centres, numerous aspects must be considered. Research in this area by B. Blocken *et al*. (2021), M. Evans & P. Farrell (2021) and A. Rosemina (2022) provided fairly extensive observations and measurement results of aerosol particle concentrations and CO_2 levels in various physical exercise scenarios with ventilation and air conditioning either on or off, which helped to understand methods of controlling the spread of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) and other infections in indoor spaces. The combination of ventilation and intensive air purification using air conditioners significantly reduces aerosol particle concentrations, lowering the risk of clients contracting various diseases. The authors identified the main obstacles as the absence of mandatory industry standards and regulations for the use of Building Information Modeling (BIM) and Lean Construction (LC), the resistance of the industry to transition from conventional practices to LeanBIM, the high cost of software licenses, and the complexities of training and implementing BIM systems.

Globalisation has a substantial impact on the architecture of fitness centres, facilitating the transfer of technological innovations in architecture and construction internationally (Kucherenko *et al*., 2024). However, it also tends to overlook uniqueness and local character. Due to globalisation, architecture may become standardised and resemble other facilities in different countries, diminishing authenticity. E. Kalsum *et al*. (2024) analyse regionalism in architecture, focusing on how local perceptions influence the design of public state buildings in West Kalimantan Province, Indonesia, reflecting local cultural and environmental contexts. E.K. Duysebay & E.E. Duysebay (2022) explore the artistic language of modern Kazakh architects, highlighting the influence of cultural heritage on contemporary architectural practices. A.M. Adil & N.L. Seitakhmetova (2020) examine the impact of design and monumental painting on modern Kazakhstan architecture, focusing on its development and reflection of national identity.

The studies by the aforementioned researchers are indeed significant, as they help to better understand the complex aspects that have influenced the development of fitness centre architecture both historically and technologically. Despite the wide range of studies in this field, there are still some gaps that need to be highlighted. Attention must be paid to preserving the uniqueness and national identity of fitness centres in the face of standardised architectural solutions. The development of innovative approaches to design and functionality will help preserve diversity and cultural heritage in the architecture of such facilities. It is also important to delve into the environmental potential of fitness centres, including the assessment and improvement of energy efficiency, the use of environmentally friendly materials and technologies, and the impact on the environment during construction and operation.

The analysis of fitness centre architecture presents a complex challenge, requiring consideration of numerous factors and features and overcoming various methodological and practical obstacles. Therefore, the purpose of this study was to analyse a multitude of global architectural practices, both in the construction and the design phase of fitness centres, considering their role in the sociocultural environment of cities. The primary objectives of the study are to identify the problems faced by architects when designing such facilities and develop recommendations for the design of fitness centres of various profiles, considering the identified issues for effective use in the practice. This also contributes to the creation of healthy and sustainable urban environments that meet the needs of citizens.

MATERIALS AND METHODS

This study examined the architectural approaches to designing sports complexes within diverse political and social contexts, including the Soviet Union and Nazi Germany. The study also evaluated the extent to which these historical periods shaped contemporary fitness centre design. The methodology entailed a comprehensive review of historical documents, architectural literature, and case studies. The study drew upon a number of key sources, including the Resolution of the Council of Ministers of the USSR No. 1395 (1986), which outlined the Soviet Union's approach to the development of sports facilities, and architectural studies of the Olympiapark Berlin in Nazi Germany, which was constructed for the 1936 Summer Olympics. These sources furnished a basis for comprehension of the manner in which ideology influenced the configuration and functionality of sports facilities within these regimes (Kercher *et al*., 2023).

The analysis of the development of fitness centre architecture began with an extensive review of existing architectural structures, assessing their planning solutions and structural features by analysing their plans and sections available in open access, such as on the internet platform ArchDaily (Fitness center/Capote Marcondes..., 2023;

Norrvikens sports..., 2023). This review allowed for the identification of key trends in fitness centre design, from historical to contemporary examples, and enabled the comparison of typological features and planning solutions in various architectural styles. A comparative analysis of architectural styles was undertaken, employing a range of criteria, including building functionality, form, the symbolic representation of political ideologies, and the socio-cultural impact of the structures in question. The historical sports complexes were evaluated in comparison with the modern fitness centres, with particular attention paid to the influence of the political agendas of the time on their design. This comparison revealed that buildings erected during the Soviet and Nazi eras were designed with the primary objective of serving as propaganda tools, whereas contemporary fitness centres are primarily concerned with providing comfort, functionality, and an optimal user experience.

The study also reviewed specific case studies of modern fitness centres that integrate contemporary technologies like BIM and artificial intelligence (AI). Examples such as the World Class Fitness Club in Minsk, Belarus, were analysed to explore how these technologies optimize building design, enhance energy efficiency, and improve the overall user experience. In this case, BIM technology was used to visualize and model the building during the design phase, facilitating efficient construction and minimizing errors. Another noteworthy aspect of the study was the analysis of fitness centres integrated into natural environments, including Plateau D'Or in Goiânia, Brazil, and Norrvikens Sports Centre in Sollentuna, Sweden. These facilities were selected for their pioneering use of sustainable construction materials, including cross-laminated timber (CLT) and solar panels, as well as their commitment to integrating architectural design with the surrounding natural environment. An evaluation of the ecological aspects of these designs was conducted in terms of energy efficiency, sustainability, and minimal environmental impact.

In addition, the article analyses examples of fitness centres in Kazakhstan, China, the USA, France and Belgium. The selection of these fitness centres was based on their relevance to the research objectives, including their innovative design approaches, technological integration, and consideration of local environmental and social factors. This methodology afforded a comprehensive understanding of the evolution of fitness centre design in response to diverse political, cultural, and technological influences.

RESULTS

The early stages of the development of sports centre architecture in the Soviet Union began with the emergence of the first sports facilities in the early 20th century. During this period, sports structures were primarily built for mass sports movements and physical culture events; fitness centres, as they are known today, have yet to exist as a concept. The focus was on creating sports facilities for large-scale sporting events, training, and competitions in specific sports. The architecture and construction in the Soviet system were closely tied to state ideology, and all architectural projects were subject to strict control by central and regional authorities.

Architects did not integrate all functions, such as gyms, swimming pools, and cardio zones, into a single facility. This can be explained by the fact that in the Soviet system, a healthy lifestyle and physical activity were considered important aspects of education and preparation for work. Despite the active support and development of the construction and reconstruction of sports facilities during the Soviet period, they were primarily geared towards mass sporting events and state programmes. The functional purpose and form of sports facilities were determined by the ideology and needs of state and public programmes rather than individual needs or trends, as is common in democratic societies. During the Soviet era, physical activity and sports were mainly carried out within the framework of sports schools, children's sections, sports clubs, and stadiums. In such a system, there was no necessity to create comprehensive fitness centres where various types of physical activity could be pursued in one place. The Resolution of the Council of Ministers of the USSR No. 1395 (1986) states: "The main tasks of the USSR State Committee for Physical Culture and Sports are: enhancing the role of physical culture and sports in the comprehensive and harmonious development of the individual, preparing young people for work and the defence of the socialist motherland, strengthening health, fostering a healthy lifestyle, and organising active leisure for Soviet people".

A characteristic feature of the architecture of Soviet sports centres was functionality, expressed in clear geometric shapes and simple lines. The exterior of the buildings typically featured austere and restrained façades, devoid of excessive decoration or ornamentation. The buildings were designed with their purpose in mind, ensuring convenience for sports and training activities. In some cases, elements of constructivism or national styles could be observed, especially in the later periods of Soviet history. The sports complex "Salyut", built in Kamensk-Uralsky in 1961, exemplifies the typical style of the Soviet era, reflecting the principles of restrained neoclassicism. This style was often expressed in rectangular building shapes with minimal decorative elements. This brick and cinder block building has a rectangular plan. On the ground floor, the building features galleries with colonnades enclosed on three sides. However, in the 1970s, the space between the columns was filled with brickwork, altering the building's appearance. The sports complex "Dinamo" in Tbilisi, Georgia: This complex was one of the largest sports facilities in the Georgian SSR. It included a stadium, a swimming pool, gyms, tennis courts, and other facilities. The architectural style may have been inspired by traditional Georgian architecture, while the layout was designed to ensure mass access to sports events. One of the first examples of sports centres in Central Europe, built in the early 20th century, is "Olympiapark Berlin", which opened in 1936 in Berlin in anticipation of the Summer Olympic Games (Fig. 1).

Figure 1. "Olympiapark Berlin"

Source: iStock (2018)

This complex was created as part of the Olympic preparation project and included various sports facilities such as a stadium, swimming pool, sports halls, and training grounds. Notably, the organisation and hosting of the 1936 Olympic Games were complex events influenced not only by the Nazi authorities but also by various German and international participants. The Olympiapark embodied the architectural and engineering ideas of its time. The buildings and structures were designed with both functionality and aesthetics in mind, incorporating innovative technologies and building materials (Lehmann, 2021). As an architectural monument, it openly reveals National Socialist ideology through its finely artistic ensemble, created around the Nazi concept of the new Aryan man. The monumental sculpture, part of the park, represents a programme aimed at building the ideal Aryan body. Visitors to the park can (or should) view these sculptures to understand the historical and ideological significance they bear. Depictions of the body were used in National Socialist ideological politics as a tool to influence public opinion and shape desired stereotypes. These images were employed for education and instruction, teaching people to distinguish between "correct" and "incorrect" bodies according to Nazi ideals (Wildman, 1998).

Examples of sports complexes and facilities in Germany and other countries associated with the Nazi era highlight the architectural and symbolic features of that time. For instance, the stands of Maifeld and Langemarck Hall, which served as centres for sporting competitions, have distinctive architecture reflecting National Socialist ideology and the cult of masculinity. These complexes often served as tools for propaganda and mass manipulation under the Nazi regime. Similarly, in the Soviet Union, sports facilities were also designed to project power and advance the regime's ideological goals. While both regimes used architecture as instruments of propaganda and mobilisation, the ways in which these buildings reflected their respective political systems differed. Nazi structures often emphasized grandeur and strength to reinforce the image of the ideal "Aryan body", whereas Soviet sports facilities, though also monumental, were more focused on serving state programmes and mobilizing the masses for collective activities. The key distinction between the architecture of these sports centres and modern fitness centres is their strong connection to the political context of their time.

Over time, architectural solutions in fitness centres have become more diverse and innovative. Buildings have become more ergonomic, featuring increased natural light and ventilation. In addition, fitness centres now include not only sports facilities but also additional services such as saunas, cafés, beauty salons, and relaxation areas. The layout of such centres typically provides a convenient and efficient organisation of space for maximum visitor comfort. Fitness centres often do not reflect local traditions but are rather examples of globalisation in architecture. These facilities frequently adhere to standards and trends that are widespread worldwide, featuring similar design and functionality regardless of location. On the one hand, this provides architects with new tools and opportunities to create innovative and sustainable projects. On the other hand, it can lead to uniformity and a loss of uniqueness in architecture (Eldemery, 2009). Investment in sports facilities is becoming increasingly significant in the context of globalisation and the commercialisation of sports, as reflected in the growth in scale and luxury of fitness centres (Sklair, 2017).

It is important for architects to consider local features and the context of the city when designing fitness centres. This involves adapting the design to the climatic conditions and local landscape and considering cultural and social aspects. Moving away from standard modernism and experimenting with diverse designs can contribute to creating unique and attractive spaces that reflect the spirit of the city and local identity. It is essential to understand that each region has its unique cultural, historical, and social specifics. When developing regionalisation strategies, these features must be considered, and local communities should be involved in the decision-making process. Only in this way can architectural and urban environments be created that reflect and respect local identity and cultural heritage. In addition, when implementing regional projects, it is necessary to consider and balance the interests between global trends and the needs of local communities (Trusova *et al.*, 2020). This may include accounting for economic, environmental, and social sustainability, respecting cultural diversity, and adhering to principles of social justice. Rethinking the impact of architecture on the external environment and the cultural identity of a city allows for the creation of more harmonious and sustainable structures. This can involve using traditional materials and construction methods, integrating elements of local architectural and cultural history, and creating spaces that promote social interaction and healthy lifestyles. This practice, therefore, has significant potential for effective implementation in the design of fitness centres.

Sports centres often become important public spaces where people gather and interact. The architectural design of these centres reflects the spirit of the community and national pride, significantly influencing visitor attraction. It serves as a means of cultural expression for the nation, reflecting its values, traditions, and identity. This is evident in the choice of architectural styles, design elements, and the use of symbolism and themes related to national heritage. Large countries strive to showcase their strength and prestige in sports by creating impressive and large-scale sports facilities, such as Olympic stadiums, arenas, and sports complexes designed for major sporting events. These structures have become symbols of national pride and are used to attract international attention and prestige.

The "Almaty Arena" Ice Palace in Almaty, Kazakhstan, built for the 2017 Winter Universiade, is an important symbol of the region's sporting and cultural life. The project utilised aluminium systems and protective structures from "ALUTECH". The Ice Palace not only contributes to the development of sports infrastructure but also serves as a place where people can gather, interact, and enjoy cultural events. Its construction and operation are crucial elements in shaping the social life of the region and strengthening the cultural and sports identity of Almaty and Central Asia as a whole. The design features simple lines, a minimalist aesthetic, and the use of glass and metal. The two colours of the Kazakh flag emphasise its national affiliation. The "National Stadium" in Beijing, China, also known as the "Bird's Nest", built for the 2008 Olympic Games, was conceived as a symbol of China's imperial heritage and its aspiration for global leadership. Other notable examples include the "Maracanã" in Brazil, the "Stade de France" in France, and the "Birmingham Arena" in the United Kingdom.

The architecture of fitness centres is often characterised by functionality and concise design, with dynamic elements to emphasise the building's sports orientation. Their external design typically aims to attract visitors, while the interior primarily reflects functionality. For instance, the "Fitnation" fitness centre in Almaty, Kazakhstan, is an example of modernist architecture, marking a transition from traditional decorative forms to an experimental and innovative approach that highlights the functional and structural aspects of the building.

The David A. Beckerman Recreation Centre at the University of New Haven seamlessly integrates two essential functions for an educational institution: a sports centre and a recreation area. This fitness centre becomes more than just a campus building; it transforms into a community hub for students, where they can not only work out but also participate in various events such as job fairs, concerts, and sports competitions (Fried & Kastel, 2020). This dual-function integration within a single space optimises resource usage and enhances the economic efficiency of both construction and operation. Constructing large-span structures to combine the sports centre and recreation areas can reduce costs for building and maintenance, as it eliminates the need for separate buildings for each function. Students can easily move between different zones within the same building or space, creating a more comfortable and functional environment. The sports complex in Kiel, Belgium, demonstrates innovative approaches to the organisation of functional zones. Using the principle of inversion, sports halls are located on the outer perimeter with maximum openness, and service areas are centralised. Space usage is optimised, and visitors' accessibility to various zones is improved.

The interior of the "Trois-en-Un" sports complex in Parsemain, France, lacks physical partitions, creating a visual separation of spaces due to its intricate architecture. This allows the sports areas to be used for large open events as well as for smaller groups requiring separate spaces. The complex features an intricate roof design with panoramic windows, allowing ample natural light to enter the space. Moreover, there are outdoor sports fields on the premises. The complex meets the Swiss Minergie standard for sustainability and energy efficiency, with its roof completely covered in solar panels.

The "Plateu D'or" fitness club in Goiânia, Brazil, comprises two main blocks. The first block is designated for the pool, sauna, and rehabilitation/physiotherapy activities, while the second block is for strength training, aerobics, and Pilates. The pool in the first block is housed in a building with a metal structure and a retractable roof, allowing for flexible use for both training and leisure on weekends. This area is integrated with the rehabilitation pool and sauna, making it fully accessible to visitors. The second block contains rooms for strength training, aerobics, and Pilates, situated under a large "shade" structure that protects from intense heat and provides greater transparency and integration with the landscape and forest. A snack area connected to these spaces supports users and club activities, maintaining good contact with the gardens and existing forest (Fitness center/Capote Marcondes..., 2023).

The centre uses natural materials such as wood and metal, reducing environmental impact and supporting sustainable resource use. The proximity of the fitness centre to the existing forest area and its integration with the landscape help preserve the natural environment and biodiversity.

The Norrvikens Sports Centre (2023) comprises three buildings on the lake shore in Sollentuna, Sweden, for canoeing and skating clubs. It uses natural materials like wood and metal with a simple yet effective design. The facades are painted blue to reflect the surrounding nature, and the interior walls are clad with hewn spruce boards, creating a cosy atmosphere. In addition, the buildings incorporate energy-efficient solutions such as the use of prefabricated CLT panels and simple tar board cladding, contributing to reduced energy consumption and emissions. The overall design allows the buildings to blend into the natural landscape, highlighting their environmental integrity and sustainability (Bandura *et al.*, 2023).

The integration of BIM and AI represents considerable potential for the transformation of the construction industry. BIM currently serves as the digital foundation for architectural, engineering, and construction projects, while AI provides new tools and methods for analysing these data and making decisions that are more informed (Pan & Zhang, 2023). BIM constitutes a digital building model containing information about its physical and functional characteristics throughout its lifecycle stages, including design, construction, and operation. BIM is a comprehensive process of creating and managing information for constructed assets. Based on an intelligent model and supported by cloud platforms, BIM integrates structured interdisciplinary data to create a digital representation of the asset throughout its lifecycle, from planning and design to construction and operation. The use of BIM in conjunction with machine learning algorithms enables the analysis of space planning data and client needs to create optimal fitness centre designs. AI can assist in predicting visitor traffic and optimising equipment placement and zones for maximal space utilisation. BIM can incorporate safety visualisations and scenario modelling to help builders make informed decisions for ensuring safety, analysing equipment service data, and predicting maintenance needs or equipment replacement, thereby enhancing service efficiency and reducing equipment downtime (Bannikov *et al.*, 2019). The application of data analysis and machine learning enables fitness centres to develop personalised training programmes for clients based on their goals and preferences. This also aids in collecting and analysing training data and client progress for continual improvement of training programmes and service delivery.

In urban environments and highly developed areas, constructing a fitness centre in a natural setting might be impractical due to the limited availability of suitable land. However, integrating fitness centres into the natural landscape can be achieved through the design of elements that mimic natural forms and objects. An example of such a solution is the concept of incorporating a green facade into a fitness centre using 3D-printed components. For instance, suitable materials and components for the green facade are selected based on a 3D model. The primary elements include pots or containers made from eco-friendly materials such as recycled plastic or composite materials and aluminium or steel frames that will attach to the building facade and hold the plant modules. An integrated drip irrigation system with automatic control capabilities is also included. A drainage tray or system prevents water stagnation and facade damage. The components are manufactured at a factory using modern technologies, with 3D printing employed to create prototypes and complex elements, thereby accelerating the process and reducing costs. For example, the 3D-VtGW modular system of vertical green walls made from concrete, fabricated using 3D printing. This system consists of two-layered concrete printed by a 3D printer, with a cavity filled with insulation. It is integrated with a 3D-printed concrete surface featuring a sinusoidal shape (Fig. 2).

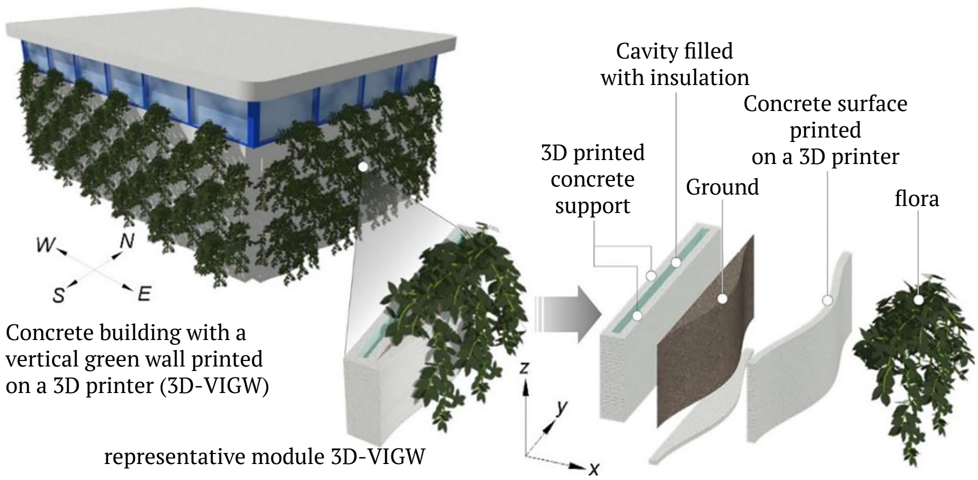

Figure 2. 3D-printed Vertical Green Wall (3D-VtGW) composition
Source: A.P. Capêto *et al.* (2024)

The structural system of the "World Class" fitness club in Minsk, Belarus, exemplifies a comprehensive solution aimed at achieving client goals such as adherence to exterior design, minimisation of construction timelines, cost optimisation, and ensuring high-quality real estate (Fig. 3).

Figure 2. "World Class" fitness club in Belarus
Source: Design project of World Class fitness club (2020)

Innovative structural solutions were employed to address these challenges. Successful implementation involved the use of unique pre-stressed concrete cantilever parts (sections 2 and 3) measuring 12 metres, fully leveraging the benefits of post-tensioning: stress relief and initial compression. BIM technology was utilised for precise visualisation and building modelling to closely align with the design project. The building was divided into several independent sections for simultaneous construction, contributing to reduced construction time. Each building section features a unique structural system tailored to its functional purpose and design requirements. For instance, the pool area is equipped with a monolithic technical floor and steel trusses, while the training zone employs reinforced concrete composite structures, optimising construction costs for each part (Tur *et al*., 2020). In this project, the application of BIM facilitated detailed structural planning and advanced three-dimensional modelling, streamlining collaboration among project participants. Furthermore, this technology enabled the verification of 3D models for compliance and the incorporation of corrections at early stages of design. As a result, there were no delays on the construction site due to incorrect design decisions or errors in the project. This demonstrates that the speed of design increased, project management with numerous participants became more efficient, and the risks of errors in the project were minimised.

DISCUSSION

The analysis presented in the study not only highlights the factors driving the development of fitness centre architecture but also touches upon the prospects for improving structural, sociocultural, and planning solutions. Particular attention is given to the efficient use of resources and the adherence to sustainable development principles, devising methods to enhance appeal to a broad audience. One way to significantly improve fitness centres during the construction and design phases is through the application of artificial intelligence practices in combination with various digital technologies.

This subject was also explored by P. Nusen *et al*. (2021), who analysed the efficiency of combining BIM and MOGA in the systematic approach to planning and scheduling renovation projects, providing valuable insights for decision-making. The authors highlight that BIM creates a digital model of a building containing data about its physical and functional characteristics, while MOGA optimises various project aspects considering multiple objectives. The study described focuses on the combination of BIM and machine learning algorithms to analyse and optimise the design of fitness centres, considering various factors such as space utilisation and client needs. In contrast, the aforementioned authors evaluate the effectiveness of combining BIM and MOGA in the systematic approach to planning and scheduling renovation projects. Thus, while both studies share a common theme of using BIM in construction, they focus on different aspects of this process in combination with other methods. The integration of various functions into a single fitness centre space represents an innovative approach that optimises resource use and enhances the efficiency of the construction and operation processes. Before such concepts became widespread, fitness centres and recreational areas were considered separate entities requiring distinct buildings and infrastructure. However, modernist architectural trends aim to create more flexible and multifunctional spaces where different functions can coexist harmoniously (Nedosnovanyi *et al*., 2023). This is particularly emphasised by the implementation of national policies in European countries, encouraging physical activity through public events and engaging the older generation.

B.S. Flowers (2017) also investigated the multifunctional approach in the design of sports architecture, analysing stadiums as centres of sociocultural activity and important elements of urban infrastructure. The author highlights the potential of stadiums for multifunctional use, including temporary stadiums that can be easily modified or even dismantled after the event, allowing cities to use spaces more efficiently and economically. This aligns with study findings indicating that the integration of multiple functions within sports buildings enhances resource and space efficiency, which is essential for densely populated urban areas. Such integration also promotes environmental sustainability and attracts a larger number of visitors.

Fitness centres can host various cultural events, such as exhibitions, concerts, dance evenings, and other activities, enriching the cultural life of the city and drawing new visitors. The current study notes that globalisation has caused significant changes in the fundamental perception of fitness centre architecture. Most of these changes include technological innovations and the re-evaluation of space utilisation for different functions. However, a major drawback is the simplification of a large category of buildings, including fitness centres, which leads to the neglect of national style and regional context. This aspect has garnered attention from numerous researchers. Among them, D. Ponzini (2020) highlights the misconception that globalisation automatically leads to the homogenisation of cities, a view that was prevalent during the industrialisation period. The author argues that such a simplistic perspective is not only incorrect but also hampers the understanding of the complex dynamics of urban transformation. The researcher emphasises that the departure from national style is inevitable but does not necessarily threaten the degradation of architectural style.

L. Lefaivre & A. Tzonis (2020) and S. Giamarelos (2022) note that after World War II, large-scale reconstruction and postcolonial building projects by state and transnational organisations often ignored local ecology, culture, and community, leading to failures in many cases. This sparked a resurgence of regionalism, which actively and critically re-embraced vernacular architectural traditions and expressed the aspirations of marginalised and forgotten communities. Critical regionalism faces the challenge of adapting to the postcolonial era, with the emergence of numerous new nation-states. While the discourse of critical regionalism emphasised context, it often remained confined within national boundaries, potentially leading to an oversimplified understanding of architectural context. Architecture can serve not only functional purposes but also carry symbolic significance, reflecting dominant ideologies and social relations (Tsyrfa *et al*., 2024). For example, strict geometric forms and rigid boundaries may symbolise authoritarian or hierarchical structures. Sports architecture has cultivated national pride, reinforced loyalty to regimes, and supported their political objectives. International sporting events, such as the Olympic Games or World Cup, continue to serve as demonstrations of a state power and prestige to the international community.

B. Hughes & P. Issaias (2023) also explored the impact of political institutions on society and space and the relationship between architecture, social relations, and ideology, using Italian architecture during the fascist regime as an example. Similar to the current study, the authors conclude that political institutions and social structures have left their mark on the architecture of sports centres and facilities, even after these structures have been formally changed or simplified. This creates challenges when altering or rethinking the use of specific spaces.

The review of the above studies and the comparison with the obtained findings demonstrated key trends in the formation of fitness centre architecture. The discussion highlights the relevance of applying BIM technology in combination with MOGA and AI. It also examines the influence of historical factors and political ideologies on the architecture of fitness centres. The degree of influence of globalisation on the architecture of fitness centres is discussed, which highlights the divergence of opinions on this issue among different authors and architects. This is crucial for analysing the multitude of factors accompanying the design and implementation of such buildings.

CONCLUSIONS

This study presents a comparative analysis of the architectural evolution of fitness centres, examining the impact of political ideologies and technological advancements on their design over time. The research demonstrated a stark contrast between the sports facilities constructed during the Soviet and Nazi eras, which were significantly influenced by state ideology, and the modern fitness centres, which prioritise functionality, comfort, and user experience. In the Soviet Union and Nazi Germany, sports complexes were designed with the explicit purpose of serving as propaganda tools, reflecting the political ideologies of their respective regimes. Such facilities were used to advance the interests of the state and to exert control over society. Their architectural style was frequently employed as a means of symbolising strength, discipline and nationalism. In contrast, contemporary fitness centres are more focused on the well-being of individuals, offering multifunctional spaces that cater to a diverse range of users.

The incorporation of contemporary technologies, including BIM and AI, has been identified as a pivotal aspect influencing the design and construction of contemporary fitness centres. These technologies facilitate more effective resource management, reduce construction costs, and enhance overall project quality. Fitness centres that integrate sustainable design elements, such as the utilisation of eco-friendly materials and energy-efficient systems, have been observed to have a positive environmental impact and contribute to a more sustainable urban environment. Furthermore, the study underscored the significance of regionalism in architectural design, advocating for the conservation of local cultural and environmental characteristics in the planning and construction of fitness facilities. It is recommended that future research concentrate on enhancing the accessibility of fitness centres in rural areas and incorporating social functions into their design, with the objective of further improving community engagement and promoting inclusivity.

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CONFLICT OF INTEREST

None.

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Розвиток архітектури фітнес-центрів: інтеграція сучасних тенденцій і традиційних підходів

Анотація. Це дослідження присвячене аналізу архітектури фітнес-центрів, з особливим акцентом на інтеграцію сучасних технологій з традиційними підходами до проектування. Мета полягала у вивченні впливу сучасних архітектурних тенденцій і технологій, зокрема інформаційного моделювання будівель і штучного інтелекту, на просторові рішення, функціональність і стійкість у контексті фітнес-центрів. Було проведено порівняльний аналіз між історичними прикладами спортивних комплексів радянських часів з ідеологічним значенням, та сучасними фітнес-центрами, орієнтованими на комфорт та індивідуальні потреби користувачів. Результати дослідження демонструють, що процес глобалізації справив значний вплив на стандартизацію дизайну фітнес-центрів, що часто призводить до розмивання національних архітектурних особливостей. Однак інноваційні підходи, такі як використання екологічно чистих матеріалів та інтеграція енергоефективних технологій, були визначені як ключові для розвитку сучасних фітнес-центрів, що відповідають потребам міського простору. На основі аналізу тенденцій у різних країнах, були розроблені рекомендації щодо створення інклюзивних, екологічних та інноваційних тренувальних просторів, які сприяють як соціальній інтеграції, так і досягненню індивідуальних цілей. Це дослідження робить значний внесок в архітектурну практику, пропонуючи шляхи підвищення ефективності фітнес-центрів завдяки використанню сучасних технологій, збереженню місцевих культурних особливостей та створенню комфортного середовища для всіх відвідувачів

Ключові слова: стандартизація; глобалізація; сталість; енергоефективність; регіоналізм; типологія

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Architectural and urban planning context of the physical dimension of urban identity

Abstract. In the contemporary context, urban identity is a critical aspect of city development. Its influence is evident in decision-making regarding the preservation of cultural heritage, the enhancement of social cohesion, and the stimulation of economic growth. For these interrelated goals, architectural and urban planning serve as foundational elements in shaping and reflecting a city's unique character and value. The study aimed to analyse architectural and urban planning determinants as essential multidimensional components in the formation and maintenance of urban identity. Using a comparative approach, the study identifies specific forms of material expression in the urban environment that foster a sense of identity and belonging among residents and visitors alike. A comparative analysis of analogous global and Ukrainian sites was conducted, including the cities of Palmanova (Italy) and Zhovkva (Ukraine); architectural and urban planning ensembles of the Circus (Bath, England) and Stometrivka (Ivano-Frankivsk, Ukraine), Empire State Building (New York, USA) and the Lviv Theatre of Opera and Ballet (Lviv, Ukraine). The findings indicate that the study of urban identity centres on a comprehensive understanding of human-place identification dynamics. The study reveals that examining urban identity necessitates a comprehensive understanding of human identification with their place of residence. Consequently, arguments for the preservation of landmark sites within established urban settings are insufficient and require specification at the level of their physical manifestations. It is proposed to emphasise the architectural and urban planning context, analysing it in alignment with three widely accepted levels of city organisation. Physical components of the urban environment, such as buildings and structures, architectural complexes and ensembles, streets and squares, as well as the city's overall territory, can serve as primary active elements, each equally contributing to the formation of urban identity. In some instances, understanding the city as a cohesive whole offers significantly greater potential compared to viewing its components separately, and vice versa. The capacity of individual elements to merge historical and contemporary aspects within a unified urban structure enhances the overall appeal and functionality of urban

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areas, further promoting a socially and culturally cohesive environment. The findings of this study can support more effective planning and implementation of urban development strategies, potentially preserving each city's uniqueness and enhancing the quality of life for residents

Keywords: urban environment; physical characteristics; urban planning theory; belonging; uniqueness

INTRODUCTION

Cities play a pivotal role in the development of contemporary society, serving as catalysts for economic growth, scientific and technological innovation, as well as cultural and social progress. When a city possesses significant potential in various areas of human activity, it opens up additional opportunities for development and prosperity. However, a city's true potential lies not only in its contemporary achievements and infrastructure but also in its rich historical and cultural heritage, which shapes the city's unique identity. A city's heritage encompasses architectural landmarks, cultural traditions, historical events, and social practices that are passed down through generations. If a city's true potential is not carefully considered, the rapid pace of urbanisation can lead to imbalanced trends. These trends can reduce the urban context to a formal level and erode social cohesion at the level of shared perspectives.

Concurrently, there has been a growing body of research focused on the issue of urban development within existing city boundaries and the assessment of its negative impact on the functioning of historically established urban environments. For example, B. Ashrafi *et al*. (2020) analysed and provided a well-argued assessment of the consequences of urban development on World Heritage cultural sites. The authors highlighted the conflict arising from the divergence between the need to preserve cultural heritage and the need for urban development. Such a problem stimulates the search for identity in architecture and urban planning and correlates with the uniqueness of specific places and their inhabitants.

Historical cities that undergo consistent and systematic renewal maintain their authenticity and identity, as affirmed by A. Pleshkanovska (2024). The author argues that a condition for the sustainable and harmonious development of an established city is its comprehensive reconstruction, and notes that reconstructive activity in its various forms, methods, and means of implementation is an integral part of a city's life cycle. H.M. Mansour *et al*. (2023a) emphasise that the nature of urban identity is multidimensional and therefore its study should not be limited to concepts of preserving cities and their heritage. In another study (Mansour *et al*., 2023b), the authors trace the fundamental connection between urban identity, place identity, city image, and its brand. They conclude that, despite physical changes occurring over time, cities have the ability to maintain their identity in various manifestations.

The contradictions arising at the level of recognising urban identity are discussed in the research of C. Hudson *et al*. (2019). The authors argue that insufficient attention paid to historical and cultural preconditions in reproducing urban identity can provoke political conflicts. B. Cherkes & J. Hernik (2021), comparing the architecture of central public spaces in the capitals of Central and Eastern Europe during their authoritarian and post-authoritarian development, demonstrate that the transformation of identity directly influences the formation and reconstruction of historical places.

The foundation of urban identity lies not only in social and cultural aspects. Physical characteristics of the urban environment also play a significant role. This is the key perspective taken by E. Manahasa & O. Manahasa (2020) in their study of the loss of identity in the city of Tirana (Albania) due to damage to its physical fabric. The authors note that the focus on the physical aspects of urban identity is a result of the influence of Modernism. This approach facilitates the recognition of the uniqueness of the urban environment and an understanding of its content. It is visual perception that is the primary way of identifying and understanding them. H.M. Mansour *et al*. (2023b) note that urban identity, as studied within the framework of urban planning, goes beyond social structure; instead, the social aspect is merely a factor that influences it. In this regard, the authors identified three directions for studying urban identity, in which spatial scale, the role of the consumer and time, urban memory, and urban identity as a dynamic transitional concept are significant.

The Ukrainian experience, studied by O. Musiyezdov & K. Maryniak (2020), also points to the variability of urban identity. It is based on the understanding of a city as a collection of different groups of people who consider it their home and feel a connection to it. Each of these groups has its own perception of the city, based on their living conditions and experiences. A. Pleshkanovska (2021) has examined the understanding of the spatial order of the city. She highlights the contradictory nature of the functional-planning organisation of Ukrainian cities formed in the post-industrial era. The author substantiates the directions for transforming the territory and development from the existing state to a city of an innovative character.

Given the rapid pace of development in European cities and the unprecedented political and socio-economic situation in Ukraine, scientific literature demonstrates a constant search for effective ways to preserve urban identity and to support and strengthen it in the contemporary world. This study aimed to identify specific forms of urban identity through the physical space and material resources, with a focus on Ukrainian settlements. Due to their uniqueness, they are not inferior to their global counterparts and require due attention. This article compares different ways of positioning objects of historical architectural and urban heritage and aspects of the relationship between city dwellers and these objects through the connection with cultural potential and emotional perception, as well as ways of using them in everyday life: work, study or leisure.

MATERIALS AND METHODS

This study draws on the experience of creating globally recognised and iconic architectural and urban planning objects to explore methods of shaping urban identity. It uses the characteristics of a city's physical space and material resources, which serve as expressions of the cultural and historical aspects of urban identity. Methodological approaches to understanding the material and spatial environment of societal life (Ashworth, 2009) have been crucial in addressing the study's objectives. The selected sample of objects allows for a detailed and systematic examination of various aspects of urban form and its evolution, facilitating clarity and precision in conducting comparative analysis. Central to this analysis is an understanding of the spatial functioning of the city according to its formal organisation across three main hierarchical levels: macro, meso, and micro. This approach reflects the need for a comprehensive analysis of popular forms of urban identity expression and their impact on different aspects of city life (Fig. 1).

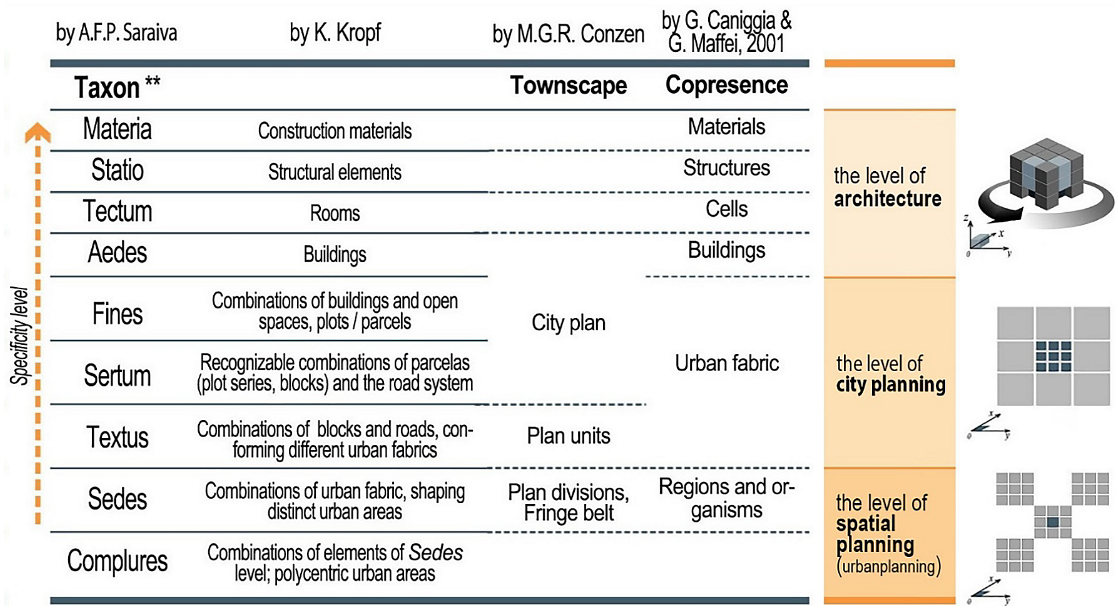

Figure 1. Comparison of the hierarchical organisation of architectural and urban planning objects and their structural elements, as well as generalisation and alignment with the commonly accepted understanding of the structural organisation of the urban environment

Source: Yu. Idak (2022)

The macro level encompasses large-scale objects and spatial structures such as cities, towns, and villages. This level provides an overview of the city and its role within the regional context. The meso level includes individual fragments of the city that form its fabric: blocks, streets, parks, squares, and other medium-scale spatial units. These elements are key to forming the local identity of residents in specific districts of the city; they reflect their daily lives and interpersonal relationships. The micro level consists of small architectural forms, individual buildings, courtyards, small parks, and playgrounds. These elements are often the most important for the personal perception of space, emotional connection to place, and the daily experiences of residents.

For a detailed study, objects at different hierarchical levels were selected: macro level – the cities of Palmanova (Italy) and Zhovkva (Ukraine); meso level – the Circus in Bath (England) and Stometrivka in Ivano-Frankivsk (Ukraine); micro level – the Empire State Building in New York (USA) and the Lviv Theatre of Opera and Ballet (Ukraine). The selection of these objects is representative as they have significant historical and cultural importance and play a key role in shaping both global and local cultural heritage. Moreover, they have international recognition, making them a focal point for study and discussion, as well as for the implementation of innovative ideas towards adapting to contemporary challenges.

The methodological foundation of the research was a comparative approach focused on identifying and analysing the similarities and differences, as well as trends in the formation of the material and spatial environment of human life. This approach made it possible not only to assess the mechanisms of functioning of the physical environment but also to interpret the processes and states of its influence on the formation of urban identity. In this context, a detailed comparison of different ways of positioning objects of historical architectural and urban heritage was conducted in the context of their interaction with the local population through the prism of cultural potential and emotional perception. Aspects of the use of these objects in everyday life, such as work, study, and leisure, were also taken into account. Given the importance of the development and management of urban spaces, the comparative approach was based on a comprehensive understanding of the problem of forming urban identity, taking into account the cultural and social significance of the living environment of society.

The research was conducted in three stages:

- The first stage, theoretical, was associated with defining the concepts and categories that describe the specifics of the self-expression of urban identity, the features of the formation of physical space, and the significance of material resources in promoting urban identity and the tourist potential of the city. This stage was implemented using the method of theoretical analysis, which is based on a systematic review and synthesis of existing scientific studies, theories, and concepts related to urban studies, sociology, cultural studies, and architecture. The methodology includes a comparative analysis of scientific literature, historical documents, and research, which allows identifying key factors and trends in the formation of urban identity and revealing their impact on the development of the urban environment.
- The second stage involved the selection of case studies and the identification of unique characteristics that define each. A comparative analysis of architectural and urban planning elements, identified as key in forming a sense of belonging to a particular settlement, was conducted. Historical, cultural, and social factors influencing the perception and significance of these objects within the context of the established urban environment were taken into account.
- The third stage aimed to determine the specific functions of the selected objects and to identify those aspects of the material and spatial environment that directly contribute to the formation of urban identity. This stage was achieved through content analysis. It allowed for the identification of key elements influencing the formation of urban identity and the evolution of urban form, including social, cultural, and economic factors that interact with these objects.

RESULTS AND DISCUSSION

The research begins by highlighting the pressing issue of the consequences of rapid urban development and the transformation of the urban environment. At the beginning of the 21st century, particular attention was drawn to the critique of urban sprawl (Brueckner, 2000). K. Nilsson *et al*. (2014) noted that since the mid-1950s, European cities have expanded on average by 78%, while the population has increased by only 33%. In 2017, the European Commission presented a report (European Environment Agency, 2017) that emphasised the unprecedented impact of urban sprawl on the environment.

At the beginning of the 21st century, the idea of urban densification, grounded in the concept of compactness, moved to the forefront of academic discourse as a logical solution to the problem of urban sprawl (Neuman, 2005). At its core, this idea involves leveraging the potential of existing urban areas to reduce the need for new resources (Pelczynski & Tomkowicz, 2019). Consequently, urban densification strategies began to be seen as a method that could contribute to sustainable development (Marique & Reiter, 2014).

Existing examples demonstrate that current urban development processes, when not integrated into the cultural context of cities, can lead to the loss of historical heritage, as outlined in the study of P. Kaur & H. Bhandari (2023). Conversely, international institutions emphasise the need to strengthen efforts for the protection and preservation of the world's cultural and natural heritage (United Nations, 2015). Questions regarding the impact on the visual integrity and aesthetic value of individual buildings (Alnsour *et al*., 2023) and historically formed urban structures (Chahardowli *et al*., 2020) have become increasingly pressing.

To influence crucial architectural and urban planning decisions and to gain the support of international organisations working to preserve historical environments and contextualise them within the framework of sustainable development, it is necessary to refine discourses on the role and significance of historical heritage in urban planning. G.J. Ashworth *et al*. (2007) emphasised that historical heritage should not be viewed solely as a city's calling card but should remain a key factor determining its potential for future development, including its economic dimension. Without exaggeration, business development and investment attractiveness have been and remain the driving force of urban development (Doel & Hubbard, 2002; Mahtta *et al*., 2022).

The problem of urban identity. R. Marmo *et al*. (2018), operating with the category of identity, emphasised that European society is closely linked to its architectural heritage, which is an indispensable resource for its inhabitants in terms of psychological, economic, and social well-being. The authors noted that the culture of collective heritage and the development of methods for its preservation evolved throughout the 19th century and was documented in the form of various reports and recommendations in the 20th century. By the late 20th and early 21st centuries, the problems arising from the rapid pace of urbanisation and industrialisation of society had become the basis for the creation of various documents aimed at preserving historical cities and urban areas. One such document was the ICOMOS Charter (1987). It emphasised the need to preserve and restore historically formed areas, as well as their development and harmonious adaptation to contemporary challenges.

In conclusion, the question of identity is one of the most contentious and ambiguous in contemporary academic and scientific discourse. For example, M.S. Merry (2010) focused on cultural, sociological, psychological, and historical aspects. Generally, in such cases, identity is viewed as a dynamic and multi-layered phenomenon shaped by numerous factors such as ethnicity, social connections, individual experiences, and historical contexts.

These issues remain particularly relevant in the context of globalisation and migration processes, which create new challenges for the preservation of cultural heritage and local identity, as highlighted in the articles of M. Castells (2000) and T. Bevz (2022). On the other hand, due to rapid globalisation, the concept of urban identity has become fragile and less popular. In this regard, A. Cheshmehzangi (2020) emphasises the importance of contextualising urban identity. The author proposes studying urban identity through the complex interplay of physical, cultural, and social attributes, focusing on how the perception of a specific place shapes the sense of identity within a particular spatial scale. At the same time, M. Ziyaee (2018) notes that the physical dimension is insufficient for assessing the quality of urban identity. It is also necessary to pay attention to non-physical aspects, which are determined at the level of the cultural landscape.

The physical dimension of urban identity. In today's world, travel plays a significant role in discovering new cultures and natural landscapes, and also contributes to a better understanding of different ways of life. Due to the high concentration of cultural heritage resources, city breaks have become particularly popular (Su *et al.*, 2018).

Meanwhile, there is a growing trend among consumers to seek out novel experiences, coupled with an increasing focus on the quality of these experiences from service providers (Richards, 2018). Destinations that capture public attention and allow visitors to identify with their location are becoming increasingly popular. The absence of interaction with key urban elements, such as historical landmarks, iconic architecture, or significant public spaces, significantly diminishes the overall visitor experience. This limits opportunities for a deeper understanding and appreciation of the urban environment, as visitors do not gain a full sense of its historical and cultural context. Consequently, insufficient integration of these elements into tourist itineraries and a lack of effective promotion can negatively impact the cultural experience and perception of the city as a whole.

Global experience convincingly demonstrates the existence of a significant number of architectural buildings, structures, and spatially defined objects. These reflect the uniqueness and embody the characteristic features of the established urban environment, actively contributing to the formation of urban identity. For example, the city of Palmanova (Italy), the urban planning ensembles of Bath (England), and the architectural objects of the Empire State Building in New York (USA). Under the right conditions, they have become key elements of interaction between tourists, investors, and the public at large. Such conditions include the integration of valuable objects into tourist routes and their support as cultural heritage sites, as well as effective use in urban development and promotional activities.

Successful city trips generate impressions in visitors. Under certain conditions, these impressions manifest themselves in cognitive perceptions, affective reactions, and evaluative judgments (Belanche *et al.*, 2017). The cognitive component is linked to the generalisation of knowledge and information. It includes ideas about the physical dimensions of the visited place, its overall structure, components, history, architecture, and infrastructure. The affective component encompasses emotions and feelings that people experience about a particular object. These can be positive or negative and convey feelings of pride, nostalgia, or even disappointment. The evaluative component refers to judgments and evaluations of a particular object. This may include personal assessments of the quality of life in a city, its convenience, attractiveness, or other aspects. Thus, the impressions formed during travel create a specific set of material and spiritual attributes that define the uniqueness of each individual city.

G.J. Ashworth (2009) proposes three categories to denote the uniqueness of a place: identity, image, and branding. Urban identity encompasses the characteristics and qualities that define a city's distinctiveness, the image includes the perceptions and associations people have of a city, and branding involves the strategic efforts aimed at shaping this perception and creating a positive and recognisable image. Each of these concepts plays a crucial role in understanding and justifying strategic approaches to the modernisation of the urban environment.

Recognising the role of urban identity, both places and people, has become a defining aspect of urban governance. The interaction between people and their urban environment is a complex and dynamic process. Studying this interaction provides valuable knowledge for effective management, creating harmonious, vibrant, and diverse cities (Mansour *et al.*, 2023a). Ultimately, urban planners and policymakers often use a clear understanding of a city's unique features and characteristics as a foundation for developing strategies that help preserve and enhance the urban environment. They consider urban identity when making decisions related to urban design, heritage conservation, urban regeneration projects, and policies aimed at preserving the city's image (Hudson *et al.*, 2019).

D.A. Bell & A. De-Shalit (2013) have argued, with specific examples, that each city has its own unique ethos. The authors emphasised that to understand and address contemporary challenges, philosophy and social science must once again turn to the spirit of cities, as was done in ancient times. They call on researchers and practitioners to seek inspiration from historical examples and adapt these ideas to modern conditions. The researchers supported their position with examples from the ancient world. For instance, Ancient Athens was a symbol of democracy, while Sparta was synonymous with military discipline and a rigid social structure. Similarly, many contemporary, especially European cities, are associated with important characteristics, based on prosperity, wellbeing, and sustainability. For example, London (England) is known for its high economic performance, Copenhagen (Denmark) – for its real-world implementation of energy-efficient initiatives and adherence to social equality, Vienna (Austria) – for its cultural diversity and high standard of living, and Frankfurt am

Main (Germany) – for its effective urban organisation and advanced technological progress.

Ultimately, the characteristics that reveal economic, environmental, social, and innovative aspects are not exhaustive. Other factors also enable the uniqueness of a city to be discerned. These include elements defined by the spatial organisation of its components, which fall within the realms of urban planning and city morphology. In morphological terms, a city can be considered from the perspective of its form, which is visually perceived and can be assessed through a plan or from the air. This understanding underlies morphological concepts that attempt to explain the specifics of a city's territorial growth (Spolaor & Oliveira, 2022), as well as the consequences of transformational processes in its functional, spatial, and structural composition (Musiaka *et al.*, 2020).

In this context, it is necessary to consider the complex nature of the structural organisation of urban reality for a deep understanding and detailed analysis of its various elements from the perspective of their physical characteristics. According to classical urban planning theory, a city consists of at least three hierarchical levels: the macro level, encompassing the city as a whole; the meso level, including fragments of the urban environment such as districts and zones; and the micro level, which encompasses individual buildings, squares, nodes, streets, or plots. All these objects can be attributes capable of articulating the identity of a specific place. Thus, urban identity can manifest itself at different levels (Cheshmehzangi, 2020) and be conceptualised depending on the scale: 1) as a separate structure or building; 2) as a territorial object within a specific settlement; 3) as a holistic urban formation. Each time, this modality is present in the material resources that fill the urban space and is present in textual, graphic, auditory, visual, and audiovisual forms.

The formation of urban identity at the micro level. Individual buildings and structures play a crucial role in shaping urban identity. They not only define the physical landscape of a city but also become its symbols and markers of cultural and historical significance. Serving as material embodiments of identity in the public consciousness, such objects often become synonymous with the city itself. In the context of the urban environment, the role of these buildings and structures extends beyond their aesthetic and symbolic value. They also act as benchmarks for architectural and urban planning innovations, setting standards for future developments. Embodying the technological, artistic, and cultural achievements of their time, these structures provide a foundation for understanding the city's development in a historical context. This, in turn, helps to preserve the continuity of the narrative of urban development, connecting past achievements with present ambitions. Furthermore, such objects influence the state of the surrounding environment. They serve as a focal point for social interaction, fostering a sense of shared identity.

For example, the Empire State Building is not merely an architectural icon in New York City (USA). It is a symbol of early 20th century technological advancement (Nye, 1996) and an efficient method of organising the construction process. Completed in 1931, this skyscraper was the world's tallest building for many years and eventually became a model of effective construction management and innovative engineering (Ghosh & Robson, 2015; Jacobsson & Wilson, 2018). Its construction, in particular, set a precedent for future high-rise buildings, and even in the 21st century, thanks to its elegant Art Deco architecture, it continues to influence global architecture and serve as a symbol of American might (Batchelor, n.d.) (Fig. 2).

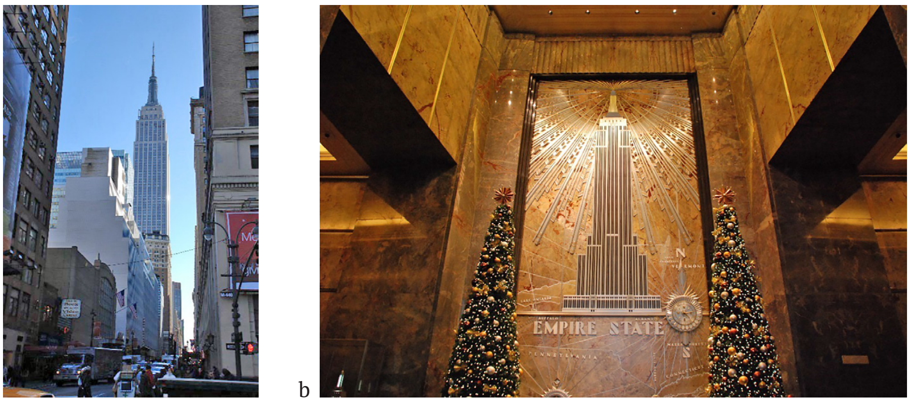

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Figure 2. Empire State Building (New York, USA) – a material embodiment of urban identity at the city micro level
Notes: a – street view; b – aluminium relief of the building in the Fifth Avenue lobby
Source: photo by Bohdan Cherkes

An interesting fact highlighting the uniqueness of the Empire State Building relates to its construction. Unlike many megaprojects that often exceed budgets and deadlines, the Empire State Building was completed not only within budget but also ahead of schedule (Jacobsson & Wilson, 2018). Its location within the urban structure is also significant (Moudry 2008). Situated at the geometric centre of Manhattan, the Empire State Building stands as a self-contained element, organically integrated into the city's planning structure and skyline (Fig. 3).

Figure 3. Empire State Building in the city structure
Source: photo by Bohdan Cherkes

The Lviv Theatre of Opera and Ballet is a striking example of a Ukrainian landmark that has remained one of Lviv's most distinguished buildings for over a century. Throughout this time, it has been a symbol of the city's cultural richness and a defining feature of its identity. From the beginning of its construction (1897), the theatre occupied a key position in the ensemble of the newly created city avenue and became the main visual focus of the grand promenade boulevard (Linda, 2008). In the 21st century, it serves not only as a venue for significant cultural events, from opera premieres to international festivals, but also remains an important organising element of the urban landscape. The theatre acts as a landmark on Liberty Avenue, anchoring the city's central street and forming a hub of social and cultural life (Fig. 4).

Figure 4. The Lviv Theatre of Opera and Ballet (Lviv, Ukraine) – a material embodiment of urban identity at the city micro level
Notes: the main facade of the building and the square with the fountain, where the crowd stands, is one of the most important and popular places for relaxation, tourist attractions, and photography for both locals and visitors
Source: photo by Bohdan Cherkes

In conclusion, the significance of individual buildings and structures in shaping urban identity cannot be overstated. The Empire State Building in New York and the Lviv Theatre of Opera and Ballet serve as both physical and symbolic markers of a city's urban structure, cultural values, and historical evolution. By defining the urban landscape and influencing social interaction, these architectural elements play a pivotal role in forming the unique identity of a city.

Formation of urban identity at the meso level. Urban identity, formed at the meso level, is a crucial aspect in determining a city's potential and development. At this level, individual neighbourhoods or districts within a city, which have strategic locations, distinct functional purposes, historical significance, or socio-cultural assets, contribute to the formation of urban identity. Additionally, specific neighbourhoods or microdistricts may possess unique characteristics that set them apart from other parts of the city. Often, such areas have a clear compositional structure and a distinctive geometric configuration. A notable example of such a territory with all of the aforementioned characteristics is the enclosed social housing complex in Augsburg – Fuggerei, founded in 1521. Since its inception, Fuggerei has functioned as a separate administrative unit with its own rules and traditions, providing affordable housing for residents with limited financial means (Giovanazzi, 2023).

Among the crucial components of a city's physical identity, historical districts play a significant role (Oktay & Bala, 2015). K. Kropf (1996) suggested that urban fabric is the most understandable element of a city's character. This characteristic possesses the ability to comprehensively express the most substantial and typical morphological features of a city's material structure at the meso and macro levels (Idak, 2020). The application of the concept of urban fabric became an important tool in urban planning in the mid-20th century. In contemporary conditions, urban fabric is used to differentiate between physically distinct territories (Marshall, 2011; Idak, 2020), assuming that the identification of different fabrics implies the identification of historically distinct territories. To preserve the identity of the city of Mery-la-Bataille (France), researcher B.N. Vis (2018) employed an approach based on mapping urban fabrics. The analysis of urban fabric allowed for the identification of key elements that define the character and uniqueness of individual districts, and based on this, strategies were developed for their preservation and integration into the overall structure of the city.

The interaction between physical elements, such as buildings and infrastructure, and socio-cultural processes occurring within a specific territory plays a key role in shaping urban identity at the meso level. This interconnectedness manifests in the creation of unique urban landscapes that reflect historical development, cultural traditions, and cater to the needs of the community. A striking example of urban identity formation at the meso level is the Circus in Bath (England). Bath's architectural landscape presents an intriguing blend of international influences, interpreted through the lens of British national identity in the 18th century and adapted to local conditions (Baigent, 2011). One of Bath's central places is the Circus, formerly the Royal Circus. The author intended to create a new, socially acceptable, and elegant place to live (Kilby, 2019). The Circus is an example of a harmonious blend of historical context with innovative urban planning solutions that were unusual for the 18th century. Despite the popular belief that the image of the square was taken from the Roman Colosseum, new research suggests that the author, John Wood the Elder, drew inspiration from Stonehenge (England), which he was studying at the time (Conway & Roenisch, 2004). The size of the square and the height of the surrounding buildings create a sense of isolation. When a visitor leaves this area, they are presented with new views of the city, creating a sense of unexpected discovery (Hammond, 2016). In the 21st century, the Circus remains a unique place that shapes a sense of identity with the city of Bath. This sense has two components: on the one hand, it is the legacy of past generations, and on the other, it is a dialogue with the environment, filled with unexpected interpretations of the historical and contemporary, the natural and artificial, the logical and the chaotic (Fig. 5).

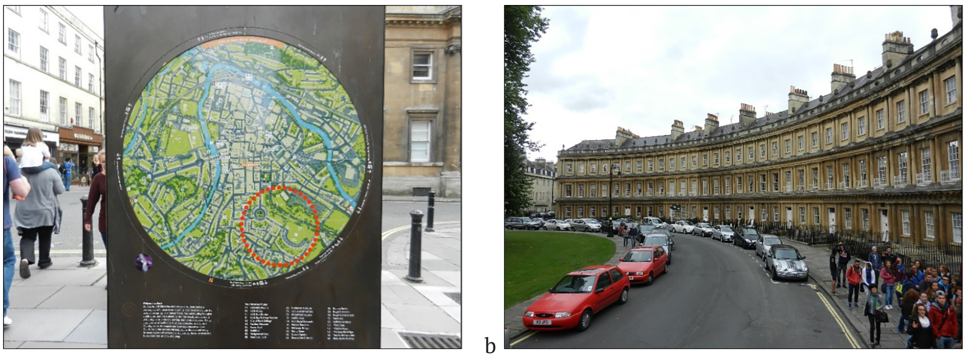

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Figure 5. Circus (Bath, England) – a material embodiment of urban identity at the city micro level
Notes: a – tourist map of the city with the circus highlighted; b – residential buildings surrounding the square
Source: photo by Bohdan Cherkes

Ukrainian cities also offer numerous examples of places that preserve their unique character and serve as symbols of urban identity at the meso level. From ancient architectural ensembles to contemporary urban spaces, these places not only recreate the memory of the past but also integrate it into contemporary life, creating a unique atmosphere and sense of belonging. Examples of such combinations include avenues, promenades, embankments, squares, quarters, and other structural elements of cities. A significant place in Ivano-Frankivsk is Stometrivka, which, along with Rynok Square, is the epicentre of the city's cultural, economic, and business life. The name Stometrivka is conditional and has nothing to do with a quantitative measure of 100 meters. In fact, it is a wide pedestrian street over 500 meters long and formally marks the beginning of the city's main street – Independence Street (Fig. 6).

Figure 6. Stometrivka (Ivano-Frankivsk, Ukraine) – a material embodiment of urban identity at the city micro level
Notes: general view of the street; on the right is Heroes Alley, and in the centre is Viche Maidan, a key site for leisure, tourist, and cultural attractions within the city
Source: photo by Volodymyr Idak

Since its establishment in the 1980s, this stretch of just under 500 meters has functioned as a multifunctional public space, serving as a promenade on weekdays and evenings, and transforming into a venue for active arts and entertainment events on weekends and holidays, including street performances, festivals, exhibitions, and other cultural events that attracted both local residents and visitors. In autumn 2022, Heroes' Alley was established on Stometrivka (Rudenko, 2024). In 2024, it remains a place of societal consolidation, where two contradictory realities intertwine: the first reflects the severe consequences of war, and the second represents a social activism that is entirely opposed to the first. Therefore, the material embodiment of urban identity, formed at the meso level, plays a crucial role in responding to contemporary challenges, preserving cultural heritage, supporting social cohesion, and developing the city's economy. It also contributes to maintaining the attractiveness and multifunctionality of individual parts of the urban space, making them important elements of the city as a whole.

Formation of urban identity at the macro level. The macro level represents a global perspective on the city, encompassing a comprehensive aspect of urban identity. While the details of the urban space may not be emphasised at this level, the social component remains significant (Cheshmehzangi, 2020). In this sense, the attributes necessary for a city's self-differentiation are symbolised at an abstract level through unique characteristics. Such uniqueness is determined not only by physical components such as buildings, geographical features, rivers, and lakes, but also through cultural events, such as fairs, exhibitions, or other entities (Manahasa & Manahasa, 2020).

In shaping urban identity, where the city as a whole plays a central role, its authenticity is of paramount importance (Nursanty *et al.*, 2023). This characteristic can be defined as key, especially when residents and visitors are confident in its genuineness and originality. This contributes to the formation of a positive city image, increasing its attractiveness to tourists and strengthening local pride among residents. Such an awareness of authenticity helps the city to preserve its individuality and remain unique even in the context of a globalised world.

A prime example of such an approach is the city of Palmanova (Italy). Palmanova preserves a significant architectural and urban heritage and is considered one of the most striking examples of well-preserved and planned ideal cities of the Renaissance. Its unique layout, including a perfectly symmetrical appearance with a radial street organisation and fortified fortification, reflects an innovative approach to urban planning at that time (UNESCO, 2017). Designed and built by a team of engineers, scientists, and military architecture experts, including Giulio Savorgnan (1510-1595) and Vincenzo Scamozzi (1548-1616), it was an "invisible" fortress city, built along the horizon to conceal it from enemy eyes. Thus, its buildings had to be low, and the walls had to be covered with earth and vegetation (Gatti *et al.*, 2017). This makes Palmanova an important element of the world's cultural and historical heritage.

In the 21st century, the inhabitants of Palmanova (Italy) are acutely aware of their city's value and take pride in its unique historical and architectural heritage. They feel a connection to its past, as many important historical sites have been preserved, despite the decline of some (Gatti *et al.*, 2017). At the same time, their sense of belonging to the city is shaped by its distinctive geometric form and layout, which has remained unchanged since its foundation. Architectural features such as the nine-sided shape of the fortress and the three entrances leading to the central square have become symbols of the city, reinforcing the sense of local identity (Fig. 7).

Figure 7. Palmanova (Italy) – a material embodiment of urban identity at the city meso level
Notes: a – tourist map of the city, engraved on a metal surface; b – a night-time view of the street emphasising the atmosphere and character of the historically formed urban environment. Sculptures placed at the beginning of each of the six streets that radiate evenly from the central square are a characteristic feature of all six streets and are an element of the recognisability of the architectural ensemble; c – a view of the central church – Chiesa del Santissimo Redentore; d – a place for religious ceremonies in Chiesa del Santissimo Redentore, decorated with a symbolic depiction of the city panorama, which emphasises its cultural and historical significance
Source: photo by Bohdan Cherkes

Ukrainian cities also demonstrate significant potential in preserving and popularising their historical and architectural heritage, which have survived in the context of the entire city. A striking example is the city of Zhovkva (Lviv region, Ukraine) with its rich historical heritage. This city is not only a living witness to history but is also actively developing as a centre of cultural tourism (Zhovkva tourist information..., n.d.). Zhovkva was founded as a private town, so it was the owners who decisively influenced the development of this settlement – its planning and organisation of urban space, and the composition of the city government (Kapral, 2016). The functional-planning structure of the city was developed according to the model of the Renaissance ideal city (Fig. 8). The city consisted of two interconnected parts: the owner's castle complex and the fortified city centre. This combination had a specific and strategic character, which emphasised the hierarchical structure of the urban space and ensured effective control and protection against potential threats (Bevz, 2019).

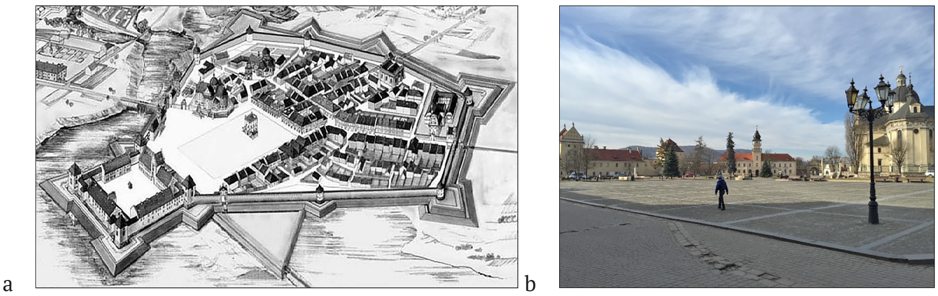

Figure 8. Zhovkva of the Lviv region – a material embodiment of urban identity at the city macro level
Notes: a – general view of the city, 17^{th}-18^{th} centuries; b – the central square of the city
Source: a – V. Tymofiyenko (2003); b – photo by Bohdan Cherkes

In 2024, Zhovkva remains a significant cultural and historical centre, uniting numerous monuments from various eras (Fig. 9). Their concentration in a relatively small area conveys the atmosphere of an ancient city, and their compositional order is evidence of the existence of stable architectural and urban planning traditions over several centuries. Among the important landmarks are medieval fortifications, a Renaissance square, Baroque churches and monasteries, as well as preserved sections of the city walls and gates. Each of these monuments reflects the city's multi-layered history, giving Zhovkva a special character and attracting tourists from all over the world.

Figure 9. Zhovkva of the Lviv region – a panorama of the square with significant city landmarks
Source: photo by Bohdan Cherkes

Therefore, the macro level of urban identity is critically important for understanding how historical events, cultural traditions, and socio-economic transformations influence the character of a city and its uniqueness. Proper popularisation and strategic management of historical and cultural assets can help historically formed cities preserve their individuality even within the framework of globalisation and urban trends.

CONCLUSIONS

Architectural and urban planning heritage serves as a foundation for creating an attractive urban environment that attracts tourists, investors, and is valued by local residents. Preserving and integrating historical heritage into a contemporary context allows the city not only to maintain its uniqueness but also to use it as a valuable resource for economic growth, cultural enrichment, and social cohesion among local residents. Moreover, awareness and appreciation of the city's heritage contribute to strengthening the local community and shaping its identity.

In the 21st century, there is a growing trend where urban identity is becoming a defining factor in making important strategic decisions within the purview of architects and urban planners. This gives rise to the need to view cities and their inhabitants as a reflection of the interconnectedness of their physical form and spiritual essence. Conversely, understanding this interconnectedness can reveal the unique characteristics of urban formations or highlight specific features inherent to each particular place. The buildings and structures that fill such places act as a kind of visualiser. It is capable of reflecting the physical essence and indicating the ideas and values that have accompanied the history of a particular place for a long time. The concept of the physical dimension used in this research refers to the direct perception of the physical properties of architectural buildings and structures or their groups, located in a well-defined territory. Due to their diversity and complexity, various logical schemes are used in the theory of architecture and urban planning. In this study, the concept of distinguishing three hierarchical levels of organisation of architectural and urban objects is used. This approach is effective for analysing urban development and in the question of the specifics of urban identity formation.

This research draws parallels between iconic landmarks on a global scale, such as the city of Palmanova (Italy), the architectural and urban planning ensemble of the Circus (Bath, England) and the Empire State Building (New York, USA), and their counterparts in Ukraine: the city of Zhovkva, the architectural and urban planning ensemble Stometrivka (Ivano-Frankivsk) and the Lviv Theatre of Opera and Ballet (Lviv). These objects serve as symbols of unique historical and cultural narratives. This highlights the importance of such objects in the context of urban identity and their influence on the perception of the city as a whole.

This study highlights the lack of attention to issues related to the peculiarities of forming urban identity and its impact on decision-making in the field of architecture and urban planning. The authors aim to continue research in this direction, focusing on studying specific examples of cities, analysing their historical and contemporary characteristics, and developing recommendations for the effective integration of heritage into urban development strategies.

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CONFLICT OF INTEREST

None.

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Архітектурно-містобудівний контекст фізичного виміру міської ідентичностів

Анотація. В сучасних умовах міська ідентичність є важливим аспектом розвитку міст. Переконливим є її вплив під час прийняття рішень щодо збереження культурної спадщини, зміцнення соціальної згуртованості та стимулювання економічного розвитку. Для цієї тріади архітектурно-містобудівне проектування є основою формування та відображення унікального характеру і цінності міста. Метою дослідження був аналіз архітектурних та містобудівних детермінант як ключових багатовимірних компонентів у формуванні та підтримці міської ідентичності. Застосовуючи порівняльний підхід, виявлено конкретні форми матеріального вираження міського середовища, які сприяють відчуттю ідентичності та приналежності серед його мешканців і відвідувачів. Проведено порівняльний аналіз аналогічних об'єктів світового та українського масштабу: міста Пальманова (Італія) та Жовква (Україна); архітектурно-містобудівні ансамблі – Батський цирк (Бат, Англія) та Стометрівка (Івано-Франківськ, Україна), Емпайр-Стейт-Білдінг (Нью-Йорк, США) і Львівська Національна Опера (Львів, Україна). Виявлено, що вивчення міської ідентичності зосереджене на комплексному розумінні проблеми ідентифікації людини із місцем свого проживання. Через це аргументи збереження пам'ятних місць у сформованому міському середовищі є недостатніми та потребують конкретизації на рівні його фізичних проявів. Запропоновано виділяти архітектурно-містобудівний контекст та розглядати його відповідно до трьох загальноприйнятих рівнів організації міста. Фізичні компоненти міського середовища, такі як будівлі та споруди, архітектурні комплекси та ансамблі, вулиці та площі, а також територія міста загалом здатні бути головними дійовими елементами і рівнозначно брати участь у формуванні міської ідентичності. Є випадки, коли розуміння міста як єдиного цілого має значно вищий потенціал порівняно з ситуацією, коли його складові розглядаються окремо і навпаки. Здатність окремих елементів поєднувати історичні та сучасні аспекти в єдиній міській структурі підвищує загальну привабливість і функціональність міських територій, а також сприяє зміцненню соціально і культурно згуртованого середовища. Результати дослідження можуть сприяти ефективнішому плануванню і впровадженню стратегій розвитку міст, що потенційно допоможе зберегти унікальність кожного та покращити якість життя їхніх мешканців

Ключові слова: міське середовище; фізичні характеристики; теорія містобудування; приналежність; унікальність

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Modern principles of the formation of facilities for the production of crop products

Abstract. The relevance of this study is manifested in the need to adapt architectural solutions to changing climatic conditions and anthropogenic factors. The purpose of the study was to examine modern principles in the formation of structures for the production of crop products and identify critical aspects that are crucial for optimising this process. Methods of analysis, synthesis, deduction, and induction were used to achieve this goal. The findings indicate that architectural solutions must be adapted to varying climatic conditions in order to optimise plant growth. This necessitates adjustments to temperature control, lighting, and water management systems. Specific architectural examples, including the Urban Vertical Farm of Brightfood in Shanghai and Vertical Farm Beijing, are presented as case studies to demonstrate these principles. The Urban Vertical Farm incorporates terraces with edible plants, advanced hydroponic systems, and transparent materials that maximise sunlight. Similarly, Vertical Farm Beijing integrates a closed-loop water system and efficient LED lighting to minimise energy and water consumption, thereby promoting urban food security. These examples illustrate the importance of adapting architectural designs to environmental and urban constraints. The study provided an opportunity to understand the importance of architectural and engineering solutions in crop production, which can lead to the development of more efficient and sustainable plant-growing systems, which in turn can increase the productivity and quality of agricultural products

Keywords: yield optimisation; natural-climatic factors; innovative agrotechnologies; structures; cultivation systems

INTRODUCTION

Crop production facilities, such as greenhouses, play an essential role in ensuring food security and growing plants in various climatic conditions. These unique facilities create optimal conditions for plant production, which allows increasing yields and diversifying the range of products on the market. One of the critical advantages of greenhouses is the ability to control temperature, humidity, and indoor lighting. This is especially important in regions with cold winters or extreme climatic conditions where traditional field farming is limited. Such structures protect plants from adverse weather conditions and also help to extend the growing season, which allows crops to be grown year-round. The problem of the study is the need to adapt facilities for producing crop products to changing climatic

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conditions, resource instability, and urbanisation. Existing approaches to architectural solutions for crop production facilities are often insufficiently effective and do not always consider all aspects that affect the productivity and sustainability of crop production.

In the most recent publication by B.E. Singleton (2023), he addresses challenges in urban planning that are analogous to those encountered in agricultural policy, particularly the inadequate budgetary allocation for social spending, the geographical remoteness of agricultural regions from major markets, and the insufficient infrastructure for rural self-governance. The author emphasises the necessity for more robust governmental interventions to support these rural areas.

Z. Haghighi *et al*. (2021) examine the discrepancy between the financial resources required for rural development and the actual levels of funding available. They identify key challenges, such as the demand for comprehensive services in rural populations and the territorial access to vital services. This discrepancy between the elevated costs for agricultural producers and the necessity for social adaptation serves to illustrate the precarious state of food security. The authors also posit that the enhancement of rural infrastructure, including the establishment of specialised facilities for plant cultivation, is a crucial step in addressing these disparities and fostering agricultural growth.

W. Yang *et al*. (2024) investigate the role of innovation in agriculture, emphasising the significance of modern infrastructure that facilitates advanced technological developments. The authors put forth a series of pivotal strategies for fostering innovation, including the establishment of dedicated scientific and technological hubs, technoparks, and the implementation of incentives for investors. The authors posit that this approach could also be applied to the design and construction of controlled-environment buildings for plant production. Widespread innovation adoption would enable medium-sized agricultural enterprises to access cutting-edge equipment, expand operations, and modernise the agro-industrial complex, thereby enhancing sustainable development in the sector (Radchenko *et al*., 2023).

A. Amirbekova *et al*. (2023) place considerable emphasis on the importance of sustainable design in the context of residential and agricultural structures. The study demonstrates that architectural adaptations to environmental factors, particularly in the design of greenhouses and other plant-growing structures, can significantly enhance agricultural productivity. The research highlights the vital importance of sustainable development principles in the creation of resilient facilities that can withstand climate and resource challenges, thereby enhancing both the efficiency and resilience of agricultural systems.

M. Guth *et al*. (2020) concentrate on the part played by architectural design and spatial planning in promoting the economic sustainability of agricultural enterprises within the context of the European Union's Common Agricultural Policy. It is emphasised that architectural strategies integrated within CAP guidelines play a pivotal role in enhancing the resilience and adaptability of rural infrastructure. The adoption of analogous architectural and planning methodologies in Kazakhstan could serve to reinforce the structural integrity of its agricultural facilities, enhance resource efficiency, and facilitate the modernisation of rural areas. This would, in turn, reinforce productivity and competitiveness in the agricultural sector.

M. Hassan & H.H. Silleli (2024) believe that the designs of modern cultivation facilities should provide the necessary biological conditions for growing plants, contributing to the production of a large volume of products through the possibility of organising a mechanised labour process and meeting all operational requirements. The modern technologies listed in the authors' study complement each other and allow approaching such an ideal scheme in which the agricultural complex will become environmentally friendly, waste-free, and economically very profitable.

According to A. Askarova *et al*. (2020), the organisation of agricultural lands and their arrangement, considering their regional natural-climatic features, is of the greatest importance in the modern conditions of Kazakhstan. The authors believe that the organisation of crop rotations and the design of the main elements of their arrangement are especially relevant since the arrangement of the arable land is the territorial basis for introducing modern soil and water protection technologies. The orderly use of pastures to prevent their degradation is of great importance, therefore, the methodology of organising pasture rotations and their arrangement was considered.

The main purpose of the study was to examine modern methods of forming plant structures and develop them.

MATERIALS AND METHODS

The study is based on a comprehensive analysis of existing architectural solutions and methods of growing plants, as well as an examination of current trends in agriculture and architecture. A review of the literature, including academic papers, as well as architecture publication ArchDaily (Stouhi, 2021; Tovar, 2024), was undertaken to identify effective contemporary methods and architectural solutions in crop production. In order to situate this study within a practical context, two prominent architectural examples were examined: the Urban Vertical Farm of Brightfood and Vertical Farm Beijing. Both facilities exemplify innovative design that integrates environmental considerations with urban food production needs, demonstrating sustainable architectural approaches in high-density urban areas.

In this study, an analytical method was employed to systematically examine the interrelationship between natural climatic factors and the architectural solutions utilised in crop production facilities. Furthermore, the analysis method was employed to ascertain the interrelationship between internal factors, such as the types of plants cultivated and the methods of cultivation, and the architectural design of crop production facilities. The analysis method was employed to ascertain how architectural solutions might be adapted to accommodate these factors, taking into account the impact of urbanisation, environmental pollution, and resource availability.

An analysis of parameters such as temperature, precipitation, humidity, solar radiation, and wind conditions in the region under study was conducted to determine the impact of climatic factors on architectural solutions. An analysis was conducted to assess the impact of temperature changes, which allowed determining the need to adapt heating and air conditioning systems in crop production facilities. The study included an analysis of the amount and distribution of precipitation affecting water supply and drainage in crop production facilities. Architectural solutions that allow controlling humidity inside structures to ensure optimal conditions for plant growth and development were analysed. Methods for optimising the availability of sunlight, such as the use of transparent materials and orientation systems, were considered to ensure optimal conditions inside the structures.

In this study, the synthesis method was used to integrate various aspects and components related to the architectural design of structures for crop production to create a comprehensive and integrated methodology. As a result of the synthesis of climate data, engineering solutions aimed at solving problems related to climatic conditions were developed. The synthesis of all the data led to the creation of an integrated approach to the architectural design of structures for crop production. This synthesis method contributes to developing effective architectural solutions that optimally match climatic conditions and ensure sustainable and effective crop production in various regions.

The method of deduction was also used in the study; principles and theories were initially generalised, after which specific conclusions were derived from them. Initially, the general statement about the importance of architectural solutions in crop production was considered, and then this statement was deductively applied to the analysis of specific aspects, such as the influence of climatic factors, internal factors, and anthropogenic influences on the architecture of structures.

The induction method was used to identify general patterns and conclusions based on specific observations and data. The study analysed specific factors such as climatic conditions, internal factors, and anthropogenic influences and then inductively drew general conclusions about the importance of architectural solutions for optimising crop production facilities.

RESULTS

Architectural solutions of crop production facilities are crucial for the successful cultivation of plants, especially in a changing climate. Climatic factors such as temperature, precipitation, humidity, solar radiation, and wind conditions play a critical role in determining the efficiency and productivity of such structures (Muzdybayeva *et al.*, 2022).

The temperature conditions in the region have an important impact on the architectural solutions of crop production facilities. Temperature changes may require the adaptation of heating and air conditioning systems in greenhouses and the selection of plants resistant to specific temperature conditions. The amount and distribution of precipitation affect water supply and drainage in crop production facilities. Consideration of the type and intensity of precipitation is essential to determine the need for water supply management systems such as rain collectors and artificial irrigation systems. Air and soil humidity play a crucial role in plant health. Architectural solutions should consider humidity control inside structures to ensure optimal conditions for plant growth and development (McClements & Grossmann, 2021). The intensity and duration of sunlight during the day affect photosynthesis and plant growth. It is essential that architectural solutions are designed in a way that enhances sunlight availability within crop production facilities, thereby ensuring optimal conditions for plant growth. This can be achieved through the judicious selection and placement of transparent materials, such as double-glazed glass, which provide thermal insulation while allowing maximum light penetration. The orientation of the structure should be designed in a manner that captures the highest amount of natural sunlight, taking into account the geographic location of the building. This can be achieved through the strategic angling of facades to maximise exposure during peak daylight hours. Furthermore, the utilisation of diverse glass types, such as low-emissivity glass, can be implemented in specific areas to regulate heat gain without impairing light transmission, thus maintaining an optimal indoor environment for plant growth across varying seasons and conditions.

The choice of materials for the construction of crop production facilities may depend on climatic conditions. For example, in cold regions, thermal insulation materials (e.g., polyurethane foam, mineral wool) may be necessary, and in hot regions – materials that protect from solar radiation (e.g., reflective coatings, UV-resistant glass) (Zhangabay *et al.*, 2023). In regions with cold winters or hot summers, heating and air conditioning systems may be necessary to maintain optimal temperatures inside structures (Kaletnik *et al.*, 2020). Water collection and distribution systems can regulate the availability of moisture to plants, especially in regions with limited rainfall. Artificial lighting can be used to compensate for the lack of sunlight, especially during periods of insufficient insolation. Architectural elements such as wind walls or barriers can be used to protect plants from strong winds. Climate change creates new challenges for crop production facilities. Extreme weather conditions, higher temperatures, and unstable precipitation may require more advanced architectural solutions. Effective management of climatic factors is becoming a key aspect of successful agriculture and crop production.

It is important to understand that internal factors such as the type of plants grown, care methods, production goals, resource availability, and technical capabilities substantially affect the form and function of these structures. Different types of plants have different requirements for the height of the premises. Tall plants, such as some tree species, may require tall greenhouses or other structures with a large volume for vertical growth. Growing field crops such as grains and vegetables may require flat or low structures to ensure maximum lighting and access to the soil. The use of hydroponic systems and vertical farming provides opportunities to optimise the use of space and may require specific architectural solutions, such as vertical cultivation systems. The use of artificial lighting to support plant growth may require special overhead lighting systems and optimal placement of light sources. Heating, air conditioning, and humidification systems may require certain architectural solutions to distribute heat and moisture evenly. Irrigation and water supply management systems should be integrated into the architecture of the structure to ensure efficient water consumption. Architectural solutions for commercial plant production can include maximising productivity and space efficiency. Facilities for scientific research of plants should be designed to provide controlled conditions and accurate measurements. In educational institutions, architectural solutions may include educational elements that allow students to study the processes of growing plants.

The implementation of innovative architectural designs in the construction of crop production facilities exemplifies the feasibility of integrating sustainable design principles with the practical aspects of food production in urban settings. The global array of vertical farming structures exemplifies the efficacy of integrating architectural and environmental solutions to address the challenges posed by urban density, resource limitations, and climate conditions. Two noteworthy projects serve to exemplify these principles in practice: the Urban Vertical Farm of Brightfood in Shanghai, China, and Vertical Farm Beijing, situated in the heart of the Chinese capital (Shao *et al.*, 2021).

The Urban Vertical Farm of Brightfood, designed by Stefano Boeri and situated in Shanghai, China, represents a significant urban agriculture initiative that integrates food production with urban spaces, with the objective of addressing the challenges inherent to urbanisation (Fig. 1). The structure, which covers approximately 110,000 square meters, embodies the concept of a "vertical forest", with terraces and balconies planted with fruits and vegetables. This enhances biodiversity and creates visual appeal in the cityscape. The 12 terraced greenhouses, constructed from ETFE film, a lightweight and recyclable material, are orientated to maximise sunlight exposure for optimal plant growth within the urban environment. The integration of greenhouses with office spaces engenders a distinctive synergy between work and agriculture, enabling employees to engage directly in the farming process and develop a stronger connection to food sources.

Figure 1. Urban Vertical Farm of Brightfood

Source: D. Stouhi (2021)

Furthermore, the Urban Vertical Farm of Brightfood exemplifies notable environmental benefits. The implementation of advanced hydroponic systems within the farm has the potential to reduce water usage by up to 90% in comparison to conventional agricultural practices. Furthermore, by situating the food production process within the city limits, this project serves to enhance local food security while simultaneously reducing the carbon footprint associated with long-distance food transport. As a pioneering urban agriculture initiative, the Urban Vertical Farm of Brightfood serves as a model for sustainable practices in both urban planning and food production. It responds effectively to the challenges of urban density while promoting ecological resilience.

The Vertical Farm Beijing, situated on the campus of the Chinese Academy of Agricultural Sciences (CAAS) in central Beijing, is an urban agricultural project designed by Van Bergen Kolpa Architects in collaboration with AgriGarden and CAAS (Fig. 2). The facility, which spans 3,500 square meters, serves as both an educational and a production centre for urban horticulture. The architectural design incorporates a faceted glass façade, which serves to create a distinctive visual presence within the urban environment. This facade allows natural light to permeate the interior while also offering views of the cultivation areas. The facility is organised around a central atrium, with three floors dedicated to the cultivation of different crops. The first two floors utilise purple LED lighting for the cultivation of fruits, berries and leafy vegetables, while the third floor relies on natural daylight for the growth of tomatoes and cucumbers. An educational route within the building provides an insight into the diverse cultivation methods employed, including automated vertical lettuce systems and open-ground fruit trees. This allows visitors to observe innovative agricultural practices in action (Xu, 2024).

Figure 2. Vertical Farm Beijing

Source: E. Tovar (2024)

Sustainability is a fundamental aspect of the Vertical Farm Beijing project. The facility utilises a closed-loop water system, whereby irrigation water is recycled and reused, thereby reducing the generation of waste. The climate control system is managed through the use of natural ventilation and evaporative cooling, with passive heat extraction from sunlight and residual heat from LED lighting employed to regulate temperature. Furthermore, the building exemplifies resource efficiency through the capture of nutrients from sewage and carbon dioxide from the atmosphere, thereby promoting a circular economy approach to urban agriculture. Vertical Farm Beijing represents a significant advancement in sustainable urban food production, demonstrating how cities can integrate food production within urban landscapes to meet local demands and address ecological challenges.

The available budget may limit the choice of materials and technical solutions when designing crop production facilities. The qualifications of staff and their knowledge in the field of plant cultivation can influence architectural decisions, as complex systems may require more advanced knowledge and skills. Local anthropogenic factors, including urban development, air pollution, changes in land use, and resource availability, can affect the architecture and functionality of crop production facilities. Air pollution from emissions and transport may require special filtration and ventilation systems to ensure clean air inside structures. The availability of high-quality water for irrigation and hydroponic systems is a key aspect of the design of crop production facilities, especially in polluted water conditions. Climate change may require updating architectural solutions to adapt to new temperature conditions, precipitation levels, and extreme weather events. Crop production facilities may require additional safety measures, such as protection from hurricanes, floods, and other natural disasters (Xu *et al.*, 2022).

Solving the problem of air pollution and providing quality water for crop production facilities may include the following steps. Development and implementation of highly efficient filtration and ventilation systems for structures to minimise the impact of emissions and transport pollution. This may include the use of innovative air filtration technologies and low-emission ventilation systems. Implementation of water purification systems to ensure the availability of high-quality water for irrigation and hydroponic systems. Using advanced water purification and recycling technologies can mitigate the problems associated with contaminated water (Dovgal *et al.*, 2024). Updating architectural solutions of crop production facilities considering climate changes. This may include the development of buildings with more efficient thermoregulation adapted to new temperature conditions and extreme weather events. The introduction of additional security measures, such as protective systems against hurricanes, floods, and other natural disasters. The development and implementation of infrastructure capable of coping with extreme environmental conditions can reduce the risks to crop production facilities. Energy supply for heating, air conditioning, and lighting systems may require effective solutions to reduce costs and environmental impacts. The treatment and disposal of waste from crop production facilities is becoming an important aspect of sustainable agricultural production. Protected soil crop production enterprises are essential in providing food in a changing climate and urbanisation (Ozpinar, 2023). They are modern agrotechnical systems, including greenhouses, where plants are grown under controlled conditions.

Agriculture and crop production play an important role in ensuring food security and meeting the needs of the population. Modern architectural and design solutions that consider the features of crop production facilities are needed for the efficient production of crops. This study considers the modern principles of the formation of structures for the production of crop products and the features of architectural and constructive solutions that correspond to them (Weingaertner & Moberg, 2014). Various types of structures are used for growing crops, including greenhouses and warehouses for storing crops and machinery. Each of them requires specific architectural and design solutions (Table 1).

Table 1. Types of structures and their architectural-design features

Type of system	Semi-closed	Closed	Closed
Irrigation system	Land irrigation	Hydroponics	Hydroponics
Light source	Natural and artificial light	Artificial light	Artificial light
Spatial distribution	Horizontal	Horizontal and vertical	Vertical
Climate management	Ventilation and heating	Automated climate control	Automated climate control
Energy costs	Medium	High	High
Water use efficiency	Medium	High	High
Efficiency	Medium	High	High
Spatial efficiency	Medium	High	Very high
The complexity of the service	Medium	High	High

Source: compiled by the authors

Modern requirements for sustainability and energy efficiency have an impact on architectural and structural solutions in crop production facilities. For example, the use of insulation materials and specialised materials to reduce energy consumption and create more stable climatic conditions; the use of solar panels and other alternative energy sources to reduce dependence on conventional energy sources; the use of water treatment and recycling systems to reduce water consumption and negative environmental impacts. Modern crop production facilities also include automated control systems that help optimise production processes and control the conditions for plant growth. The use of monitoring and control systems for temperature, humidity, lighting, and other parameters. Automatic irrigation, fertilisation, and cleaning systems are used. Integration of management systems into digital platforms for data monitoring and analysis for more effective decision-making. An important aspect of achieving efficiency and sustainability in crop production is the development of modern architectural-structural solutions that consider the engineering infrastructure and its impact on the spatial planning solutions of the main buildings.

The choice of location for agricultural facilities and crop production enterprises depends on the availability of engineering infrastructure such as water, electricity, and sewerage systems. This affects spatial planning solutions, as the availability of communications and resources determines the possibilities for expansion and development of production. Engineering water supply and irrigation infrastructure is crucial for successful crop production. Modern architectural and design solutions include systems for collecting, storing and distributing water and innovative irrigation methods such as drip irrigation, which efficiently use water resources and provide plants with water in exact quantities (Bacon *et al.*, 2012). The engineering infrastructure includes energy supply and energy management systems. Modern crop production facilities actively use alternative energy sources such as solar panels and wind turbines to reduce dependence on conventional sources and the environmental footprint. The engineering infrastructure includes air quality control systems, critically important for preventing plant diseases and ensuring high yields. Filtration and ventilation systems provide optimal conditions for plant growth and reduce the risk of infections. The engineering infrastructure also includes digital technologies and automation systems that allow monitoring, managing production, and resource optimisation. This affects spatial planning solutions, as modern structures must be ready for integration with digital systems.

Urban planning placement of crop production facilities in the structure of a settlement poses a number of tasks related to the optimal use of land resources, considering the needs of the population and ensuring environmental sustainability. The basic principle of urban planning of plant-growing enterprises is to consider the needs of the population in terms of products and their accessibility. The location of crop production enterprises is close to populated areas can substantially reduce transportation costs and increase the availability of fresh products (Xue *et al.*, 2024). It also contributes to the development of the local economy and job creation. Urban planning of crop production facilities near settlements has the advantage of minimising transportation costs. This is important to reduce CO_2 emissions and environmental impacts, save resources, and reduce product costs. When placing crop production enterprises in the structure of settlements, it is important to consider the principles of sustainable development and environmental protection. The use of modern technologies and methods, such as green roofs, wastewater treatment, and reduction of soil pollution, helps to reduce the negative impact on nature and neighbouring settlements (Czyżewski *et al.*, 2019).

The climatic and natural conditions of a particular region should be considered in the formation of the structure. This includes determining optimal planting seasons, microclimatic features, and landscape features. For example, greenhouse complexes can be located in such a way as to maximise the use of solar energy in the region. Rational master plans should ensure the maximum use of land resources. This includes choosing the optimal locations for planting areas, minimising crop losses, and maximising yields per unit area. The preparation of master plans also includes the structuring of production processes. For example, observing crop rotation and planning places for storing crops and equipment. Optimisation of transport routes and logistics is also an important aspect. Rational master plans should include consideration of modern technologies and innovations. This includes using automation, digital technologies, and control and monitoring systems to optimise production processes and increase efficiency.

The examination of architectural solutions in crop production and their adaptation to climatic conditions is of great importance, especially in light of climate change. The approach to designing buildings for crop production should consider factors such as temperature, humidity, and lighting to ensure optimal conditions for plant growth and yield. An analysis of the influence of these climatic factors on the architectural parameters of structures was conducted, and a new design methodology is proposed. High temperatures may require cooling, ventilation, and thermal insulation systems inside greenhouses or other crop production facilities. Cold climates require effective insulation, heat pumps, and air heating (Mysak *et al.*, 2016). Humidity control inside structures plays an important role in preventing plant diseases and creating optimal conditions for their growth. Humidification and drainage systems may be necessary to regulate humidity inside structures. Depending on the climate and time of year, artificial lighting may be required to ensure the necessary daylight hours for plants. Architectural solutions should consider the placement of windows and transparent walls and the possibility of using LED lighting. A new design methodology that considers climatic factors may include the following elements:

1. Integrated climate control systems: automatic temperature, humidity, and lighting control systems can be configured to optimise growth conditions in real-time, depending on climate data.

2. Effective insulation and ventilation: using modern insulation and ventilation materials can help maintain stable conditions inside the structure.

3. Renewable energy use: the integration of solar panels and other renewable energy sources can reduce energy costs and make climate management systems more sustainable.

4. Modularity and flexibility: structures should be modular to adapt to different climatic conditions and plant species.

5. Data monitoring and analysis: it is important to collect data on climatic conditions and plant growth to continuously improve the design methodology.

By synthesising these elements, it is possible to develop architectural solutions that optimally match climatic conditions, ensuring sustainable and efficient crop production in different regions. This may include creating multifunctional greenhouses, using innovative materials and technologies, and active resource management to minimise adverse environmental impacts.

DISCUSSION

The study highlights the necessity for implementing adaptive architectural solutions in crop production facilities to facilitate resilience in the context of evolving climatic conditions and urbanisation trends. The study's principal conclusions highlight the necessity of climate-sensitive architectural designs and the incorporation of green technologies to guarantee the sustainability of crop production. Similarly, as demonstrated by D. Karamanis *et al.* (2024), the incorporation of green building elements, such as photovoltaic panels and greenery, can enhance urban sustainability. The present study also suggests crop production facilities could benefit from such integration to improve environmental performance and energy efficiency. Such an approach would not only optimise the use of sunlight but also assist in regulating internal temperatures, particularly in regions characterised by extreme climates.

By the findings of Z. Wu *et al.* (2024), which indicated that the integration of green spaces within urban infrastructure could serve to mitigate the Urban Heat Island effect, the study proposes that crop production facilities should consider the incorporation of analogous architectural elements to maintain optimal internal climates. The installation of green roofs and walls could assist in stabilising temperatures, reducing cooling costs and providing additional insulation, which is of paramount importance in maintaining a stable environment for crop growth.

Moreover, Um-e-Habiba *et al.* (2024) emphasise the significance of integrating smart systems to enhance energy efficiency in buildings. Similarly, the study lends support to the integration of smart technologies, such as automated climate control systems and LED lighting, to improve energy management within crop production facilities. The implementation of these technologies has the potential to markedly reduce energy expenditure and advance sustainable practices in agriculture, particularly in urban and semi-urban regions where resource efficiency is of paramount importance. This study is also in accordance with the findings of A. Gamal *et al.* (2023), who presented a framework for vertical greening systems to enhance urban resilience in hot, humid climates. For facilities engaged in crop production, vertical greening represents a sustainable solution for urban agriculture, offering improvements in spatial efficiency and resource utilisation. By optimising the use of vertical space, facilities could achieve the dual objective of maximising crop yields while minimising land usage, which is particularly relevant in densely populated areas.

A. Maciejewska *et al*. (2024) examined the role of greenery in enhancing the quality of life of urban residents. Similarly, the incorporation of green architectural solutions within crop production facilities serves not only to enhance agricultural productivity but also to confer societal benefits, namely the promotion of green spaces that improve air quality and biodiversity in urban environments. In a similar vein, Y.-H. Jung & Y.-S. Park (2023) investigated the potential of eco-corridors in urban settings, which is consistent with the findings on the design of crop production facilities that integrate natural ventilation and sunlight. The findings of their study lend support to the concept of utilising eco-corridors or open-air designs in crop production facilities. This approach could enhance natural airflow and light, thereby reducing reliance on mechanical systems for climate control.

The study by J. Bosch Abarca (2024) on single-row planning models in German cities provides insights into optimising spatial distribution for sustainability. In a similar context, the research proposes the implementation of modular and scalable architectural designs for crop production facilities, which can adapt to various environmental conditions and urban layouts. Such flexible planning can support both large and small-scale operations, thereby aligning with the sustainable urban development goals. In contrast to conventional designs that may fail to consider environmental sustainability, the study proposes a more integrated architectural approach. In alignment with the findings of A. Maciejewska *et al*. (2024), it is imperative to emphasise that architectural designs must be adapted to align with local climatic and urban conditions to facilitate sustainable crop production. To illustrate, the closed-loop water system described in Vertical Farm Beijing represents a model for the implementation of water recycling solutions within crop production facilities, particularly in regions with limited water resources (Xu, 2024).

Additionally, the findings underscore the impact of intrinsic factors, including crop varieties, production objectives, and cultivation techniques, on the architectural necessities associated with these plants. The environmental conditions required by different plant species are distinct, and these can be met through the implementation of specific architectural adaptations (Mero *et al*., 2023). For instance, crops that are of considerable height may necessitate vertically spacious structures, whereas those that are low-growing or cultivated hydroponically may benefit from modular designs that are horizontally efficient. In addition, local anthropogenic factors, including urbanisation and pollution, have an impact on the architectural and operational aspects of crop production facilities. Specialised filtration and ventilation systems must be employed to maintain optimal air quality within these structures, particularly in urban settings where pollution levels are elevated (Hezentsvei & Bannikov, 2020). In a similar manner to the environmental performance framework presented by A. Gamal *et al*. (2023), the research proposes the implementation of adaptable and resilient architectural solutions to mitigate the impacts of urban and climatic changes on crop production.

This study serves to reinforce the idea that any architectural solutions for crop production facilities must give priority to sustainability, adaptability and efficiency to meet the challenges posed by climate change and urban expansion. The incorporation of intelligent technologies, energy-efficient systems and environmentally conscious design features can facilitate the attainment of sustainable agricultural output within urban environments, thereby ensuring the dual objectives of food security and environmental resilience.

CONCLUSIONS

This study highlights the significance of adaptive architectural solutions in optimising the efficiency, resilience and sustainability of crop production facilities in response to the evolving climatic and anthropogenic challenges. The findings demonstrate that external environmental factors, including temperature fluctuations, precipitation patterns, humidity levels, and sunlight exposure, as well as internal variables such as plant type, care methods, and production goals, have a significant impact on the architectural design and operational functionality of these structures.

The study demonstrates that regional temperature conditions are a key factor in determining the selection of insulation materials and the integration of heating and cooling systems, with the objective of creating optimal growth environments. Similarly, the architectural design must take into account local precipitation and humidity levels, which affect water supply needs, irrigation system integration, and overall moisture control within the facility. The utilisation of transparent materials and structures orientated in a strategic manner serves to enhance the availability of sunlight, thereby supporting essential photosynthetic processes. Furthermore, wind conditions are taken into account in the structural design of buildings in order to maintain stability and safety, which is becoming increasingly important in regions that are prone to extreme weather events.

The findings underscore the significance of sophisticated architectural techniques, such as vertical farming and hydroponic systems, in enhancing spatial efficiency and resource utilisation. The implementation of closed-loop water recycling systems, energy-efficient lighting, and climate control technologies has the dual benefit of reducing water and energy consumption while also facilitating sustainable crop production within urban and resource-limited settings. Notable examples such as the Urban Vertical Farm of Brightfood in Shanghai and the Vertical Farm Beijing demonstrate the viability of integrating food production within urban areas, promoting biodiversity, and achieving substantial resource savings through innovative architectural design.

In conclusion, the study demonstrates that the application of sustainable design principles to crop production facilities enhances food security, minimises environmental impact and ensures long-term agricultural productivity. It is recommended that future research explores emerging technologies, such as artificial intelligence for climate monitoring and renewable energy solutions, in order to further improve the adaptability of crop production facilities to meet the demands of diverse and challenging environments.

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CONFLICT OF INTEREST

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Сучасні принципи формування об'єктів для виробництва рослинної продукції

Анотація. Актуальність цього дослідження проявляється у необхідності адаптації архітектурних рішень до змінних кліматичних умов та антропогенних факторів. Метою дослідження було вивчення сучасних принципів формування структур для виробництва рослинної продукції та виявлення критичних аспектів, що мають вирішальне значення для оптимізації цього процесу. Для досягнення цієї мети були використані методи аналізу, синтезу, дедукції та індукції. Результати дослідження показують, що архітектурні рішення мають бути адаптовані до різних кліматичних умов, щоб оптимізувати ріст рослин. Це потребує коригування систем контролю температури, освітлення та управління водними ресурсами. Конкретні архітектурні приклади, зокрема Міська Вертикальна Ферма компанії Brightfood у Шанхаї та Вертикальна Ферма в Пекіні, представлені в якості тематичних досліджень для демонстрації цих принципів. Міська Вертикальна Ферма компанії Brightfood включає тераси з їстівними рослинами, сучасні гідропонічні системи та прозорі матеріали, що максимально використовують сонячне світло. Подібним чином, Вертикальна Ферма в Пекіні інтегрує систему водного замкненого циклу та ефективне світлодіодне освітлення для мінімізації енергоспоживання та витрати води, сприяючи тим самим продовольчій безпеці міста. Ці приклади ілюструють важливість адаптації архітектурних проектів до екологічних та міських обмежень. Дослідження дало можливість зрозуміти значення архітектурних та інженерних рішень у виробництві рослинної продукції, що може привести до створення більш ефективних та стійких систем вирощування рослин, що, у свою чергу, може підвищити продуктивність та якість сільськогосподарської продукції

Ключові слова: оптимізація врожайності; природно-кліматичні фактори; інноваційні агротехнології; структури; системи культивації

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The genesis and fortification of the castle architecture of the early Middle Ages

Abstract. This study was devoted to a detailed analysis of the genesis and fortification of castle architecture of the early Middle Ages, covering the period from the 5th to the 11th century. An extensive review of historical documents, drawings, works of historians, and reports of archaeological research was conducted. The study examines the architectural, social, and economic aspects of castle architecture, paying special attention to the impact of historical events on defensive structures and the changes caused by the integration of construction methods from different cultures. The main attention was paid to the examination of the evolution of castles from simple wooden fortifications to powerful stone ones and the analysis of construction methods used in various regions. The castle architecture of the early Middle Ages borrowed many elements from ancient Roman and Byzantine fortifications, such as towers, walls, and gates. These elements adapted and developed in the face of frequent invasions and instability, which led to the creation of more powerful and functional fortifications. Castle architecture was born gradually, starting with simple fortifications, such as the Roman fortifications of Autun, Saxon burgs, the location of which is recorded in the list of Burghal Hidage, compiled in the 9th century. One of the first types of castles were Motte and Ringwork or similar in function, motte-and-baileys, first common in England and Germany, representing fortifications on artificial hills and plots of land surrounded by moats and ramparts, which played

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an important role in strengthening the power of the feudal lords in the 11th-12th centuries. Examples of such fortifications are the Peñerudes Tower in Morcina and the Castle of Canossa. Marlborough Castle in Wessex, Berkeley Castle and Castello Firmiano Castle are important monuments of fortification of castle architecture of the 5th-11th centuries, demonstrating a more developed approach to strengthening in comparison with their predecessors. The findings are important for analysing the development of castle architecture and understanding the historical processes that influenced its formation

Keywords: motte-and-bailey; fortified walls; defence; towers; Anglo-Saxon burgs

INTRODUCTION

Castle architecture, which originated in the Romanesque style, continued to exist even after this style gave way to Gothic, Baroque, and Classicism. The question of the origin of castles and their connection with general security remains relevant and causes a lot of scientific debate. Discussions usually describe the development of castle building as a reaction to the increasing threats of attacks and the need for protection. However, the first castles began to appear in the 9th and 10th centuries, and the connection between the level of security and fortification construction was not always direct. Sometimes, castles were built in relatively safe places as a symbol of the power and status of the owner. Meanwhile, some border areas remain uninhabited and unprotected.

Castles are complex fortified systems based on a strong connection between the territory and architecture. The territory defines the context of development, access and protection conditions, and the architecture adapts to the context, offering fortified structures in accordance with the orography of the area. Both factors are crucial for understanding the historical evolution and social role of castles over time. Motte-and-bailey-type structures that predate the appearance of the classical image of the castle, concerning which historians and archaeologists have different hypotheses and archaeological research data, often lead to contradictory conclusions regarding the dating and place of origin.

The architecture of the early Middle Ages covers the period from the end of the 5th century to the beginning of the 11th century. This period begins with the fall of the Western Roman Empire and continues until the beginning of the Romanesque style of architecture, which began to develop in the 11th century, but until that moment, the architecture of castles transformed from primitive fortified buildings to full-fledged architectural structures integrating elements of defence, housing, and centres of social activity. E. Cirelli (2020) and H. Little (2022) examined this issue. The pre-Romanesque style is defined as the dominant one among the castles of the early Middle Ages, often representing simple, massive structures designed for defence and housing. It is also noted that the original function of the castles was defensive. They represented not only military fortifications but also centres of social and economic activity, which is confirmed by the finds of various objects and structures.

The examination of castles and fortifications dating from the period from the 5th to the 12th century is complicated by the high level of destruction of these structures. Many of them have either not been preserved or are ruins, which creates substantial difficulties for research and understanding of their history and architectural features. Researchers A. Marciniak-Kajzer (2020), M. Brintley (2020) and R. Barber (2022) drew attention to this issue. It is emphasised that the dating of motte-and-bailey structures is often based on the analysis of ceramics, which may be inaccurate. An example is the Douai-la-Fontaine monument, which dates back to the Carolingian era, but an artificial mound appeared there only in the 11th century (Marciniak-Kajzer, 2020). Most of the archaeological material is usually discovered as a result of random excavations or non-targeted research, while targeted excavations often yield a limited number of finds (Barber, 2022). Most castles from the early Middle Ages did not survive until the development of archaeology, which could provide modern methods of research (Brintley, 2020).

The examination of fortifications and the origin of castle architecture in the early Middle Ages requires a comprehensive analysis, including regional and architectural features of this period, as well as social and economic contexts. S.D. Kirk *et al*. (2020) emphasised that it is necessary to consider the term “castle” more broadly. These monumental structures should be analysed considering the cross-cultural behavioural processes that led to their emergence in different parts of the world, without limiting their interpretation only as a feudal or Christian phenomenon.

S. Ozola (2020) highlighted that the knights from Lubeck and Bremen, to implement their policy on the conquered lands inhabited by the Balts, founded economically independent stone castles with chapels. These castles served not only as military outposts but also as centres of administrative and economic management. S.D. Kirk *et al*. (2023) noted that state castles owned by centralised authorities included defensive fortresses and palaces until the 16th century, and then investments moved to border-control castles. Non-state castles also moved from defensive fortresses to palaces but did not reach the stage of border control castles. J. Hložek *et al*. (2023) highlighted that the symbolic role of early medieval fortresses and castles located on mountain peaks was often reduced to demonstrating power over the surrounding area.

The studies of these researchers are really important because they help to better understand the problem of understanding the factors that stimulate the construction of castles, which can be much more complex and include social, economic, and even cultural aspects. However, despite the substantial contribution of these studies, certain gaps remain. It is necessary to consider in more detail the specific construction methods for the fortification of castles of this period; it is also important to analyse the buildings preceding the appearance of castles; attention should be paid to the integration and exchange of castle construction methods between different cultures and regions.

The purpose of this study was to examine the origin and development of castle structures from their original forms to more complex and monumental castles and to analyse the role of castles in the social and defensive life of the early Middle Ages. This contributes to a deeper and more objective understanding of the processes of development and functioning of castle architecture during this period, which allows expanding the perception of castles not only as architectural monuments but also as important buildings reflecting the social and historical events of that time, which contributes to a deep understanding of their role in shaping social and cultural practices of the early Middle Ages. Literature analysis and photogrammetric analysis were used to conduct the study, the paper is theoretical. The historical document Burghal Hidage (n.d.), deciphered by Lawrence Nowell in 1562, was considered. An important stage of the study was the search for the most accurate and detailed plans, drawings, and 3D models for the reconstruction and analysis of early medieval castles.

THE ORIGINS OF CASTLE ARCHITECTURE: THE INFLUENCE OF ANCIENT CIVILISATIONS AND BYZANTINE CANONS OF URBAN PLANNING, GERMAN AND ANGLO-SAXON FORTIFICATIONS

The Middle Ages have long been considered a dark and barbaric period. However, between the 5th and 9th centuries, despite the decline of civilisation, knowledge, and art due to invasions and riots, after the 10th century, European society began to change due to the interaction of ancient Roman culture, Germanic customs, and Christianity, reaching its heyday in the 13th century. In the period from the 5th to the 6th centuries, Europe was fragmented: Roman centralisation gave way to political division, and barbaric invasions led to violence, destruction, instability, and epidemics. Despite this, the Germanic tribes introduced new elements to civilisation. The fortifications of the 4th-6th centuries were characterised by a reduction in urban life and the revival of defensive structures. Cities have turned into small fortified cores built from the materials of abandoned buildings to protect against violence and invasions.

The formation of a medieval castle involves the development of key elements such as city walls and towers, which together create an architectural synthesis. The castle, as an association of defensive structures, is not unique to the feudal era, it reflects both functional and symbolic aspects. After the classical era, castles became a means of control and resource extraction, symbolising an agreement between influential members of society and the population, forming a new understanding of the territory and its inhabitants (Greco, 2023).

Fortifications that preceded castles were built in the 8th-7th centuries BC on the territory of Assyria. Prototypes of castles are also present in the architecture of Ancient Rome, where the country residences of Roman emperors were strengthened, such as Diocletian's Palace in Split, modern Croatia (Barker *et al*., 2023). Ancient Roman fortifications had a substantial influence on the architecture of medieval castles. Byzantine fortification structures, such as city walls with multiple lines of defence, towers and gates, also made an important contribution to the development of castle architecture. Byzantine cities like Nicaea and Athens used high walls and reinforced gates for protection. These fortifications were adapted in Western Europe by the 9th century, preserving elements of Byzantine architecture and technology.

In the early Middle Ages, Byzantium was actively involved in conflicts with Sassanid Persia and the Arabs, which influenced its defensive strategy. Important battles, such as the Battle of Chersonesos in 625 and the sieges of Constantinople in 674-678 and 717-718, contributed to the development of Byzantine fortifications. These elements, such as towers, walls, and gates, were adapted in Europe, especially in the 12th century, to protect cities, estates, and monasteries (Kontogiannis, 2022).

The origin of European castles dates back to ancient times. The original fortifications, similar to modern castles, copied Roman military camps with tents and a palisade. Since Norman times, castles have begun to build more complex stone structures. Since the 12th century, the castle has become a fortress with stone walls and defensive towers, which allowed effectively controlling and protecting the territory (Shatkovskyi & Tupchienko, 2023). Although the formation of castle architecture began earlier, various countries developed their own versions of castles but they all adhered to common principles and included basic fortification elements.

The first builders of fortified settlements were the Germanic tribes of the Angles and Saxons in the early Middle Ages. These tribes strengthened their positions in the conquered territories by building burgs, which were fortified cities with an important defensive and administrative role. Rural burgs were smaller and included wooden structures such as halls and towers, and were not classified as castles due to their functional specificity and size. Early fortifications, such as Saxon burgs and Iron Age hillforts, served as centres of command and control, anticipating later castles that became residences of feudal lords and symbols of their power (Haslam, 2023).

Due to the list of Burghal Hidage (n.d.), compiled during the reign of Edward the Elder, son of Alfred the Great (899/901-924), the location of all Burgs was recorded (Maitland, 1897). This list mentions 33 fortified towns located in such a way that any resident of Wessex could be no more than 20 miles from the burg. This approach ensured a wide coverage of the territory by defensive structures and strengthened the position of the Saxons in the struggle for power and security in territories subject to enemy attacks (Fig. 1).

Figure 1. The location of the Burghs based on the list of Burghal Hidage in 10th century England
Source: History Chronicles (2023)

The Anglo-Saxon Burghs provided the Normans with the existing concept of fortified settlements, which were used to protect and control the territory. The Norman conquerors often built their castles in places where the burgs had previously been, using their defences or adapting them to their needs. Norman castles not only performed military functions but also served as high-status residences and estate management centres, and they also played a symbolic role in demonstrating power and dominance. In the context of Wessex, Marlborough Castle is an example of an 11th- and 12th-century castle building, demonstrating the features and functions of Norman castles in the region. Burgs had a simpler layout with earthworks and moats, while Norman castles developed from motte-and-bailey to complex stone fortresses (Creighton, 2022).

The development of castles was a complex and multi-stage process, starting with simple fortified houses and moving on to more complex structures in response to changes in military tactics and socio-political conditions. One of the first types of castles were mounds (motte) and circular defence (ringwork), which appeared in Western Europe, especially in Normandy, from the 10th century. These castles, common in England after the Norman conquest of 1066, were wooden or stone buildings on an artificial earthen mound, surrounded by additional defensive structures such as moats and walls. The main idea was to raise the defensive structure to an elevation to increase its protection (Cantor, 1982).

Ringwork castles were built without an embankment hill and were fortified plots of land with ditches and earthen ramparts. The first such castles appeared in Germany in the 10th century and became popular in England in the late 11th and early 12th centuries. There could be a manor house or a tower in the centre but without an elevation on the hill. Over time, they have become more complex, including stone walls and other defensive elements. Many of these early castle forms were replaced by motte-and-bailey structures, which combined an embankment hill with courtyards and fortifications and were simpler and faster to build.

The Peñerudes Tower, located in Morcina and dating from the early Middle Ages, namely the 12th century, is located at an altitude of 530 metres above sea level on a hill on the north side of the city of El Campo in the parish of Peñerudes. The tower has a quadrangular plan with a wall thickness of almost 2.5 metres and a height of about 17 metres. Inside, traces of reinforcement beams that divided the tower into three floors can be seen. Externally, the southern facade of the building is missing, but the northern wall and a substantial part of the remaining walls have been preserved (Fig. 2).

Figure 2. Photo of the Penerudes Tower
Source: Peñerudes Tower (n.d.)

The preservation of only some elements from the original form of the Matilda fortress demonstrates a number of difficulties associated with the study of the architecture of castles of the early Middle Ages. Historical castles and fortresses have often been destroyed and rebuilt over the centuries. This led to the loss of original materials and structures, which makes it difficult to accurately recreate and interpret them.

The castle of Canossa, built on top of an isolated cliff, has substantial strategic and defensive importance. The first mention of the fortified system at the top of the Canossa cliff dates back to the beginning of the 10th century. This castle played an important role in the medieval history of Europe, especially during the reign of Countess Matilda of Canossa, who used it as a political and military centre in internecine conflicts spanning the territory from Lombardy to Tuscany. The castle of Canossa was part of a complex system of fortifications typical of the Apennine territory of Reggio Emilia. Most of the original fortress, dating back to the Matilda era, has not been preserved. The remains that can be seen today mostly date from the late Middle Ages and later periods (Fig. 3). Some elements of the foundation, however, date back to Matilda's original time (Russo *et al.*, 2023a).

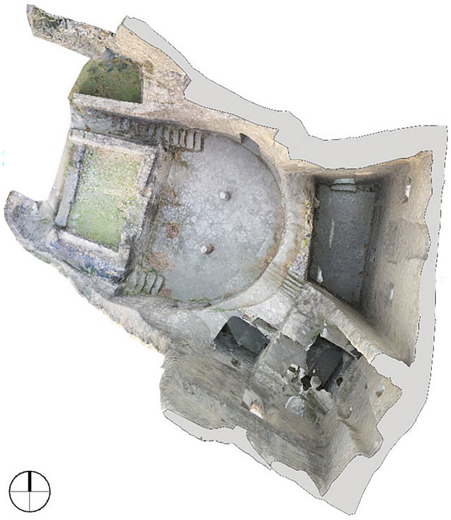

Figure 3. View of the Castle of Canossa from above
Source: M. Catellani *et al.* (2021)

The castle's location on a white sandstone hill indicates the strategic use of natural features for defence. The remains of the fortifications demonstrate how the castle controlled the surrounding area and ensured the security of the region. The raised part of the eastern tower is a defensive structure that could serve to control the surrounding area and provide visual surveillance. It clearly illustrates the transition from wooden to stone fortifications (Russo *et al.*, 2023b). In addition, the fortification element is the foundation of the gate tower, located to the south of the main building, which indicates the existence of entrance fortifications that protected the main entrance to the fortress.

THE FORMATION OF CASTLE ARCHITECTURE AND FORTIFICATIONS IN THE EARLY MIDDLE AGES: SYMBOLISM AND THE IMPACT OF SOCIAL CHANGE

The city of Autun, located in the region of Burgundy, in France, is an interesting example of a city with an ancient history, important for understanding the development of castle architecture in the early Middle Ages and the influence of the historical context on the development and fortification of architecture of the early Middle Ages. The fortifications in Autun, covering an area of 200 hectares, included a battlement with a diameter of 6 km, a thickness of 2.5 m and a height of 11 m, 52 tall semicircular towers, four main gates, and six secondary rear gates. These fortifications greatly enhanced the prestige and wealth of the city, although they did not play a key military role. In the following centuries, Autun was destroyed several times. In the 6th century, the collapse of the Western Roman Empire led to substantial changes in the political and social organisation of the former Roman provinces, accompanied by migrations of peoples, barbarian invasions, and the formation of new state structures. In 674, the city was ravaged by Vandals and Franks, in 731 it was attacked by the Moors, in 895 the city was robbed by the Scandinavians.

During the early Middle Ages, the architecture of castles began to actively develop in the direction of strengthening and defence (Andresyuk, 2024). Castles became more massive and functional with the addition of towers, walls, and other elements to sustain long sieges and attacks. In the 6th century, the construction of a castle with a cathedral and a bishop's residence took place. At that time, castles became a necessary element to protect the population and church institutions from attacks. In Autun, the castle was fortified and included a cathedral and a bishop's residence, reflecting a combination of defensive and religious functions. Roman fortifications dating back to the 1st century were located around the perimeter of the city (A), and framing it, the castle territory became the final part of this fortification system (B). The medieval fence of the 12th century (CC) complemented the fortification system, located in the southern part of the city, crossing its centre (Fig. 4).

In conditions of instability and frequent invasions, the construction of fortified castles has become necessary to protect the population, church, and royal mansions from barbarian attacks and other threats. Castello Firmiano, also known as Sigmundskron in German, is a substantial fortification located in the vicinity of Bolzano, the capital of South Tyrol. The castle is now part of the Messner Mountain Museum. The first mention of Castello Firmiano dates back to 945 when it appeared under the name of Formicaria. In 1473, the ruler of Tyrol, Sigismund the Rich, acquired the castle and renamed it Sigmundskron, and adapted it to firearm protection. Only fragments of the original Formicaria have been preserved, mainly in the highest sites of the area. The castle's design includes towers evenly spaced along the perimeter of the outer walls. This layout allowed the defenders to conduct a circular bombardment, which made it more difficult for enemies to approach the castle and increased the difficulty of destroying its walls (Biran *et al.*, 2023). Since then, only a few fragments of buildings have been preserved, mainly at the highest points of the area. The towers, located evenly along the outer walls, allowed the defenders to conduct a circular bombardment, which made the approaches to the castle dangerous for opponents and complicated their task of destroying the walls (Fig. 5).

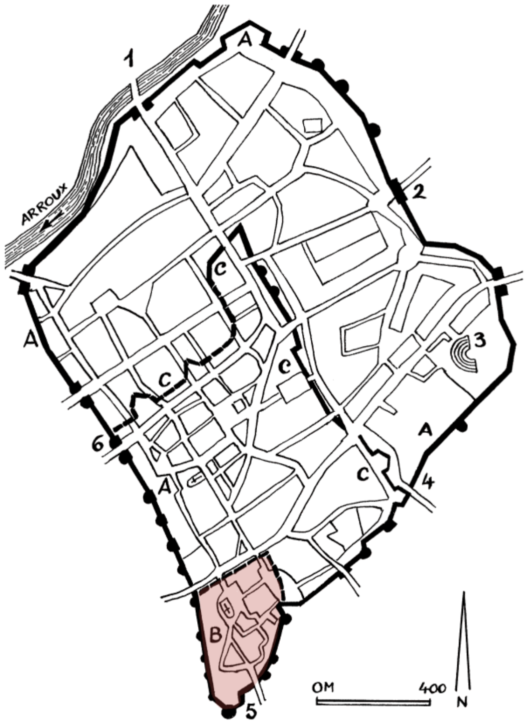

Figure 4. The location of the 6th-century castle with the Cathedral of Saint-Lazare and the episcopal residence in Autun
Source: J.-D. Lepage (2015)

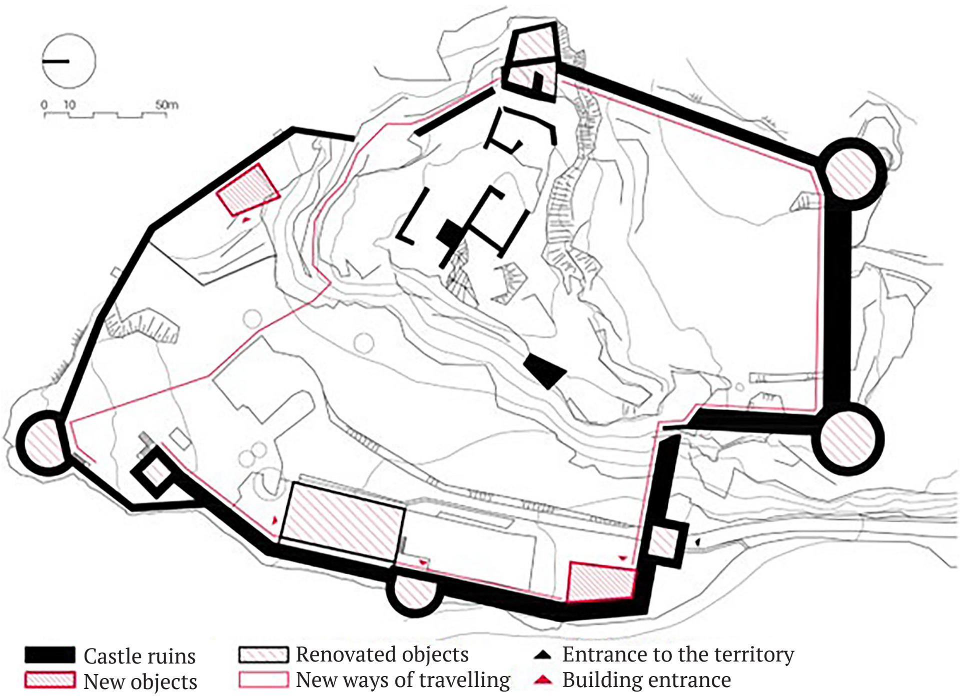

Figure 5. Firmiano Castle. Location and spatial relationships of ruins and modern buildings
Source: I. Wilczek (2021)

Berkeley Castle is an interesting example of fortification architecture from the period of the 12th century with various elements characteristic of the era of the Angevin dynasty. Berkeley was a royal domain in the time of Edward the Confessor (1042-1066). The initial castle included a motte (artificial hill) with a moat on three sides and natural defences on the south side. The stone from the pre-existing cathedral was used to build the foundation of the castle. Despite the original boundary function, Berkeley Castle became part of a larger system. Evaluating the data on the preserved structures of the 12th century, it can be assumed that the original form of Berkeley Castle was a palisaded courtyard, inside or next to which there was an artificial hill with a donjon on top (Fig. 6).

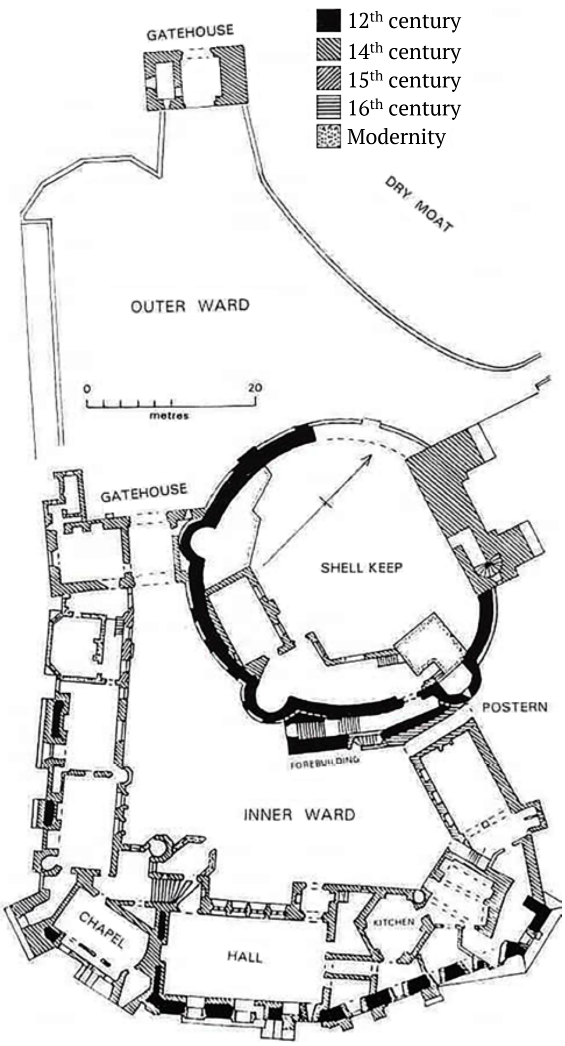

Figure 6. A plan of Berkeley Castle showing the various stages of its development
Source: S.J. Prior *et al*. (2023)

The motte castle was erected by William Fitz Osbern, 1st Earl of Hereford, in 1067. For the next three generations, it belonged to the knight Roger de Torcy and his descendants, who adopted the surname de Berkeley. At the beginning of the 12th century, they began the reconstruction of the castle, replacing wooden fortifications with stone ones. This process was lengthy and required substantial resources. However, in 1152, due to the refusal to support the Plantagenet dynasty during the feudal troubles, the last of the Roger de Berkeley lost the castle. The king handed over the castle to Robert Fitzharding, who continued to strengthen and rebuild it. In Berkeley Castle, the towers are also placed evenly along the perimeter of the outer walls. This allows for the creation of reliable protection and effective use of the castle's internal space. The uniform placement of the towers increased resistance to siege and allowed the defenders to conduct a round-robin fire. In small castles, towers often served as the main fortress, but as castle construction developed, they began to be connected to the walls, which made the fences more durable and improved visibility for defenders.

During the early Middle Ages, substantial changes took place in the socio-economic, political, and cultural spheres in Central Asia. These transformations were reflected in the architectural and fortifications of the region, demonstrating the evolution of construction technologies and defensive strategies. During this period, the territory of modern Kyrgyzstan was influenced by various cultures and peoples, which substantially influenced the development of fortifications. One of the key aspects of fortification was adaptation to geographical conditions. Fortresses and fortified settlements were often located on high ground, hills, and mountain slopes, which provided natural protection and a good view of the surrounding area (Dzhedzhula, 2023). This choice of location allowed effectively defending against numerous enemies, including nomadic tribes and conquerors. Fortifications of the early Middle Ages included high fortress walls, often reinforced with towers and loopholes. The entrance to the fortress was protected by massive gates and additional fortifications such as moats and barbicans. The layout of the fortifications could vary from simple rectangular or square to complex, adapted to the terrain. Over time, fortification technologies were constantly improved, under the influence of various cultures and peoples passing through the territory of Kyrgyzstan. An example of this is the Ak Beshim settlement, where archaeological excavations have shown several construction periods reflecting the development of fortification architecture (Biran *et al*., 2023). The fortified citadel is located in the centre of the settlement, protected by a fortress wall with preserved remnants of watchtowers. The citadel functioned as the core of the city and the main defensive structure (Silachyov & Akymbek, 2023).

The main element of protection was the powerful fortress walls, often reinforced with towers and loopholes. Inside fortified cities, there were often citadels and central fortified units that served as the last line of defence. Fortress walls were often decorated with bastions and battlements to improve defensive capabilities. The entrances to the fortresses were protected by massive gates and additional fortifications such as barbicans (Eshquvvatova, 2024). Castles served as strategic positions that marked the boundaries of the territory, but as residences they became a support for the representation of power. Therefore, they needed to turn to a symbolic repertoire expressed through architecture. The construction of castles depended on private initiative and was directly related to feudalism, fortified buildings illustrated the decline of political and military power and reflected a social order based on the desire for power. In this context, a private "castle", designed for everyday life and inhabited by both civilians and soldiers, was substantially different from a "fort", which was built exclusively for military purposes. The influence of ideological concepts dating back to the classical era and newly opened for experimentation was traced in construction technologies. Thus, it is important to note that in Europe, most of the monumental and defensive architecture, controlled by powerful elites, served as a symbolic form of legitimisation and affirmation of hierarchy. Masonry, initially practical, gradually gained symbolic importance in the development of castle forms.

THE EVOLUTION OF FORTIFICATION ARCHITECTURE OF CASTLES: ADAPTATION OF TECHNIQUES AND MATERIALS

The evolution of European castles demonstrates the transition from simple wooden fortifications to powerful stone ones. Initially, the castles were enclosed by a wooden palisade, which provided minimal protection and was easily destroyed during attacks. However, the military actions showed the inefficiency of such structures, which led to the replacement of wood with more durable materials – stone and brick. The very first castles were enclosed with wooden fences, which provided basic protection. They were vulnerable to fire and easily destroyed by siege weapons. The transition to the use of stone has substantially increased the protective capabilities of castles. The stone walls were resistant to fire and more durable, which made it more difficult to destroy them. This allowed to prepare for the defence in advance.

C. Coulson (1979) discusses the architectural features of castles, which demonstrate thoughtful steps to reduce hazards. The internal factors that determine the layout of castles are often underestimated. Ideal military castle plans include polygonal shapes to minimise the vulnerability of corner towers. Examples of such plans include Bolingbroke Castles, Boulogne-sur-Mer, Fer-en-Tardenois, Castel del Monte, and Hlemutsi. The castles of Castello Firmiano and Berkeley demonstrate the strategically uniform placement of towers along the perimeter of the outer walls, which contributed to effective protection. This arrangement ensured the protection of all sections of the walls and allowed the defenders to easily control the approaches to the castle. The polygonal shape allowed creating an effective firing system, reducing dead zones, and improving visibility.

S. Sur & U. Serin (2023) also explored medieval construction methods, using the example of the Genoese fortifications in Galata (mid-15th century), they highlighted the adaptation of local construction techniques and materials, the use of various types of stone and brick, improving the quality of building materials, the development of mortar technologies to improve the binding of stones. The Eastern influence, borrowed by the Crusaders and presented to the Byzantine masons by the Genoese, is also emphasised. In turn, P. Purton & C. Krauskopf (2021) noted how the transformation of the castle fortification was accompanied by thickening and strengthening of the outer walls, especially during the appearance of powder artillery in the second half of the 15th century, bastions with fortified corners capable of withstanding direct blows from artillery guns were also added.

Building materials in the early Middle Ages were limited by available local resources, and wood and soil were mainly used. In the late Middle Ages, castles turned into complex and powerful stone fortresses. This period is characterised by substantial development of construction technologies and the use of more durable materials. Castles have become not only defensive structures but also symbols of power and status (Demessie, 2024). The example of the Genoese fortifications of Galata shows how local construction techniques and materials have adapted. The walls were built of rubble and rough-hewn stone with pieces of brick in the mortar seams, which was a characteristic feature of late Byzantine architecture. The Genoese, despite the limitations, built quickly, using all available materials.

A. Özmen (2022) examines the history of the reconstructions of the Castello Firmiano castle. In the 15th century, the castle came into the possession of the ruler Sigismund, who turned it into a powerful defensive fortress using advanced technologies of the time. Most of the preserved parts of the castle belong to this period. Over time, the castle acquired political and symbolic importance, becoming the site of calls for autonomy during the 1957 protests. Over the centuries, the Castello Firmiano Castle has undergone many alterations and reconstructions while maintaining its defensive function. By the 20th century, although it had lost its original purpose, its historical importance remained an important symbol. Initially, the defensive architecture was distinguished by its harsh appearance and was not influenced by Gothic, but with the beginning of the Renaissance, castles lost their utilitarian goals, and Gothic and Renaissance elements began to penetrate into their architecture. During the Baroque period, castles corresponded to the aesthetic and functional trends of the era.

D. Lanera (2024) conducts a detailed examination of Castel del Monte, starting with its historical context and unique architectural form and ending with a mathematical analysis of its geometric structure. He emphasises the importance of the castle as an object of research and historical legacy, especially in the context of its unique octagonal layout. P. Kocańda *et al*. (2020) also emphasise that later fortifications, especially in the form of sconces and redoubts, began to have a more regular shape. This indicates the use of old fortifications for new purposes or their modification for military needs. Early defensive structures often had an uneven shape. An example is the fortification at Brzezow in Poland, where regularity of form was rare for the early Middle Ages. Early defensive structures, as a rule, had an uneven shape, which was often explained by the need to adapt to the terrain and the limitations of construction technologies of that time. In such fortifications, natural features of the landscape were often used to strengthen the defence, which led to an asymmetric and complex structure of fortifications.

The evolution of fortification architecture from uneven forms to more regular and symmetrical ones was due to the development of siege weapons and tactics, which required more thoughtful and effective defensive structures (Tsyrfa *et al.*, 2024). Improved construction technologies and planning methods have allowed architects to create more complex and geometrically precise fortifications. Finally, the accumulated experience and knowledge in the field of fortification architecture allowed builders to better understand and apply the principles of symmetry and regularity to improve the defensive properties of fortifications. Beaumaris Castle, built at the end of the 13th century, has incorporated a number of innovations and improvements compared to early medieval architecture. These innovations made it one of the most perfect examples of medieval fortification architecture. F.W. Lloyd (2021) notes that Beaumaris Castle, founded in 1295, is known for its concentric design and almost perfect symmetry. His gatehouse is almost identical in size and shape to the gatehouses in Harlech.

Unlike early medieval castles with a dungeon in the centre, Beaumaris has a concentric structure with two rings of walls. Instead, the emphasis is on powerful exterior and interior walls. This created a multi-layered defence, where the inner walls could continue to defend even when the outer ones were captured. The concentric structure of the castle allowed for a better organisation of the defence. In the event of a breach of the outer wall, the defenders could retreat to the inner wall and continue their effective defence. The moat around the castle was connected to the sea, which allowed large ships to approach almost directly to the castle and unload at the gate. This provided supplies and convenient logistics in the event of a siege. The layout of the castle was carefully thought out and symmetrical, which improved both its protective properties and functionality for the garrison. These innovations made Beaumaris Castle an example of the advanced fortification architecture of its time, substantially surpassing early Medieval castles in terms of efficiency and thoughtfulness of defensive solutions.

Since the beginning of the High Middle Ages, castle architecture began to acquire decorative elements, and attention to the appearance of castles increased. The integration of the beauty of the exterior with the defensive function of the castle has become more explicit. For example, Castel del Monte demonstrates how the architect preserved the defensive characteristics of the castle while experimenting with the shape of the plan to give it a unique appearance and interior layout.

ARCHITECTURAL AND CONSTRUCTION FEATURES OF LATE MEDIEVAL CASTLES, THE INFLUENCE OF EARLY FORTIFICATION CONCEPTS

The choice of the site for the construction of the medieval castle played a key role in its defensive strategy and symbolic significance. One of the important factors was the successful natural location. Castles were often built by the water, on natural hills, rocks, or in the middle of lakes. This arrangement provided not only a magnificent view of the surroundings but also a substantial complication for enemies seeking to approach the walls of the fortress. The first fortresses of the motte-and-bailey type were built on artificial hills, which gave a substantial advantage in defence. This practice has become widespread throughout Europe. Castles built in the middle of lakes or near the banks of rivers had natural protection from attacks. Water not only made it difficult for enemies to access but also provided an additional source of resources for the inhabitants of the castle.

D. Janíková (2016) highlights that the Normans, despite their reputation as innovators in the field of military architecture, did not actually bring radically new ideas to fortification construction. Many features of motte-and-bailey type castles already existed in earlier structures such as Celtic hills, Roman forts, and Anglo-Saxon burghs. The Anglo-Saxon Burghs provided the Normans with the concept of fortified settlements, which they adapted to their needs, building castles in the places of the former burgs and developing them from motte-and-bailey to complex stone fortresses. An example of such castles is the Castello Firmiano, a fortification with many reinforcements, where the uniform placement of towers along the perimeter of the outer walls provided the defenders with the opportunity to conduct a circular bombardment. The fortresses located on the tops of the cliffs were practically impregnable. They had return routes leading to the gatehouse, which allowed the defenders to effectively fire at the enemies, preventing them from approaching the walls. Castles with spacious panoramic views allowed controlling large territories and noticing the approach of enemies in advance.

M. Sýkora (2021), exploring the development of castle architecture in Northwestern Bohemia (13th-17th centuries), highlighted that the first castles in the 13th century were characterised by the presence of a bergfried (battle tower) and a palace or donjon. In turn, K. Pachnerová Brabcová *et al*. (2023), using radiocarbon dating of the northern tower of the Rismburk Castle, clarified the construction time of the northern tower to the period 1287-1300. Regular castle locations were limited to royal cities. Royal residences were concentrated in the lowlands, near rivers and royal cities, while noble castles were built in mountainous areas. The author identifies the 17th century as the end of the era of castles.

The donjon or central tower in early Medieval castles, which served as both a residence and the last stronghold of defence, continued to play an important role in late Medieval castles, often becoming more massive and fortified.

During almost the entire 14th century, the emphasis was on the military component in castles. However, in the last quarter of the century, there has been a decrease in the use of defensive components and improvements in residential and representative units. These elements of fortification show how the early principles of castle construction continued to evolve and improve, responding to the challenges of the time and technological changes. The basic canons laid down in the early period became the foundation for the further development of castle architecture in the Middle Ages.

B. Elortza (2020) analysed the development of castle architecture in Scandinavia (12th-13th centuries) and highlighted the construction of earthworks and fortifications to protect siege camps and to block access to castles. Castles with strong stone walls and flanking towers, such as Vordingborg, Hammershus, and Nykoping, could not be easily stormed. Trebuchets and other heavy siege engines became widely used by the end of the 13th century. The idea of a multi-layered defence, where the castle is surrounded by several defensive elements (for example, walls, moats and towers), was borrowed and developed in later stone castles. In the early Middle Ages, these could have been simple earthen ramparts and wooden walls, but by the 13th century, they were replaced by stone walls with flanking towers. Towers and gates, which were used in early medieval castles for surveillance and protection, remained important elements in later castles. In the 13th century, the towers became more complex and durable, and the gates received additional protective devices. In the early medieval castles, internal residential and economic zones were developed, which were preserved in later stone castles. In the 13th century, they became more structured and adapted for a long stay. Due to the virtual reconstruction of the medieval castle of San Salvador De Todea, built in the 12th-15th century, researchers P. Valle Abad *et al*. (2022) highlighted that the northern gate was the main gate of the castle. They were large in size and integrated into the shaft; the southern gate represented a second access or an entrance. They were smaller in size compared to the north gate and probably served as a secondary entrance.

The internal distribution of the castle was complex and included two different complexes separated by a shaft. Access between them was via a staircase carved into a rocky ledge leading to the upper platform of the hill. The inner gate gave access to a narrow pentagonal covered space adjacent to the tower and two sections of the rampart wall. This design allowed access to the upper platform and surrounded the basement of the tower. The upper part of the shaft was probably passable, although the exact access to it remains unknown. As in early medieval castles, the walls of Salvador de Todea were massive and high, which provided protection from siege weapons and made it difficult to overcome them. Multiple gates, including the main northern and secondary southern gates and internal passages, which were also typical for castles of the early Middle Ages, provided various ways of access and protection.

The examination of the presented papers and their comparison with the results of the study allowed identifying key aspects of the evolution of fortification architecture of the early Middle Ages. This discussion highlights that the trend of fortification of castle architecture persisted until the end of the 16th century. The Anglo-Saxon Burghs had a substantial influence on the formation of castles in Normandy and England, evolving from motte-and-bailey type structures to sturdy stone structures. Notably, the first mention of the fortified system at the top of the Canossa cliff dates back to the beginning of the 10th century. A comparison of early Medieval and late Medieval castles demonstrates the evolution from simple wooden defensive structures to complex and powerful stone fortresses, reflecting changes in military tactics, construction technology, and political conditions. Castles have become not only defensive structures but also symbols of power and status. Their architecture and location reflected political and social importance. This allows for a more accurate understanding of the evolution of castle architecture and fortification methods, which is especially important for understanding how historical events and social changes influenced the development of castles and fortifications.

CONCLUSIONS

Since the 10th century, the interaction of ancient Roman culture, Germanic customs and Christianity has led to substantial changes in medieval society, reaching its peak in the 13th century. They began to form on the basis of ancient Roman, Anglo-Saxon burgs and Byzantine fortifications, including city walls and towers, adapting to the conditions of Europe. In the early stages, castles were often built of wood. Wooden walls, towers, and palisades were cheap and quick to build but less resistant to fire and heavy attacks. Castles of the early Middle Ages were, as a rule, simple and functional buildings. The main purpose of such castles was to provide security and protection from attacks.

Log walls reinforced with earthen ramparts were often used, which added an additional level of protection. Berkeley Castle demonstrates typical elements of the early Middle Ages, such as the motte-and-bailey structure, the use of moats and natural barriers. The motte was an embankment hill with a tower on top, and the Bailey was an adjacent fenced yard. Moats made access to the walls more difficult and slowed down the advance of the attackers, and towers integrated into the walls strengthened the entire fortress.

The strategic location and design features of the Peñerudes Tower provide important information about the feudal system and defensive structures of that time. The Castle of Canossa is an example of the fortification features of early castles of the early Middle Ages. In its original form, it included the typical elements of defence that characterised the numerous fortified structures of the time. The Castello Firmiano Castle, also known as Sigmundskron, is a large fortification with many reinforcements located in the vicinity of the city. Berkeley Castle, built in the 12th century and gradually reconstructed from wooden to stone fortifications, is an example of the fortification architecture of the Angevin dynasty, demonstrating the uniform placement of towers along the perimeter of the walls to strengthen defensive capabilities. The construction of a castle with a cathedral in the city of Autun in the 6th century reflects the complex changes in the political, military, cultural, and social life of early medieval Europe, updating the fortification solutions of that time.

The influence of various cultures and peoples on the territory of modern Kyrgyzstan in the early Middle Ages led to the development of fortifications adapted to geographical conditions, including high fortress walls, towers, loopholes, massive gates and moats, as can be seen from the example of the Ak-Beshim settlement and the Chumysh fortress. The analysis allowed assessing how these castles illustrate the transition from primitive wooden defensive structures to more complex and powerful stone castles. The basic canons of fortification of medieval castles were laid down in the early period. The influence of the historical and social context demonstrates how castles continued to develop as symbols of power in the following centuries, up until the 16th century.

Most previous studies have focused on castles of the High and late Middle Ages, not enough examining the fortification and the influence on the development of the architecture of early castles. It also caused difficulties that most of the castles of the early period did not survive until the 21st century, and the number of archaeological examinations of early medieval defensive architecture is extremely small. Further research should be directed to less examined regions and their contribution to the development of castle architecture, such as Central Asia and Eastern Europe.

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Генеза та фортифікація замкової архітектури раннього Середньовіччя

Анотація. Це дослідження присвячене детальному аналізу генезису і фортифікації замкової архітектури раннього середньовіччя, що охоплює період з V по XI століття. Здійснено великий огляд історичних документів, креслень, праць істориків і звітів археологічних досліджень. Дослідження розглядає архітектурні, соціальні та економічні аспекти замкової архітектури, приділяючи особливу увагу впливу історичних подій на оборонні споруди та змінам, спричиненим інтеграцією будівельних методів із різних культур. Основну увагу приділено вивченню еволюції замків від простих дерев'яних укріплень до потужних кам'яних фортифікацій, а також аналізу будівельних методів, застосованих у різних регіонах. Замкова архітектура раннього середньовіччя запозичила багато елементів із давньоримських і візантійських укріплень, як-от вежі, стіни і ворота. Ці елементи адаптувалися і розвивалися в умовах частих вторгнень і нестабільності, що призвело до створення потужніших і функціональніших фортифікаційних споруд. Замкова архітектура зароджувалася поступово, починаючи з простих укріплень, таких як Римські укріплення Отена, Саксонські бурги, розташування яких зафіксоване в списку Burghal Hidage, складеному в IX столітті. Одними з перших типів замків були Motte та Ringwork або схожі за функцією мотт і бейлі, спершу поширені в Англії та Німеччині, що являли собою укріплення на штучних пагорбах і ділянках землі, оточених ровами й валами, які відігравали важливу роль в укріпленні влади феодалів у XI-XII століттях. Прикладом таких укріплень стали вежа Пеньєрудес у Морсині та замок Каносса. Замок Мальборо у Вессексі, замок Берклі та замок Кастелло Фірміано є важливими пам'ятками фортифікації замкової архітектури V-XI століть, демонструючи більш розвинутий підхід до укріплення, порівняно зі своїми попередниками. Отримані висновки є важливими для аналізу розвитку замкової архітектури та розуміння історичних процесів, що вплинули на її формування

Ключові слова: мотт і бейлі; укріплені стіни; оборона; вежі; англосаксонські бурги

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BIM technologies adoption and implementation challenges in Eastern European countries analysis

Abstract. The study aimed to assess the level of integration of digital information technologies in the construction industry in Eastern Europe. Quantitative data on the implementation of Building Information Modelling (BIM) services in Eastern Europe was collected, and a comparative analysis of the dynamics of their use in 2020-2023 was conducted. The results of the study show a significant difference in the level of BIM implementation in Eastern European countries, which is closely related to the level of economic development, the state of the construction industry and support from government agencies. Countries with more developed economies and stable regulatory frameworks, such as Poland and the Czech Republic, have demonstrated the highest rates of BIM adoption. In these countries, various BIM services are actively used at all stages of the construction project life cycle, from design and modelling to construction management and facility operation. Government support in these countries includes the development of national standards, the introduction of mandatory requirements for the use of BIM in public tenders and the implementation of educational programmes to improve the skills of specialists, which promotes the active implementation of technologies and increases the efficiency of the construction industry. On the other hand, countries with less developed economies and limited government support have seen a slower process of BIM integration. In countries such as Ukraine, Bulgaria, and Romania, BIM has been applied mostly in individual projects, but the mass adoption of BIM is being held back by the lack of national standards, insufficient skilled personnel, and low awareness among market participants. The findings can be used to identify the key factors that influence the success of BIM implementation in the construction industry and can be used in the future to further develop effective digitalisation strategies in the region

Keywords: information modelling; construction processes; usage dynamics; project management; development strategies

INTRODUCTION

Building Information Modelling (BIM) is an advanced technology that is radically changing the way the construction industry designs, builds and operates facilities. BIM can be used to create three-dimensional digital models of buildings, as it is a comprehensive system that includes all the information needed to manage a project at all stages of its

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life cycle. These models contain data on architectural, engineering and construction components, as well as information on materials, costs, lead times, performance. However, when implementing BIM technology, different countries in Eastern Europe may face several significant challenges due to differences in economic development and other factors. Such differences in the initial conditions for BIM development make it impossible to implement a single universal approach for the entire region and require careful adaptation of the technology to the specific needs and capabilities of each country. The additional resources and effort required for such adaptation can be a serious obstacle for small companies and organisations, limiting their ability to fully take advantage of the benefits offered by BIM technology and implement innovative approaches in their operations.

A study of BIM adoption in Eastern Europe could fill important gaps in understanding the local challenges and potential of this technology in different economic and regulatory environments. This study can help identify effective strategies to overcome the obstacles associated with the implementation of BIM, as well as develop recommendations for creating favourable conditions for the development of this technology. This will not only help to harmonise standards in the region but also increase the overall efficiency of the construction industry in Eastern Europe. One of the main factors influencing the implementation of BIM is the level of technological readiness and economic development. M. Voloshyn & A. Petiakh (2021) analysed BIM technology and noted that this technology opens up wide opportunities for construction but requires significant technological changes for the implementation of BIM. V. Andrukhov & A. Potekha (2023) noted various factors in BIM integration, pointing out the importance of clear methods and technological adaptation for the successful development of the technology. H. Yuan & Y. Yuan (2020) emphasised the economic aspects that affect the adoption of BIM among industry professionals, emphasising their importance for the successful implementation of the technology. Thus, all these studies point to the need for a general and comprehensive approach for the successful implementation of BIM in Eastern Europe, which accounts for all the above factors and drivers.

An important factor in the implementation of BIM technology is the level of training and qualification of personnel in the field of BIM. J. Semaan *et al*. (2021) highlighted the importance of cooperation between educational institutions and industry to ensure the relevance and practical orientation of training. O. Casasayas *et al*. (2021) analysed the impact of government support on the development of BIM and demonstrated that countries with active government policies in the field of construction digitalisation are making much greater progress in implementing this technology. This confirms that for the successful implementation of BIM in Eastern Europe, it is also necessary to address such aspects as improving professional training, intensifying government support and adapting the technology to the specific conditions of each country.

Another factor that can affect the effectiveness of BIM implementation is the integration of the technology into existing infrastructures and processes (Kudabayev *et al*., 2022). K.-Y. Kang *et al*. (2022), in a study on the integration of BIM into traditional construction practices, determined that the adaptation of existing systems to new technologies is a critical success factor in this area. Q. Tushar *et al*. (2021) also investigated the interaction of BIM with other construction management tools, determining that synchronising data between different platforms can significantly increase efficiency. S. Girginkaya Akdag & U. Maqsood (2020), who analysed the implementation of BIM in the specific conditions of countries with different levels of infrastructure development, noted that the lack of standards and the need for individual solutions often slow down the integration process. However, these studies do not always consider in detail the specifics of individual countries and the challenges faced by these countries in implementing BIM, requiring further research to better understand the real opportunities for BIM implementation in different contexts.

The study aimed to comprehensively study the implementation of BIM technology in Eastern Europe and identify the key factors that influence the success of this process. In particular, the study included the task of investigating the existing problems and obstacles that accompany this process. Another important task of the study was to conduct a detailed review of 2020-2023 trends in the use of BIM, as well as to develop recommendations for optimising the implementation of the technology at the national level.

MATERIALS AND METHODS

Initially, a thorough analysis of the available information on BIM implementation in various Eastern European countries was carried out, which identifies the key benefits, obstacles and opportunities associated with BIM implementation. The next step was to create a classification of Eastern European countries according to their level of BIM adoption. This classification was based on several criteria, including the existence of national strategies for the digitalisation of the construction industry, the level of government support, the extent of BIM use in the private and public sectors, and the availability of educational programmes for training in this area. Four groups of countries were identified: leaders in BIM adoption, countries with a moderate level of adoption, countries in the early stages, and countries with a low level of adoption.

For a more detailed analysis, based on open information from the Eurostat Database (n.d.), quantitative data on the use of various BIM services in Eastern Europe, in particular for the periods 2020-2023, were collected. This process included an assessment of the dynamics of the adoption of such services, which cover various aspects of construction projects, from modelling and design to construction management and facility operation, which was used to track how the level of BIM adoption changes over time and identify the main services that are most widely used.

Particular attention was devoted to the analysis of awareness and use of such services among various construction market participants in Eastern Europe. In particular, the dynamics of changes in the percentage of BIM services used, as well as the level of awareness of their capabilities, were studied. The analysis of these data identified general trends in the implementation of BIM, as well as obstacles that hinder the spread of this technology, such as insufficient training, lack of national standards or financial constraints.

A key part of the research was the study of specific cases of BIM implementation in countries such as Poland, the Czech Republic, Hungary, Slovakia, Ukraine, Romania, North Macedonia, Bulgaria, Moldova, Serbia, Latvia, Lithuania and Estonia, which identified both common features and unique approaches to integrating this technology in different environments. This process included researching the identification of BIM projects and initiatives in the selected countries, as well as analysing detailed case studies, such as large infrastructure projects, commercial buildings, or government initiatives that have used BIM at various stages of the construction lifecycle. The study also included specific aspects such as technological infrastructure, staff education and training, and the level of support from the government and the private sector. Thus, the effect of these factors on the effectiveness of BIM implementation in different contexts was analysed, identifying general trends and specific differences in BIM implementation that are critical to the successful integration of this technology. Based on the data obtained, recommendations were developed for further implementation of BIM in Eastern Europe, focused on creating adaptive strategies that consider local conditions and country specifics to maximise the effect of BIM implementation and promote the development of the construction industry in the region.

RESULTS

BIM is an advanced technology that enables the creation of detailed digital models of buildings and infrastructure facilities, providing an integrated approach to their design, construction, operation and dismantling. At the centre of this approach is a three-dimensional model that can be used to display the geometry of the object and contains all the necessary data on its physical and functional characteristics. This includes information about materials, engineering systems, cost and time parameters, as well as data related to the performance and durability of the building.

The process of creating BIM begins with design, when architects, engineers and other specialists develop a three-dimensional digital prototype of the future facility. This model contains detailed information about all building components, including walls, floors, roofs, windows, doors, and utilities such as electricity, water, sewage, ventilation and air conditioning systems. Each element of the model has its unique characteristics, such as dimensions, materials, properties and precise location in the building structure, which can be used to create a visual representation of the building, analysing its behaviour in depth under real-world conditions. BIM is also a source of data for all project participants at all stages of the building's life cycle. During construction, the model can be used for work planning, material management, and quality control. Thanks to the integration of time parameters (4D), the timing of work can be predicted, which optimises resources and negates delays. Cost parameters (5D) can be used to control the project budget in real-time by analysing the costs of materials, labour and equipment (Marzouk & Elmaraghy, 2021).

During the operational phase, BIM is a key aspect of building management. It contains the entire history of the facility, including data on maintenance, repairs, upgrades and system replacements, which provides accurate and quick access to the necessary information for informed decision-making on the operation and further development of the facility. In addition, BIM improves the energy efficiency of buildings by enabling energy consumption to be analysed and the operation of heating, ventilation and air conditioning systems to be optimised. During the dismantling phase, BIM is central in containing data on all materials used and their possible reuse or recycling, which allows for efficient planning of the dismantling process, reducing costs and minimising environmental impact. BIM technology significantly contributes to the improvement of construction practices by introducing process standardisation and improving the quality of construction (Andrukhov *et al.*, 2024). Detailed digital models can be used for more accurate calculations and analyses, resulting in lower material costs, reduced waste and improved environmental performance. Additionally, BIM facilitates deeper integration of modern technologies such as automation, robotics and the use of innovative materials, making construction more flexible and adaptable to new challenges.

Analysis of studies by R. Samimpay & E. Saghatforoush (2020) and A. Abobakirov & O. Omonboev (2023) in the field of BIM demonstrates that the introduction of this technology brings significant benefits to construction projects. For instance, one of the key advantages of the technology is the ability to plan and forecast all aspects of a project in detail based on a digital model. The introduction of BIM technology can significantly improve the quality of construction project management and increase the efficiency of all participants, which can be used to determine in advance the best ways to implement the project, considering all technical, material and organisational factors. As a result, projects are implemented with maximum precision and coherence, which increases their efficiency and achieves high-quality standards. The use of BIM facilitates closer interaction between project participants, ensuring effective information exchange and coordination. Each project participant has access to up-to-date information in a convenient digital format, which enables quick adaptation to changes and informed decision-making. This improves the quality of communication and reduces the risk of misunderstandings or delays in the process. BIM also enables more accurate forecasting of project needs, which helps to ensure an uninterrupted supply of materials and resources. Thus, all project phases can be completed with optimal resource utilisation, increasing productivity and ensuring continuous progress in project implementation. This approach can be used to achieve a high level of customer satisfaction, as projects are implemented on time and with high quality.

An important aspect of BIM is its role in ensuring transparency and compliance with project requirements at all stages. This increases the trust of clients and investors, as they can monitor the progress of the project and be sure that all work is carried out following the established standards and requirements (Mesároš *et al.*, 2020). BIM can be used to control the quality of tasks and adapt to changes in project requirements, which ensures flexibility and adaptability of processes. This makes BIM a significant aspect that is transforming the way construction projects are managed, enabling high quality, efficiency and customer satisfaction. However, despite these advantages, the implementation of BIM is still accompanied by certain problems and obstacles that may hinder its spread in the construction industry. First, there is a significant difference in the level of awareness and interest in this technology among professionals of different specialities. While most architects, engineers and project managers acknowledge the potential of BIM, the level of implementation readiness can vary. This is because many participants in the construction process fear the risks associated with the transition to a new technology and often resist changes that may require significant efforts to adapt to new conditions (Saber & Wali, 2020).

Financial barriers also hold back BIM adoption. The costs of staff training, software and hardware can be significant, especially for small and medium-sized companies. In addition, the need for ongoing updates and support for the technology adds additional costs, which can discourage businesses from investing in BIM. Additionally, technical difficulties, such as compatibility issues between different software products, also hinder BIM adoption. The lack of universal standards and the difficulty of integrating BIM with other systems can create additional challenges for project teams, while insufficient technical support and limited access to specialised training programmes can delay the adoption of the technology (Toyin & Mewomo, 2022). Contractual and legal aspects are also noteworthy. Modern contracts often do not address the specifics of BIM, which can create uncertainty about the liability and ownership of digital models. Issues related to intellectual property and the rights to use BIM can complicate cooperation between different project parties, leading to additional legal risks (Bruggeman, 2020).

Non-technical factors, such as cultural differences and the willingness of project participants to cooperate, also have a significant impact on the success of BIM implementation. Differences in work approaches and different beliefs can hinder effective interaction between project participants. At the same time, a lack of willingness to share information and collaborate effectively can significantly reduce the potential benefits of using BIM. Thus, although BIM has significant potential to improve construction processes, several obstacles need to be overcome for its successful implementation. When analysing BIM technology in Eastern European countries, it should be noted that its implementation is uneven, depending on the level of economic development, government policy, and the readiness of the construction industry to innovate. Based on these factors, Eastern European countries can be classified into several groups, shown in Figure 1, which differ in terms of the level of adoption and implementation of BIM.

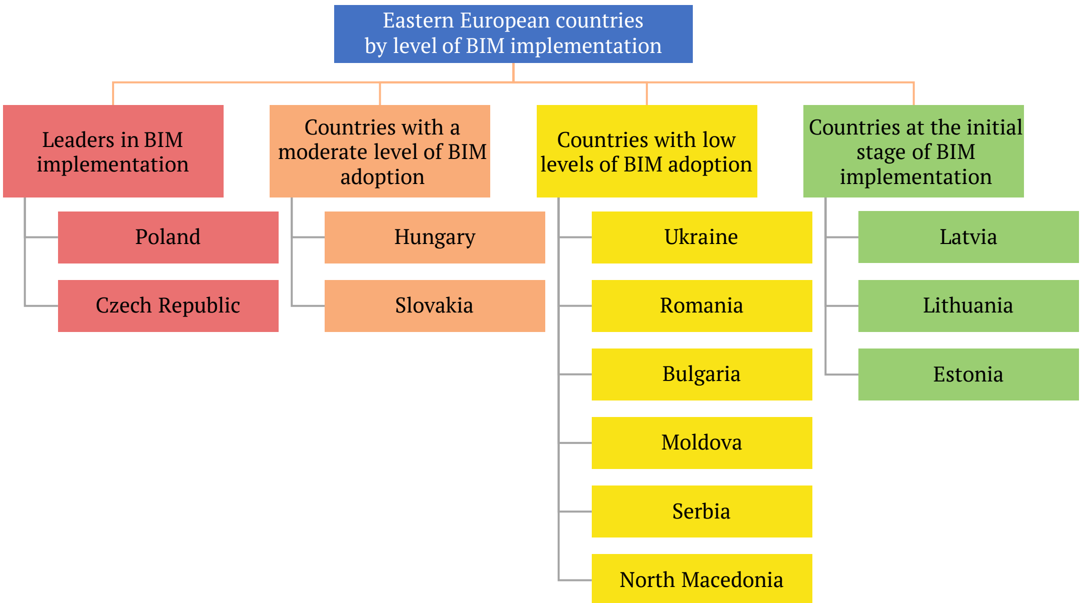

Figure 1. Classification of Eastern European countries by the level of BIM implementation
Source: compiled by the authors based on Eurostat Database (n.d.)

The first group includes countries that actively implement BIM at the state level, supporting its development through regulations and standards. Poland and the Czech Republic, being the leaders in the implementation of BIM technology among Eastern European countries, demonstrate an active approach to the integration of this technology into the construction sector at the state level. These countries recognise the importance of digital tools for improving construction efficiency and are actively working to create regulations and standards that promote the spread of BIM in practice.

The introduction of BIM technology in Poland is systematic thanks to the support of government agencies. The adoption of Directive No. 2014/24/EU of the European Parliament and the Council (2014), which became the basis for the requirements for the use of BIM in public procurement, was an important step. The Polish government launched the project "Digitisation of the construction process in Poland", which ended in 2020 with the development of "A roadmap for the implementation of BIM" (2021). One of the key goals of this strategy is to achieve a level of BIM adoption similar to that of the UK by 2025. Particularly noteworthy is the initiative to introduce MacroBIM in complex or risky public projects with a budget of more than 10 million EUR from 2025, and by 2030 – in all investment projects (Digitization of the Construction..., 2022). In addition, since 2023, Polish citizens have been able to submit electronic applications for a building permit, which was a significant step towards digitising the entire construction process (Decree of the Minister of Development and Technology of Poland No. 45, 2022).

The integration of BIM into public projects in the Czech Republic has also made significant progress in BIM adoption. The responsibility for this process lies with the Ministry of Industry and Trade, which developed a BIM implementation strategy back in 2017 (Concept of introducing the BIM..., 2017). This strategy was subsequently updated to reflect new challenges and opportunities. An important event was the decision to make BIM mandatory for public projects that exceed the threshold set by the EU starting in 2024 (Commission Delegated Regulation (EU) No. 2023/2497, 2023). Therefore, all major public projects in the Czech Republic will be implemented using BIM, which will significantly increase their efficiency and transparency.

The second group includes countries where BIM is being implemented moderately and gradually, mainly as part of private initiatives and without active government support. Hungary and Slovakia are prime examples of such countries. Although interest in BIM is growing in these countries, widespread adoption of the technology is being hampered by several factors, including insufficient government support, lack of clear standards and regulations, and certain inertia in the construction industry. In Hungary, interest in BIM from large construction companies and investors has been observed during 2020-2024 (Szabó, 2023). However, this interest has not yet led to large-scale industry-wide adoption of the technology. The main drivers of BIM development in Hungary are private companies that recognise the benefits of digital tools to improve project efficiency and accuracy. Furthermore, although there were attempts to develop national standards for BIM in the country, they did not receive adequate support from the state. The absence of a legal framework that would regulate the use of BIM in construction is slowing down the process of technology adoption in Hungary. A national strategy that could support BIM is currently under development or discussion. Slovakia is in a similar situation to Hungary, although BIM is already being actively used in large projects, particularly in industrial and infrastructure construction. However, the adoption of this technology on a mass scale is constrained by the lack of clear standards and regulations that would govern its use. For the most part, BIM is used voluntarily, in particular by large companies that have access to the necessary resources and investments. The Slovak government has not yet introduced mandatory requirements for the use of BIM in public projects, which limits the spread of this technology in public procurement and general construction projects.

The third group includes countries where BIM adoption is at an early stage and where there are significant barriers to its spread. This group includes countries such as Ukraine, Moldova, North Macedonia and Serbia. BIM adoption in these countries faces similar challenges, including a lack of a proper regulatory framework, an insufficient number of qualified professionals, and limited financial resources. Ukraine is showing some progress in the implementation of BIM technologies, although the process is still at an early stage. As of 2024, the use of BIM in Ukraine is mainly limited to large investment and international projects where the requirements for modern construction management technologies are part of the contractual terms (Nenastina *et al.*, 2024).

The first steps towards the implementation of BIM in Ukraine were taken in 2017 when pilot projects were launched with the participation of international companies and government customers (Trach *et al.*, 2022). For example, the Boryspil Airport reconstruction project included BIM elements to improve the management of the construction process. At the same time, BIM is not mandatory at the level of government programmes and regulations, and the technology is being implemented mainly at the initiative of individual companies and international investors. Ukraine lacks a clear national strategy or regulatory requirements for the implementation of BIM, which limits the widespread use of the technology, as many companies continue to use traditional methods of design and construction management. In particular, the lack of standards and an insufficient number of qualified BIM specialists significantly hinder the process of mass adoption.

In 2021, several conferences and seminars on BIM were held in Ukraine, including events organised by the Ukrainian BIM Association and other professional organisations (Levchenko *et al.*, 2022). These events helped to raise awareness among professionals and stimulate interest in the technology. However, to achieve large-scale adoption, additional efforts are needed to develop national standards, create educational programmes and encourage the public sector to adopt BIM as part of the national strategy for the development of the construction industry.

Romania is gradually moving towards the introduction of BIM in construction processes, although the process remains rather slow. The lack of a national strategy and standards for BIM is one of the main obstacles to the widespread use of this technology. As of 2024, BIM is used mainly in the private sector, in particular in large international projects implemented with the participation of foreign investors. In 2020, the Romanian Ministry of Transport, Infrastructure and Communications initiated several pilot projects using BIM, but so far these are only isolated cases. Education in BIM also needs to be developed, as curricula at Romanian universities are just beginning to include courses on the subject. Bulgaria, similar to Romania, is just starting to implement BIM in its construction processes. In 2020, the government published "Digital transformation of Bulgaria for the period 2020-2030" (2020), which includes plans for the digitalisation of the construction sector, including the introduction of BIM. However, as of 2024, BIM is not mandatory in Bulgaria, and its use is limited to certain large projects, especially those with international participation. Most Bulgarian companies are still using traditional construction methods, and only a few are starting to apply BIM in their work. The lack of qualified professionals and the absence of national standards are among the main challenges the country faces. Moldova has only recently started to consider the possibility of introducing BIM at the state level. There are no specialised programmes or courses to train professionals in this field in the country, which makes it difficult to develop BIM. In addition, most construction companies in Moldova follow traditional approaches to design and construction management, which further slows down the process of transition to digital technologies. North Macedonia and Serbia also face similar challenges in implementing BIM. In both countries, the lack of a clear government policy on the digitalisation of the construction sector and limited funding for research and development make it difficult to widely adopt BIM. Most construction companies in these countries operate using traditional methods, and only a small proportion of large projects involve the use of BIM.

The fourth group of countries with an initial level of BIM adoption includes the Baltic States – Latvia, Lithuania and Estonia. Although these countries are geographically part of Northern Europe, they are historically and culturally closely linked to Eastern Europe. The implementation of BIM in these countries is at an early stage but has its characteristics in each of them. Latvia has begun to introduce BIM into construction processes mainly through private initiatives and international investors. In 2018, a programme was launched to promote digitalisation in the construction sector, including the introduction of BIM (Latvian National Standard (LVS) No. 1052:2018, 2018). However, national standards for BIM have not yet been developed, and the technology remains less popular in public projects. The greatest progress has been made in the commercial sector, where BIM is being used in new investment projects, especially with the participation of international partners. Lithuania is also in the early stages of BIM integration. In 2016, the Lithuanian Ministry of Transport and Communications initiated the Digital Construction project aimed at developing digital technologies in construction, including BIM (Guidelines for Digital Construction..., 2014). As part of this project, several training seminars were held for construction professionals. However, as in Latvia, BIM standards have not yet been introduced at the national level, and most projects using BIM are concentrated in the private sector. Estonia, known for its commitment to digital innovation, is showing greater interest in BIM implementation. In 2019, the Estonian government launched the "E-construction Platform" (Vision of e-construction..., 2018) project, which sees BIM as a key element in the digitalisation of the construction sector. Estonia is also actively developing national standards for BIM, which are planned to be introduced in the coming years. However, as of 2024, BIM is used mainly in pilot projects and initiatives of large construction companies. The dynamics of the rating of the use of various BIM services in Eastern Europe (as a percentage of the total number of projects using BIM) is presented in detail in Table 1. Dynamics of the level of adoption, use, and general awareness of BIM technologies in Eastern Europe in 2020-2023 are shown in Figure 2.

Table 1. Dynamics of BIM services usage in projects in Eastern Europe

BIM service	2020	2021	2022	2023
Building modelling	22%	29%	36%	41%
Construction process management	-	-	31%	33%
Project coordination	-	-	24.5%	30.3%
Expenditures analysis	12.5%	15%	18.4%	22.8%
Information management	12%	18%	22%	27%
Technical support	10.5%	12%	15.9%	19%

Source: compiled by the authors based on P. Fiamma & S. Biagi (2023)

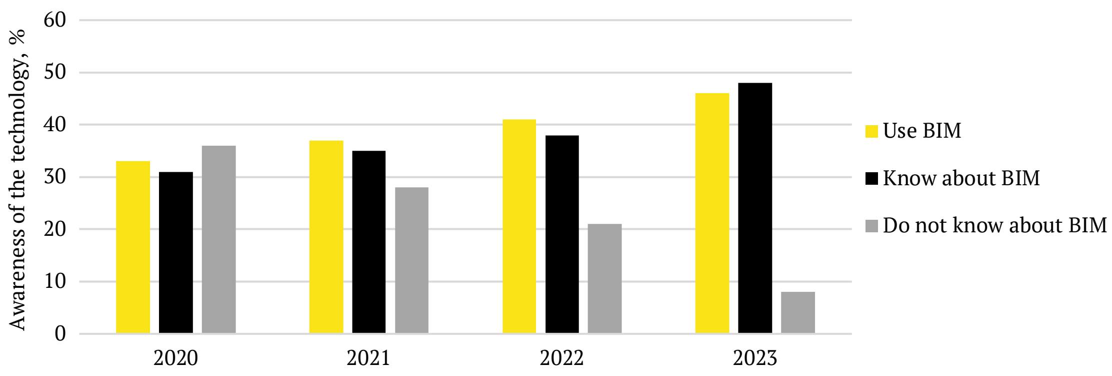

Figure 2. Implementation of BIM technology in Eastern Europe
Source: compiled by the authors based on P. Fiamma & S. Biagi (2023)

In general, the implementation of BIM in Eastern Europe is a complex and heterogeneous process that depends on many factors, including economic development, government policy, availability of skilled personnel and the readiness of the construction industry to change. While some countries, such as Poland and the Czech Republic, have already made significant progress in implementing BIM, most countries in the region are still in the early stages of the process and require additional efforts to overcome existing obstacles. An analysis of the experience of developed countries has made it possible to identify a comprehensive approach for the successful implementation of BIM technology in countries with a low level of its use, which includes several key stages, as shown in Figure 3.

Figure 3. Scheme of successful implementation of BIM technology
Source: compiled by the authors

Thus, the first step for the successful implementation of BIM is to create national standards and regulations that would govern the use of BIM in the construction industry. This should include the development of official guidelines for the design, construction and operation of facilities using BIM technologies. Standardisation is key to ensuring that all market participants can use the same methodology and technology. Educational campaigns and training programmes for BIM specialists are an important aspect. It is necessary to develop and implement educational programmes in higher education institutions, as well as organise refresher courses for already working professionals, which will increase the level of awareness and knowledge of the technology among architects, engineers, project managers and other participants in the construction process. To attract interest in BIM technologies, it is necessary to create financial and other incentives for companies that are willing to invest in the digitalisation of construction processes. This could include tax breaks, research and development grants, and support from government agencies in the form of subsidies.

One of the most effective ways to stimulate BIM adoption is to require its use in public construction projects. This can set an example for the private sector and create demand for the technology. In addition, it is important to ensure interoperability and compatibility of the various software solutions used for BIM to avoid technical obstacles. It is also necessary to regularly monitor the BIM implementation process and evaluate progress to identify problems and address them promptly, which may include periodic updates to standards, analysis of the impact of BIM implementation on the construction industry, and assessment of the cost-effectiveness of the technology. Thus, the introduction of BIM in Eastern Europe is an important step towards the modernisation of the construction industry. Despite the existing challenges, this process offers significant opportunities to improve the efficiency, transparency and quality of construction. In the future, the development of BIM in the region could become the basis for a more sustainable and innovative approach to construction project management, contributing to economic growth and strengthening international competitiveness. The full implementation of BIM will require efforts from both the government and the private sector, which will be key to creating a modern, digitally oriented infrastructure in these countries.

DISCUSSION

This study examined the implementation of BIM technology in Eastern European countries, which was used to identify significant differences in the level of its development and application. The results of the study showed that in countries with developed economies and progressive regulatory systems, such as Poland and the Czech Republic, the level of BIM adoption is significantly higher, which is reflected in the active use of various BIM services at all stages of the project life cycle. At the same time, in countries with less economic development and less government support, BIM implementation faces numerous challenges, such as the lack of clear national standards and a lack of qualified professionals. The study emphasised the importance of developing and implementing local standards and training programmes, which can help reduce the technological gap between countries in the region and ensure more efficient use of resources in the construction industry. M. Xing *et al*. (2023) also addressed the impact of public policy on BIM adoption, showing how different approaches to regulation and financing can affect the speed of technology integration. L. Wang *et al*. (2020) analysed educational programmes in the field of BIM, revealing significant gaps in the training of specialists in different countries, as well as the need to update curricula to meet modern requirements. A. Ganah & G. Lea (2021) studied the impact of international initiatives and standards on the development of BIM, which indicated the importance of harmonising national practices with international standards to achieve a greater level of integration and efficiency. Thus, the results of this study, alongside the results of the above-mentioned works, emphasise the importance of considering the specific conditions of each country when implementing BIM. They indicate that successful integration of the technology requires an analysis of existing practices and standards, as well as consideration of local economic and educational factors that influence its development.

The study also examined in detail the advantages and obstacles to implementing BIM technology. In particular, the Main benefits of BIM were found to include significantly improved coordination between the various stakeholders in a construction project through a single digital model, which reduces the likelihood of errors and conflicts in project data. BIM technology also helps to improve design accuracy and optimise construction costs by enabling early detection of potential problems and conflicts (Piddubna *et al*., 2024). These aspects highlight the importance of BIM implementation to improve the quality and efficiency of construction projects. However, the study also identified several significant obstacles that hinder the widespread adoption of BIM in the region, including the lack of uniform national standards and regulations for BIM, insufficient number of qualified professionals, insufficient attention to training and professional development, and limited government funding and support for the implementation of BIM in building infrastructure, which delay the modernisation process. Y.Y. Al-Ashmori *et al*. (2020) also studied in detail the benefits of BIM, including increased design accuracy and improved coordination between project participants. A. Pidgeon & N. Dawood (2023) analysed the main aspects that provide the benefits of BIM technology, showing that the use of BIM significantly increases the efficiency of processes in construction, which is an important factor for successful implementation. At the same time, K.M. Tönis & H. Voordijk (2023) analysed technical shortcomings, such as the lack of common standards for data exchange and problems of integration of different BIM systems. Comparing the results of these studies with the results of the present study, it should be emphasised that the present study provided a more comprehensive overview of the advantages and disadvantages of BIM implementation. While the aforementioned works are aimed at studying specific cases in the use of BIM, this study included both the study of positive aspects and analysis of obstacles to the implementation of the technology, which was used to better understand the complexity of the problems and develop more effective strategies to overcome them.

The analysis of the dynamics of the use of various BIM services over the years noted a significant increase in their implementation and popularity. A steady increase in the use of building modelling services was noted, indicating the growing importance and prevalence of this technology. Cost analysis also showed growth, highlighting the growing recognition of the importance of accurate cost management in construction projects. Additionally, information management and technical support services also showed positive trends, reflecting an overall improvement in the awareness and use of BIM technologies in various aspects of the construction process. In terms of overall BIM awareness, the data showed a significant increase in both the level of knowledge of BIM and the actual use of the technology. This indicates a positive trend in the adoption of the technology and a decrease in the number of people who are unaware of BIM. Thus, the results indicate the growing popularity and understanding of BIM technologies, which, in turn, may contribute to their wider adoption in the future. A.O. Baarimah *et al*. (2021) also analysed the dynamics of growth in the use of various BIM services, showing a steady increase in the integration of technology into construction projects. X. Chen *et al*. (2021) analysed the effectiveness of using various BIM services, revealing significant variations in the way they are used depending on the goals and objectives. R. Alshorafa & E. Ergen (2021) studied the effectiveness of implementing BIM services in large projects, which revealed a positive impact on the overall level of technology adoption and awareness of BIM. Comparing the results of this study with the results of the above-mentioned works, it should be emphasised that, unlike other works that investigated the use of BIM in other regions, this study confirmed the general growth trends in the implementation of BIM services, and allowed to detail specific aspects of the dynamics of their use in Eastern Europe. This provided a better understanding of the implementation mechanisms and effectiveness of different approaches, which is important for the further development and optimisation of the BIM implementation strategy in the construction industry in the region.

This study proposed a methodology for successful BIM implementation that includes several key steps: developing national standards, training and awareness raising, stimulating innovation, integrating into public projects, and monitoring and evaluation. Establishing formal standards and guidelines is critical to ensure consistency and quality in the application of BIM at all levels of the construction process (Dmytrenko *et al*., 2024). The development of standards creates clear guidelines for market participants and reduces misunderstandings and errors that can arise from the lack of uniform rules. Training and awareness-raising through the introduction of educational programmes in higher education institutions and courses is another important step to ensure that professionals develop the necessary skills and knowledge. Stimulating innovation through financial incentives and support encourages investment in technology and facilitates the faster introduction of innovative solutions into the construction process. Integration of BIM into government projects, including through the requirement to use the technology in government tenders, ensures widespread use and demonstrates the government's commitment to modernising construction infrastructure (Kramskyi *et al*., 2023). Monitoring and ongoing analysis of progress allow for rapid response to changes and adaptation of strategies to meet new requirements and trends. Together, these elements form a comprehensive approach to BIM implementation that ensures efficiency, quality and sustainability in the development of the construction industry. S.M.N. Sakib (2020) considered the aspects of developing standards for BIM, emphasising the importance of clear regulations for the successful implementation of the technology in different countries. M. Xie *et al*. (2022) also focused on the study of the process of standardisation of BIM technology, showing that it is critical for successful development and contributes to the faster implementation of BIM. The results of the current study, together with the mentioned works, present a holistic approach to the implementation of BIM, focusing on the need for an integrated approach. This allows for an effective framework for the widespread adoption of BIM, which in turn ensures higher quality, reduced costs and improved management of construction projects.

Thus, all such studies are critical to understanding and successfully implementing BIM technologies. By providing a comprehensive analysis of existing practices and identifying the main benefits and obstacles, such studies help to formulate effective strategies for BIM implementation. They contribute to the development of optimal approaches that consider the specifics of different countries and their needs, which in turn increases the efficiency of construction projects, reduces costs and improves quality. This creates an important basis for the successful modernisation of the construction industry and the introduction of the latest technologies, which will contribute to its sustainable development.

CONCLUSIONS

This study analysed the level of BIM adoption in Eastern European countries and found that this level varies significantly and depends on many factors, including government support, the availability of national standards, educational programmes and the overall readiness of the construction industry to adopt digital innovations. The study showed that some countries, such as Poland and the Czech Republic, are at the forefront of BIM adoption, demonstrating active government support and strategies aimed at digitalising the construction industry. These countries are actively working to create national regulations for BIM, which allows the technology to be integrated into large infrastructure projects. Other countries in the region, such as Hungary and Slovakia, are at a moderate stage of BIM adoption, with the main burden of implementation falling on private companies and individual projects. In these countries, there is interest in using BIM, especially in large construction companies, but widespread adoption of the technology is limited by a lack of systematic government support and clear standards. The third and fourth groups of countries, which include Ukraine, Bulgaria, Romania, the Baltic States and other countries, are at a low and early stage of BIM implementation. In these countries, there is a low level of BIM use, which is associated with a low level of government support, a lack of national standards, and a shortage of qualified personnel. In Ukraine, in particular, BIM technologies are used in large international projects where it is a requirement of investors, but the technology has not yet become widespread at the national level.

The study determined that several obstacles need to be overcome for the successful implementation of BIM in Eastern Europe, the most important of which is the lack of a clear regulatory framework, an insufficient number of specialists, and low awareness of the benefits of using BIM among a wide range of construction stakeholders. An important condition for the successful implementation of BIM is close cooperation between the state and the private sector, the development of national standards, and active support for educational programmes aimed at training specialists in this field. Notably, this study has certain limitations, including limited coverage of regional and sectoral specifics of BIM implementation in individual countries, as well as the lack of a detailed analysis of the impact of economic crises and political changes on the implementation of this technology. For further research, it is recommended to focus on conducting more in-depth case studies in countries with different levels of BIM adoption, as well as on studying the role of various factors in the process of technology integration.

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None.

CONFLICT OF INTEREST

None.

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Аналіз проблем впровадження та адаптації BIM-технологій у Східній Європі

Анотація. Метою дослідження була оцінка рівня інтеграції цифрових інформаційних технологій у будівельну галузь у країнах Східної Європи. Зібрано кількісні дані щодо впровадження сервісів інформаційного моделювання будівель (BIM) у країнах Східної Європи та проведено порівняльний аналіз динаміки їх використання у 2020-2023 роках. Результати дослідження свідчать про значну різницю в рівні впровадження BIM у країнах Східної Європи, що тісно пов'язано з рівнем економічного розвитку, станом будівельної галузі та підтримкою з боку державних органів. Країни з більш розвиненою економікою та стабільною нормативно-правовою базою, такі як Польща та Чехія, продемонстрували найвищі темпи впровадження BIM. У цих країнах різні BIM-сервіси активно використовуються на всіх етапах життєвого циклу будівельного проєкту – від проєктування та моделювання до управління будівництвом та експлуатації об'єкта. Державна підтримка в цих країнах включає розробку національних стандартів, введення обов'язкових вимог щодо використання BIM у державних тендерах та реалізацію освітніх програм для підвищення кваліфікації фахівців, що сприяє активному впровадженню технологій і підвищенню ефективності будівельної галузі. З іншого боку, в країнах з менш розвиненою економікою та обмеженою державною підтримкою процес інтеграції BIM відбувається повільніше. У таких країнах як Україна, Болгарія та Румунія, BIM застосовується переважно в окремих проєктах, але масове впровадження BIM стримується відсутністю національних стандартів, недостатньою кількістю кваліфікованого персоналу та низькою обізнаністю учасників ринку. Отримані результати можуть бути використані для визначення ключових факторів, що впливають на успіх впровадження BIM у будівельній галузі, і можуть бути використані в майбутньому для подальшої розробки ефективних стратегій діджиталізації в регіоні

Ключові слова: інформаційне моделювання; будівельні процеси; динаміка використання; управління проектами; стратегії розвитку

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Formation of the principles of tectonics of modern architectural forms

Abstract. The purpose of the study was to create a theoretical model that reveals the principles of tectonics development of modern architectural forms, considering technological innovations, environmental requirements, and cultural context. The results show that the concept of tectonics has changed from the classical to the modern multidimensional approach. The basis of modern tectonics is determined by three key elements: technological innovations (parametric design, 3D printing, robotic production), environmental requirements (energy efficiency, bioclimatic design, circular economy), and cultural context (hybrid tectonics, digital language). The developed theoretical model contains five main principles (integrative, adaptive, optimisation, contextual, and expressive) that form the tectonics of modern architectural forms. Based on the analysis of modern architectural projects, the paper identified promising areas for the development of tectonic principles, including smart tectonics, bio-tectonics, and digital localism. The study emphasised the growing

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role of adaptive facade systems in shaping the tectonics of modern architecture and demonstrated the potential of the proposed model to predict the development of architectural forms, considering technological trends and environmental requirements. The study confirmed the importance of an interdisciplinary approach to architectural design and laid the foundation for the development of architectural theory and practice that can meet the challenges of modernity, especially in the context of sustainable development and cultural identity

Keywords: digital fabrication; parametric modelling; adaptive facades; bioclimatic design; morphogenesis; structural systems

INTRODUCTION

Modern architecture of the 21st century is undergoing profound changes caused by a number of key factors, including the impact of rapid technological progress, changing societal needs, and growing attention to environmentally friendly and sustainable building solutions. The construction environment is enriched by the integration of digital technologies, the use of innovative building materials and the development of environmental components in construction, which creates new opportunities for architects and designers. The study of the theoretical foundations that determine the tectonics of modern architectural forms is determined by three crucial trends. Globalisation and digitalisation of the construction industry have led to the need to develop universal tectonic principles that can align local specifics with global technological changes. However, increased attention to environmental sustainability requires rethinking the relationship between form, function, and energy efficiency of a building. In addition, advances in parametric design have enabled the creation of complex geometric shapes, the implementation of which requires the development of fundamentally new tectonic approaches.

Recent research demonstrates the versatility of scientific research in the field of tectonic principles. Important contribution of H. Al-Alwan & Y.B. Mahmood (2020) represents the evolution of tectonics in architectural theory through the prism of historical development and focuses on the dynamic nature of this concept. The study by Y. Hurol (2022) deepens the influence of tectonics on modern architecture, exploring the psychological perception of space and the emotional resonance of architectural forms. Research by A.F.H. Almaz & M.A.F. Farahat (2023) highlights the potential of sustainable tectonics to create sustainable structural systems. In addition, the importance of the concept of tectonics for the development of architectural design is emphasised by demonstrating the integration of ecological principles with aesthetic expression. A significant breakthrough in understanding the dynamic aspects of tectonics is reflected in the papers by Y. Akgün *et al.* (2022), which investigate the principles of kinetic architecture and adaptive systems. The study by M. Lakkala (2023) reveals the complex dialectic between traditional building materials and innovative finishing techniques. The researchers show how modern digital manufacturing techniques transform the properties of materials and create new opportunities for tectonic expression. The methodology developed by the authors for assessing architectural quality considers both technical and promising aspects of materiality in architecture.

A fundamental study of the spatial aspects of tectonics is presented in the paper by B. Yazdani *et al.* (2023). Based on the analysis of cultural characteristics from 1978 to 2020, the researchers developed a conceptual model of the relationship between internal spatial configuration and external entities. The proposed methodology shows how the cultural function of a building affects the formation of its tectonic image. A review of tectonic approaches in landscape architecture by M. Naghibi *et al.* (2023) describes the possibility of applying tectonic principles at the urban planning level. The analysis of the interaction of natural and anthropogenic elements of the urban environment allowed the researchers to formulate the principle of landscape tectonics. Y.I.P. Hematang & I. Ikaputra (2022) based on a systematic analysis of the literature, identified four main aspects of tectonics (structural, material, spatial, and symbolic). The theoretical framework developed by the researchers provides a basis for analysing tectonic systems, considering both technical and cultural-semantic aspects of architecture.

Critical analysis of research papers indicates insufficient study of the influence of digital technologies on the formation of tectonic principles, mechanisms for integrating environmental elements into tectonic solutions, and methodological foundations for the analysis of multidimensional architectural spaces. Special attention should be paid to the study of the correlation between the technical capabilities of modern architecture and the aesthetic expressiveness of architectural forms, and the influence of environmental imperatives on the development of tectonic solutions. A difficult task for the theory of modern architecture is to rethink the traditional concept of tectonics in the light of new technological opportunities and environmental requirements. The study of tectonics in modern architecture requires a comprehensive approach that covers not only architectural and aesthetic aspects, but also socio-cultural, economic, and environmental factors. It is particularly important to develop a methodological framework for analysing and designing tectonic systems that can adapt to changing environmental conditions and meet the growing requirements for energy efficiency and sustainability of buildings. The purpose of this study was to develop a theoretical model that would explain the formation of tectonic principles in modern architecture by systematising and analysing the impact of technological innovations, environmental requirements, and cultural context on the development of architectural tectonics.

LITERATURE REVIEW

The study of the formation of tectonic principles of modern architectural forms covers a wide range of scientific studies that consider this topic from different standpoints. Analysing the literature, the main research areas and key concepts that form the modern understanding of architectural tectonics can be identified. Fundamental to understanding the evolution of the principles of tectonics is the study by O. Remizova (2023), which analyses the constitutive language and logic of architecture in historical contexts. The researcher traces the development of tectonic concepts from classical forms to modern experimental approaches, emphasising the importance of cultural context in shaping the expressiveness of architecture. L. Tiutina (2021) considers plastic language as a result of the evolution of tectonic principles in architecture of the 20th and 21st centuries. She shows how technological innovations and changing social needs have influenced the transformation of tectonic forms. The researcher pays special attention to the relationship between the constitutive potential of architecture and its aesthetic expression.

Fundamental study by L. Tiutina & A. Davydov (2021) reveals the multidimensional nature of factors influencing the development of modern architecture. The researchers developed a comprehensive analysis method that considers the interaction of technological capabilities, social demands, and economic constraints in the formation of tectonic solutions. Special attention is paid to the mechanisms of transformation of conventional construction technologies under the influence of digitalisation and automation of production processes. M.A. Kamal (2020) presented a systematic review of the latest achievements in materials science and their impact on the development of facade systems. The study revealed a correlation between innovations in the creation of composite materials and the expansion of architectural plasticity capabilities. Classification of modern facade systems according to the criteria of manufacturability and adaptability to climatic conditions is proposed. The cultural dimension of architectural theory appears in the paper by M. García Vergara & A. Pizza (2021), which is based on the analysis of Mediterranean architecture and traces the relationship between regional traditions and modern formative trends. The researchers offer an innovative approach to understanding regional architectural practices in the context of global transformation.

S. Buravchenko (2019) developed a theoretical understanding of the aesthetic and typological foundations of modern architecture. The paper offers a methodology for analysing tectonic solutions through the prism of the historical evolution of architectural forms, which allows predicting promising areas for the development of the architectural language. In the subsequent study, S. Buravchenko (2023) develops an understanding of the tectonic prerequisites for the development of various architectural forms. The researcher develops a conceptual model of the relationship between the design capabilities and plastic capabilities of modern building systems, showing how technological innovations expand the range of possible architectural solutions. H. Al-Alwan & Y.B. Mahmood (2020) explore the importance of tectonics in architectural theory, revealing the multi-layered nature and cultural conditionality of the concept. The study demonstrates the influence of different cultural contexts on the interpretation and application of tectonic principles. Y. Hurol (2022) analyses tectonic influences in modern architecture and focuses on the emotional impact of architectural form. The work expands the understanding of tectonics, including psychological aspects of the perception of architectural space. A.F.H. Almaz & M.A.F. Farahat (2023) explore the use of sustainable tectonics to create long-lasting architectural frameworks with artistic dimensions and expressive design. The study highlights the importance of including sustainability principles in modern tectonic solutions. Y. Akgün *et al*. (2022) explore the tectonics of kinetic architecture, offering new possibilities for dynamic tectonic forms. The study shows how technological innovations push the boundaries of traditional understanding of architectural tectonics. J.C. Gomes *et al*. (2022) consider tectonics as a means of reconciling minds and emotions in architectural projects. The paper emphasises the importance of balancing technical requirements and aesthetic expressiveness in the development of tectonic principles. M. Tawa (2020) reveals the interdisciplinary potential of the concept of tectonics through the analysis of frame action in tectonic strategies of cinema and architecture. The study demonstrates the possibilities of applying tectonic principles in various fields of art and design. M. Lakkala & J. Pihlajaniemi (2021) explore tectonics and architectural quality in contemporary Finnish wooden architecture. The study reveals methods for rethinking traditional materials in the context of modern tectonic approaches.

A. Copley & O.M. Weller (2024) offer a perspective on understanding construction tectonics on a landscape and urban scale by considering continental tectonics in a geological context. I. Bulakh *et al*. (2022) expand the understanding of tectonics to the scale of the urban environment through the study of the integrity of the artistic image of the city based on symbolisation. B. Yazdani *et al*. (2023) analyse the role of spatial tectonics in the development of cultural buildings. The study highlights the importance of the relationship between internal space and external form in the formation of the tectonic principle. M. Naghibi *et al*. (2023) expand the understanding of tectonics from a single building to a landscape scale through a tectonic approach in landscape architecture. Yu. Ivashko *et al*. (2020) analyse the impact of the natural environment on the transformation of architectural styles, identifying important aspects of the development of modern tectonic principles, considering environmental factors. C. McCoy (2021) examines building structures in the context of architectural theory, emphasising the importance of integrating technical aspects into the theoretical understanding of tectonics. Y.B. Mahmood & H.A.S. Al-Alwan (2023) offers a new approach to integrating environmental principles into tectonic solutions by studying the relationship between tectonics and sustainable architecture. Y.I.P. Hematang & I. Ikaputra (2022) present a systematic approach to the analysis of tectonic principles in modern architecture by defining four aspects of structural tectonics. M.P. Louw (2021) reveals the importance of cultural context in shaping tectonic principles through the study of hybrid tectonics in modern African architecture.

The literature review demonstrates the diversity and interdisciplinarity of research in the formation of tectonic principles in modern architectural forms. The analysis reveals key areas of research: the impact of technological innovations, environmental requirements, cultural context, and psychological aspects of perception on the formation of modern tectonic principles.

MATERIALS AND METHODS

The theoretical study of the principles of tectonics of modern architectural forms was based on an exhaustive analysis of data obtained from leading scientometric databases, such as Web of Science and Scopus. Specialised architectural repositories were also involved, in particular, the Avery Index and RIBA Library Catalogue, covering the period from 2020 to 2024. The search procedure was carried out using keywords that have a direct architectural context. Among them, special attention was paid to such concepts as architectural tectonics, digital manufacturing, sustainable architecture, parametric design, eco-tectonics, hybrid architecture, and smart building systems. Additional terms were used to better understand the topic, including adaptive facades, biomimetic architecture, digital morphogenesis, and adaptive architecture.

The study analysed peer-reviewed publications that highlight three key aspects of tectonics: technological innovation, environmental characteristics, and cultural context. The selection of materials was based on the actual availability of empirical data, a transparent methodology, and a well-defined architectural approach. The study of digital tectonics was carried out through a detailed analysis of technical documentation on parametric design, additive technologies, and robotic production. The focus was on digital instrument specifications, production protocols, and additive system specifications.

The theoretical analysis covered research on modern construction projects for the period from 2020 to 2024, based on the systematisation of scientific publications in leading architectural journals and professional databases. In particular, studies by A.F.H. Almaz & M.A.F. Farahat (2023) on stable tectonics, Y. Akgün *et al*. (2022) on kinetic architecture, and B. Yazdani *et al*. (2023) concerning the role of spatial tectonics in the formation of cultural buildings were used. The projects were analysed through the prism of three main aspects: technological innovations in architecture, reflected in the study by M.A. Kamal (2020), environmental solutions considered by Y.B. Mahmood & H.A.S. Al-Alwan (2023), and the cultural context considered by M. García Vergara & A. Pizza (2021). This approach helped to comprehensively understand current trends in the development of tectonic principles and substantiate the theoretical model.

Special emphasis was placed on the integration of digital technologies into construction processes and their impact on architectural decision-making. The analysis of eco-tectonics was carried out by studying data on energy-efficient solutions, bioclimatic design, and circular economy principles. Technical documentation on building energy efficiency, certificates of environmental standards and passive air conditioning systems were carefully investigated. The impact of renewable energy sources and environmentally friendly materials on architectural practice was analysed. The study on urban tectonics was carried out by analysing urban planning documentation and projects related to the integration of architectural objects into the urban environment. Materials that reveal the formation of architectural ensembles, the interaction of buildings with the historical context, and the creation of new urban dominants were investigated. Technical documentation for scaling tectonic principles from the level of a separate building to an urban block was analysed, covering the specifications of public spaces, transit zones, and communication nodes.

The study of hybrid tectonics was based on material analysis to combine traditional and innovative construction approaches. The documentation of projects that combine local traditions with technological innovations that emphasise the reinterpretation of traditional methods in modern conditions was studied with particular interest. The concept of regenerative design was explored through the analysis of project documentation that integrates buildings into natural ecosystems. Bioclimatic strategies, rainwater harvesting systems, green roofs, and vertical landscaping were considered to minimise the negative impact of buildings on the environment. Virtual tectonics was studied by analysing digital documents describing the formation of an architectural space using augmented reality technologies and interactive systems. Special emphasis was placed on adaptive facade systems and smart technologies to ensure dynamic interaction of the building with its environment.

RESULTS AND DISCUSSION

Modern architecture is increasingly weaving dynamic tectonics into its designs, creating shapes that convey a sense of movement and liveliness through complex geometric structures. This trend reflects the transition from traditional static forms to more organic and plastic solutions. Based on parametric design and digital technologies, architects can implement complex curved shapes. Environmental considerations are becoming an important factor in modern architectural tectonics. Biomimetics inspires the creation of buildings that not only resemble natural forms, but also function like natural ecosystems, which contributes to increased energy efficiency and sustainability. The concept of smart tectonics is becoming increasingly relevant as it integrates intelligent systems into architecture, allowing buildings to adapt to changing environmental conditions and the needs of residents. This can manifest itself in changing facades, adjusting lighting and ventilation, and transforming the interior space. Tectonics ceases to be static and reacts to external and internal variables. Modern architecture does not develop in a vacuum, it is closely linked to culture and social change. Architects strive to express collective values and identity through architectural forms, making structures expressive of social and cultural aspects. Globalisation and digital technologies have a significant impact on the development of modern tectonic approaches. This observation is consistent with research by L. Tiutina (2021), which analyses plastic language as a consequence of the evolution of tectonic principles in the architecture of the 20th and 21st centuries. The results of the conducted research on the impact of technological innovations on the development of tectonic principles correspond to the fundamental studies by L. Tiutina & A. Davydov (2021). In these studies, the researchers analysed in detail various factors that influence the development of the aesthetic language of modern architecture. The studies demonstrate how innovations in the technological sphere significantly affect tectonic solutions, which, in turn, leads to significant changes in architectural design methods and construction processes. The fusion of different architectural traditions with innovative technologies creates a new hybrid language of architectural expression that can adapt at different scales – from global to local.

The concept of architectonics has its origins in ancient times, in particular, in the era of Ancient Greece. Initially, this term was used to describe the universal principles of shaping in the field of architecture. However, over time and historical development, the content of this concept has evolved significantly: from a simple definition of the logical structure of compositions to a more complex and multi-layered concept that integrates the technical, aesthetic, and cultural aspects of architectural creativity (Al-Alwan & Mahmood, 2020; Hematang & Ikaputra, 2022). A thorough analysis of the architectural styles of past eras demonstrates a dynamic change in the perception of tectonic principles over the centuries (Tiutina, 2021). During the neoclassical period, the emphasis was placed on a clear and expressive reflection of the internal logic of the building's composition. Regional architectural traditions played an important role in shaping specific tectonic solutions, which was particularly pronounced in various cultural contexts, such as in the architecture of the Mediterranean region (García Vergara & Pizza, 2021; Louw, 2021).

Drastic changes in approaches to tectonics occurred in the 19th century with the spread of the latest building materials. The introduction of metal and reinforced concrete structures has radically transformed the methods of creating architectural forms. Of particular importance was the transition from traditional load-bearing walls to innovative frame systems, which opened up new horizons for creative facade solutions and allowed architects to use space much more boldly (Kamal, 2020; Tiutina, 2021). Over the course of the evolution of architectural styles, there was a clear transformation from classical canons to modern experimental forms. Each epoch brought its own unique understanding of tectonics, which was reflected in the characteristic features of the erected structures. From the strictness of the classical order to the smooth forms of modernity, from the functionalism of modernism to the complex configurations of deconstructivism – each style developed its own tectonic language, interacting with the technical capabilities and aesthetic requirements of a particular time (Tiutina, 2021; Remizova, 2023).

The introduction of curtain facades marked a significant breakthrough in the field of construction tectonics, significantly changing the approach to creating architectural structures. The separation of load-bearing structures from external walls opened up unlimited opportunities for creativity for architects, allowing them to implement facade solutions in a variety of stylistic directions. This transition was a harbinger of a new era in architecture, when the structure was no longer limited to strictly structural requirements. Current trends in architecture demonstrate a wide range of approaches to the expression of tectonic concepts (Kamal, 2020; Tiutina & Davydov, 2021). Parametric architecture uses advanced computer technology to create complex geometric shapes, while bionic architecture draws inspiration from natural shapes and processes (Buravchenko, 2019; Ivashko *et al.*, 2020). Minimalism, for its part, elevates the purity and simplicity of lines, which allows each of these styles to build its own unique tectonic language, reflecting modern technological capabilities and discoveries in the field of aesthetics. The concept of hybrid tectonics emerged as a response to the challenges of globalisation. Combining modern technological innovations with local construction traditions allows creating authentic architectural solutions that preserve cultural identity in the context of global standardisation of construction technologies. Innovations in digital design and manufacturing have significantly expanded the boundaries of tectonic expression (Tiutina, 2021). Methods of parametric modelling, generative design, and additive technologies have made it possible to create rather complex forms. Such tools not only radically changed the design process, but also influenced self-awareness of the essence of tectonics in the field of architecture. Environmental requirements have become a key factor in the formation of modern tectonics (Dovgal *et al.*, 2024). Sustainable architecture concepts require new approaches to creating forms where energy efficiency and environmental aspects are a priority (Almaz & Farahat, 2023; Mahmood & Al-Alwan, 2023). This led to the emergence of bioclimatic architecture, where the tectonics of buildings are organically connected with natural processes.

Kinetic architecture opens a new chapter in the development of tectonic principles. Mobile building components, adaptive facades, and transformable spaces form dynamic tectonics that respond to changes in the environment and user needs (Akgün *et al.*, 2022). This radically changes the established ideas about architecture as something static. The integration of natural elements into architectural design is becoming an important component of modern tectonics. Green facades, biophilic design and regenerative architecture develop a new type of expression that blurs the boundaries between natural and artificial environments. This approach reflects the desire to create a harmonious living environment. Urban tectonics is developing as a separate discipline focused on the study of the interaction of buildings in a saturated urban environment. The development of an integral urban space requires a specialised approach to tectonic representation, because each structure acts as part of a greater compositional unity (Bulakh *et al.*, 2022; Yazdani *et al.*, 2023; Naghibi *et al.*, 2023).

Virtual tectonics has emerged due to the significant development of digital technologies, and the possibilities of augmented reality, which are increasingly integrated into everyday life (Hematang & Ikaputra, 2022). This technology allows overlaying virtual elements on the physical structure of a building, thereby creating a completely new level of architectural expressiveness. In this concept, tectonics acquires the ability to exist simultaneously in both real and virtual space, leading to the creation of dynamic and innovative architectural forms that are constantly adapted and changed in accordance with context and needs. In modern architecture, one of the most important areas is the development of the concept of intelligent tectonics (Gavkalova *et al.*, 2024). This concept focuses on integrating smart management systems directly into architectural forms, which thus acquire the ability to actively interact with users. In addition, such systems allow buildings to flexibly adapt to changing environmental conditions, contributing to the formation of a new type of architectural space. In this space, tectonics takes on a new meaning, because it becomes not only a static structure, but a real interactive component that can change and respond to the needs and challenges of time (Akgün *et al.*, 2022).

With the development of virtual and augmented reality technologies, a new level of virtual tectonics is emerging, where the physical structure is enriched with digital elements, opening up new opportunities for creative solutions and rethinking the relationship between form and function. Modern approaches in the field of tectonics serve as an important tool in creating a more sustainable and environmentally responsible environment. This is confirmed by numerous studies that analyse the practical application of the basic principles of sustainable tectonics in the development of building structures that can withstand the test of time (Mahmood & Al-Alwan, 2023). In modern conditions, architects are increasingly considering building structures not only as separate objects, but as an integral part of a larger ecosystem, focusing on their organic integration with the surrounding landscape and natural processes. This approach contributes to the development of environmentally responsible strategies in the field of architecture, where tectonic solutions are harmoniously combined with advanced environmental design strategies, ensuring a balance between innovation and maintaining natural balance (Almaz & Farahat, 2023).

Greenery and vertical gardens become an integral part of architectural solutions, creating a new synthesis of artificial and natural. The idea of open tectonics emphasises the creation of flexible spaces that can adapt to different functions and needs, which requires innovative approaches to structural systems that must simultaneously maintain stability and transformation. 3D printing technologies have significantly expanded the horizons of architectural expression, breaking down traditional barriers of construction technologies (Kamal, 2020; Subramani *et al.*, 2024). This creates a new language of tectonics, where once theoretical forms are now moving into reality, and the boundaries between sculpture and architecture are increasingly blurred. Modern urban architecture strives for harmony between individual buildings and urban development, creating a holistic architectural narrative. The formation of tectonic principles is a constant search and experimentation in response to the social, technological and environmental challenges that modern architects face (Tiutina, 2021; Tiutina & Davydov, 2021).

The development of tectonic principles in modern building structures is a complex and multifaceted process that reflects significant changes in the understanding of architecture and its role in the modern world. From integrating cutting-edge technologies to environmental solutions, from creating dynamic and adaptive spaces to expressing cultural identity, modern tectonic innovations demonstrate a commitment to sustainability and harmony with the environment (Mahmood & Al-Alwan, 2023). In order to systematise the basic principles of tectonics in the context of modern building forms, a classification covering key aspects of architectural design has been developed (Table 1). This classification reflects the evolution of tectonic principles, transforming them from basic combinations of structure and shape to more complex integrated solutions. The latter consider technical capabilities, environmental requirements, and cultural context. Each principle is described in detail, with an emphasis on its main characteristics and specific applications.

Table 1. Principles of tectonics of modern architectural forms

Principle	Description	Example of application
Integration of design and form	Organic combination of structural elements with overall design	Exposed steel structures as part of the building's aesthetic
Use of innovative materials	Application of new materials to create lightweight and durable structures	Facades made of composite materials that create the effect of weightlessness
Dynamic tectonics	Creation of forms that convey a sense of movement and change	Parametrically designed curved facades

Table 1. Continued

Principle	Description	Example of application
Environmental awareness	Implementation of sustainable development principles in architectural solutions	Bioclimatic buildings with adaptive facades
Smart tectonics	Integration of intelligent systems into the building structure	Adaptive facades that respond to environmental changes
Cultural context	Reflection of cultural values and identity in architectural forms	Buildings that combine modern technology with traditional motifs
Virtual tectonics	Use of VR and AR to expand physical space	Projections on facades that change the perception of the building
Open tectonics	Creation of flexible spaces that adapt to different functions	Transformed interior spaces in public buildings
3D printing in architecture	Use of additive technologies to create complex shapes	3D-printed facade elements or entire buildings
Urban tectonics	Consideration of tectonics in the context of the urban landscape	Complexes of buildings that form a single composition in urban space

Source: created by the authors based on M. Tawa (2020), J.C. Gomes *et al.* (2022), M. Lakkala (2023)

Dynamic tectonics is becoming a key element of modern architecture, increasingly showing complex geometric shapes that convey a sense of movement. Architectural solutions move from static shapes to organic, plastic structures, which is achieved through parametric design and digital technologies that embody complex curved shapes. Environmental aspects have become an integral part of the architectural process. The biomimetic approach, where natural forms and processes are the inspiration, contributes to the creation of buildings that function as natural systems. This allows building energy-efficient and environmentally sustainable structures with a form and function consistent with the natural environment.

Adaptive architectural structures and deformed spatial structures open up the ability for buildings to actively respond to various changes in environmental conditions and consider the needs of users, which may vary over time (Sikorska *et al.*, 2024). This innovative approach lays the foundation for a fundamentally new perception of architectural tectonics, which is transformed from a traditionally static form to a more dynamic and flexible adaptability of the architectural environment, allowing these structures not only to maintain their functionality, but also to optimise it in response to external influences (Akgün *et al.*, 2022). Such an architecture can actively respond to external factors, changing the shape of facades, and adjusting lighting and ventilation. The development of tectonic principles does not occur in isolation, but is linked to cultural context and social changes.

Modern architecture not only embodies the logic of structures, but also reflects cultural and social features, becoming a means of expressing collective identity and values. The impact of globalisation and digital technologies has led to the emergence of hybrid architectural forms and changes in traditional construction practices (Dmytrenko *et al.*, 2024). This encourages the development of a unique tectonic language that meets global trends and at the same time adapts to local conditions, considering local features and historical heritage. New advances in design and construction have significantly expanded the traditional understanding of the relationship between the shape and structure of a building (Zhangabay *et al.*, 2023). Sustainability is becoming a priority in modern tectonics due to the introduction of environmental solutions in construction. Architects are increasingly considering buildings as part of an integral ecosystem that interacts with natural processes, which, in turn, affects the transformation of architectural styles under the influence of the environment. The integration of natural elements such as vertical gardens and roof landscaping is becoming an important component of the new architectural language, shaping the tectonic approach in landscape architecture (Ivashko *et al.*, 2020; Almaz & Farahat, 2023).

The concept of open tectonics provides for the creation of spaces that are easily adapted to various functions and needs of users, which is especially relevant in the context of mobility architecture and adaptive systems. Modern design solutions should provide both stability and flexibility, which is achieved through the use of innovative materials and technologies in the facade system. Architectural practice is enriched with new shaping techniques, such as parametric design and digital fabrication, which affect morphological changes in architecture. In an urban context, tectonics is particularly important because individual buildings form a common urban narrative. This is confirmed by symbolism in modern architecture. Architects try to create harmony between structures in the overall urban fabric, considering technical and cultural contexts. Modern architecture continues to evolve through a combination of historical aspects and an innovative approach to creating building forms. Architects are actively looking for new ways of expression through forms, materials, and techniques that form the new tectonic language of modern architecture. This evolution highlights the importance of an integrated design approach that considers the technical, environmental, and aesthetic aspects of architecture (Buravchenko, 2019; Kamali, 2024).

Analysis of the implementation of adaptive facade systems in the context of modern architecture (Fig. 1) shows that as of 2023, despite the dominance of traditional facades, adaptive facades make up a significant share (40%) of current architectural solutions (Kamal, 2020; Hurol, 2022).

This indicates a growing trend of integrating innovative technologies into the formation of modern architectural structures. The analysis of the evolution of the concept of tectonics in architecture highlights three key periods: classical, modernist, and contemporary. Each of them has its own characteristics in understanding tectonics and its role in shaping architectural solutions.

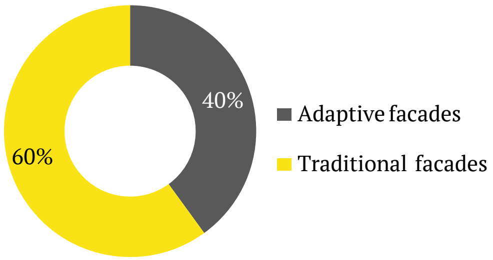

Figure 1. Use of adaptive facade systems in contemporary architecture
Source: created by the authors based on M.A. Kamal (2020), A.L. Samalavičius (2021), Y. Hurol (2022)

The development of modern architecture is characterised by significant changes in approaches to the formation of the basic principles of tectonics. The architecture of the 20th and 21st centuries has undergone a significant evolution, which is reflected in the change and transformation of its formal language. Research of the factors influencing the emergence of this new language highlights the extremely important role of innovative materials and compositional solutions in the development of architectural forms (Kamal, 2020; Tiutina & Davydov, 2021). In modern architecture, the tendency to integrate stable tectonic principles is particularly noticeable, which significantly contribute to the creation of long-lasting architectural structures with expressive and aesthetically attractive characteristics. This process is accompanied by the active development of morphological transformation strategies in digital architecture, which opens up new prospects for architectural shaping and provides more opportunities for creativity and innovation. The aesthetic and typological foundations of the new tectonic language of modern architecture are based on the synthesis of technical, aesthetic, and constructive aspects. The artistic expression of the regularities of architectural forms and structural systems remains one of the foundations of the key principles of architectural tectonics. These changes, if viewed from a historical perspective, reflect the constant process of evolution of approaches to architectural design and the development of the language of architectural composition, which is evidence of the dynamism and continuous development of this industry (Tiutina, 2021; Almaz & Farahat, 2023).

The development of modern architecture demonstrates the growing importance of environmental impact, embodied in the use of energy-efficient technologies and adaptive facade systems. The integration of these technological innovations with the principles of sustainable development marks a new stage in understanding the interaction of buildings with the environment. There is a fusion of global architectural approaches with local traditions, which creates a unique balance between modern design standards and cultural identity. This synthesis of trends has led to the development of a conceptual scheme that reflects the interrelation of technical, ecological, and cultural aspects in the formation of modern tectonic principles. Figure 2 shows the multifactorial influence on the formation of modern tectonic principles. The data provided reflect the levels of influence of technological innovations, environmental requirements and cultural context on the development of tectonic principles in modern architecture, and the nature of their interaction.

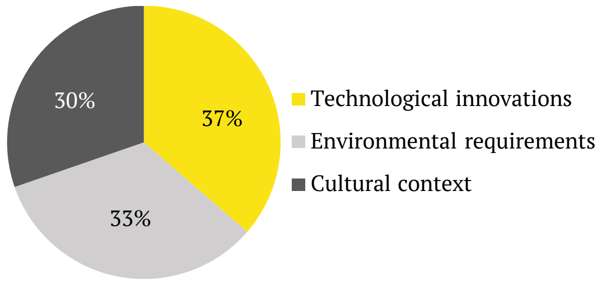

Figure 2. Interrelation of factors in the formation of tectonic principles
Notes: percentages indicate the degree of influence of each factor on the formation of tectonic principles
Source: created by the authors based on M.P. Louw (2021), Y.I.P. Hematang & I. Ikaputra (2022), Y.B. Mahmood & H.A.S. Al-Alwan (2023)

According to the developed model, the tectonic principles of modern architectural forms are determined by three main areas of influence: technology, environment, and culture. Technologies include digital design and manufacturing tools that expand the possibilities of creating and optimising structures. The environmental aspect focuses on the principles of sustainable development, energy efficiency, and adaptation to climate change. The culture reflects the interaction between global architectural trends and local traditions. The model demonstrates that modern tectonic principles arise as a result of the complex interaction of these spheres. For example, parametric design (technology sphere) contributes to improving the energy efficiency of buildings (environmental sphere), while forms can reflect traditional architectural motifs (cultural sphere).

The analysis of modern innovative architectural projects of the period 2020-2024 confirmed the feasibility of the theoretical model. It was found that the most innovative and successful projects integrate technical, environmental and cultural elements into their solutions. For example, the project of the Guggenheim Museum in Abu Dhabi, led by Frank Gehry, illustrates the use of modern digital methods to create complex geometric shapes that correspond to the climatic conditions of the region, and reflect elements of traditional Arabic architecture

(Elsheshtawy, 2020). Table 2 shows that the concept of tectonics in the architectural field has undergone significant transformations over the course of historical development, reflecting technological innovations and the evolution of social demands. This periodisation coincides with the study by O. Remizova (2023), which explores compositional languages and architectural logic in a historical context, which can provide a basis for understanding the evolution of tectonic principles. The study focuses on modernity and its specific challenges.

Table 2. Evolution of the concept of tectonics in architecture

Period	Key features	Representatives
Classical (before 1950)	Matching the design form, order system	Vitruvius, Alberta
Modernist (1950-1990)	Experiments with new materials, free plan	Le Corbusier, Mies van der Rohe
Contemporary (since 2000)	Digital tectonics, environmental integration	Zaha Hadid, Norman Foster

Source: created by the authors based on S. Buravchenko (2019), J.K. Grütter (2020), L. Tiutina (2021)

Based on the conducted research, a number of key principles for the development of tectonics in modern architecture were formulated. First of all, it is the integration of technical, environmental, and cultural elements. It is also important to ensure that architectural solutions are adaptable to changing environments and user requests. In addition, it is essential to optimise the shape and structure of buildings, considering functional, environmental, and aesthetic requirements. It is also necessary to consider the cultural and natural context of the environment. In addition, the architecture must have expressiveness, functioning as a means of expressing identity. Although these principles should not be considered exhaustive or universal, they reflect the main trends in the development of modern architectural tectonics.

The study also highlighted the challenges associated with integrating technological competence with environmental responsibility. This dilemma requires architects to find a balance between aesthetic expressiveness and environmental sustainability. Another challenge is the globalisation of architectural practices, which can lead to a loss of local identity. It is important to develop tectonic principles that combine global technologies with local traditions. The future area of development is the integration of smart systems and the Internet of Things into the architecture. This would allow creating adaptive buildings that actively interact with users and the environment. The potential for the introduction of bio-tectonics, which combines biomimetic and ecological approaches in the development of architectural forms, is also revealed. In the context of cultural identity, it is important to develop methods of digital nationality to preserve cultural diversity in the context of the globalisation of architecture.

In facade systems, the study of tectonic transformation marks a significant departure from traditional approaches. While the study by M. Lakkala & J. Pihlajaniemi (2021) focus on the classical principles of tectonics in static construction, the present study points to an important paradigm shift. Analysis of modern construction projects shows that 40% of structures use adaptive facade systems, which indicates the emergence of a new view on tectonic principles. Environmental factors are becoming increasingly important in architectural tectonics. Digitalisation significantly affects the principles of tectonics, more deeply than it is presented in the study by C. McCoy (2021). Parametric design and the introduction of additive technologies radically change not only modelling methods, but also expand the boundaries of architectural expressiveness, opening up new prospects for experiments with form and space. The link between global technical capabilities and the local cultural context plays an important role. B. Yazdani *et al.* (2023) emphasise the importance of cultural identity in architecture. The study examines a more complex process, not only the preservation of cultural features, but also their creative transformation using modern technologies to create unique hybrid architectural forms. This multi-faceted study highlights the complex dynamics of tectonic changes in modern architecture and points to new areas for further research, in particular, in the field of integration of virtual technologies and the development of adaptive building systems.

The integration of environmental factors identified during the current study into tectonic solutions is closely consistent with the study by S. Buravchenko (2019), which analyses the aesthetic and typological sources of formation of a new tectonic language of modern architecture. The findings regarding the impact of energy efficiency, bioclimatic design, and the use of renewable materials on the development of tectonic principles enrich the understanding of the relationship between architecture and environmental aspects. However, the focus is primarily on the biomimetic approach, and the study offers a broader perspective, including aspects of adapting building forms to changing environmental conditions. This expansion of the concept of ecotectonics opens up new opportunities for creating buildings that not only minimise the negative impact on the environment, but also interact positively with the ecosystem.

The study focuses on a cultural context that plays a crucial role in shaping the principles of tectonics. This is consistent with the findings of I. Bulakh *et al.* (2022), which analyse the integrity of the artistic image of the city through the prism of symbolisation. The identified trend towards hybrid tectonics, which combines elements of local traditions with global technologies, is a reflection of the complexity of cultural identity in today's globalised world. Integrating technological innovations, environmental requirements, and cultural context, the theoretical model depicts the multidimensional nature of modern approaches to architectural morphogenesis. The model was developed from the ideas about tectonic influences in modern architecture proposed by Y. Hurol (2022), and also serves as a basis for creating practical tools to implement these concepts in more specific applications. The main focus is not only on technical aspects, but also on the complex perception and use of architectural forms in various socio-cultural and natural environments. The described possibility of smart tectonics develops ideas of Y. Akgün *et al*. (2022) on the tectonics of kinetic architecture and the possibility of creating buildings that actively interact with their users and the urban environment.

The term bio-tectonics reflects the study by A.F.H. Almaz & M.A.F. Farahat (2023) on the application of stability tectonics to create strong building structures. However, this concept expands to include aspects of the functioning of living systems within the entire building complex. This approach can serve as a basis for a new area in architecture, where buildings are considered not as static structures, but as dynamic ecosystems that can adapt to changes in the environment and user needs. This opens up horizons for the development of more sustainable, energy-efficient, and environmentally integrated solutions in construction. The idea of digital locality reflects the growing interest in preserving cultural identity in the context of globalisation. This idea is related to the paper by M.P. Louw (2021), dedicated to the study of hybrid tectonics in contemporary African architecture, bringing these ideas into the context of the digital age.

The results of the study highlight the urgent need to review educational programmes related to architectural design. Outdated methods of teaching tectonics often do not reflect the rapid development of technologies and paradigm shifts in architectural practice. The proposed theoretical model serves as a basis for developing new courses that integrate the technical, environmental, and cultural aspects of tectonics. In general, the development of tectonic principles of modern building forms is a complex and dynamic process that reflects global challenges and opportunities. The developed theoretical model and formulated principles lay the foundation for further development of the theory and practice of architectural design, aimed at creating innovative, sustainable, and culturally significant architectural forms. Promising areas of further research are a deeper study of the relationship between tectonic principles and psychological perception of architectural space, and an analysis of the economic aspects of implementing innovative tectonic solutions. Thus, this study presents a new perspective on the formation of tectonic principles of modern architectural forms, integrating technical, environmental and cultural aspects. The developed theoretical model and formulated principles are the basis for further development of the theory and practice of architectural design, focused on the creation of innovative, sustainable and culturally significant building forms.

CONCLUSIONS

In the course of the study, the main factors influencing the formation of the principle of tectonics in modern architecture were identified and a classification of modern tectonic systems based on their technical, ecological and aesthetic characteristics was developed. Analysis of the evolution of the concept of tectonics shows a transformation from the classical approach focused on the logic of composition to the modern multidimensional approach. This approach considers digital technologies, environmental sustainability, and the cultural context. It is revealed that the principles of modern tectonics are developed under the influence of three main factors: technological innovations, environmental requirements, and cultural context. In particular, it was found that digital technologies had a significant impact on the development of new tectonic approaches due to the use of parametric design, 3D printing, and robotic production. These technologies allow implementing complex geometries and optimising structures that did not exist before.

The growing role of environmental factors in the development of tectonic principles is manifested in the creation of energy-efficient buildings, the use of bioclimatic design, and the integration of circular economy principles into architecture. This reflects the complexity of cultural identity in today's globalised environment and the need to create architectural forms that can reflect this multi-layered nature. Based on the analysis, a theoretical model of the tectonic principle of development of modern architectural forms is developed. Three basic principles of tectonic development of modern architectural forms that correspond to key areas of influence were identified. The first principle –technological, concerns the latest methods of design and construction. The second principle – eco-friendly, which focuses on creating sustainable and energy-efficient solutions. The third principle – cultural, which ensures the preservation and development of architectural identity. The model offers a comprehensive approach to architectural design, considering technical capabilities, environmental requirements, and cultural context. The study also identified promising areas for the development of tectonic principles: smart tectonics, bio-tectonics, and digital locality. These concepts open up new opportunities for creating adaptive, environmentally sustainable, and culturally significant building forms. Promising areas of further research are the study of the relationship between tectonic principles and psychological perception of architectural space, the analysis of economic aspects of the implementation of innovative tectonic solutions, the study of the potential of tectonic principles in the context of space exploration and the creation of extra-terrestrial settlements.

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CONFLICT OF INTEREST

None.

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Формування принципів тектоніки сучасних архітектурних форм

Анотація. Мета дослідження полягала у створенні теоретичної моделі, яка розкриває основи формування тектоніки сучасних архітектурних форм, враховуючи технологічні інновації, екологічні вимоги та культурний контекст. Результати показують, що концепція тектоніки змінилася від класичного до сучасного багатовимірного підходу. Основу сучасної тектоніки визначають три ключові елементи: технологічні інновації (параметричний дизайн, 3D-друк, роботизоване виробництво), екологічні вимоги (енергоефективність, біокліматичне проектування, циркулярна економіка) та культурний контекст (гібридна тектоніка, цифрова мова). Сформована теоретична модель містить п'ять основних принципів (інтегративний, адаптивний, оптимізаційний, контекстуальний та експресивний), що формують тектоніку сучасних архітектурних форм. На основі аналізу сучасних архітектурних проектів виявлено перспективні напрями розвитку тектонічних принципів, які включають смарт-тектоніку, біо-тектоніку та цифровий локалізм. Дослідження підкреслило зростаючу роль адаптивних фасадних систем у формуванні тектоніки сучасної архітектури та продемонструвало потенціал запропонованої моделі для прогнозування розвитку архітектурних форм з урахуванням технологічних тенденцій і екологічних вимог. Робота підтверджує важливість міждисциплінарного підходу в архітектурному проектуванні та закладає основу для розвитку архітектурної теорії та практики, яка може відповідати викликам сучасності, особливо в контексті сталого розвитку та культурної ідентичності

Ключові слова: цифрова фабрикація; параметричне моделювання; адаптивні фасади; біокліматичний дизайн; морфогенез; конструктивні системи

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The impact of the railway on the development of Bishkek

Abstract. This study aimed to conduct a detailed analysis of how the railway has influenced the development of the city of Bishkek. The study employed historical-analytical and geographical methods, analysing archival documents, cartographic materials, and academic publications to ascertain the impact of the railway on Bishkek's growth. The findings indicated that the construction of the Turkestan-Siberian railway played a pivotal role in shaping the urban structure of Bishkek. The railway facilitated the city's economic growth, population increase, and industrial development. New residential and industrial areas emerged around railway stations and routes, leading to a significant expansion of the urban territory. Furthermore, the railway enhanced the city's transport accessibility, fostering trade and interregional connections. The influence of the railway was also evident in the city's architecture, characterised by the emergence of buildings and structures typical of the railway era. Over time, the role of the railway in urban life has somewhat diminished, yet its historical influence remains significant. The study revealed that the railway contributed not only

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to economic development but also to cultural changes in Bishkek. The emergence of a railway hub led to increased migration and alterations in the city's demographic structure, attracting new residents and labour resources. The railway also facilitated the development of infrastructure and public services, such as electrification and water supply, which improved the quality of life in the city. Ultimately, the railway became a crucial factor in integrating Bishkek into regional and international transport networks, enhancing its strategic importance in the region. The railway played an essential role in the establishment and development of Bishkek, exerting a multifaceted influence on its economy, social structure, and urban planning. The historical experience of developing the city's railway infrastructure can serve as a foundation for planning its future development

Keywords: railway station architecture; interregional connectivity; urban planning; urban framework; transport network

INTRODUCTION

The relevance of this research lies in the fact that railways have always played a crucial role in the development of cities and regions, fostering economic growth, enhancing transport accessibility, and accelerating urbanisation processes. The primary challenge of this research was to conduct a comprehensive analysis of the numerous factors that influenced the city's development under the impact of railway infrastructure. It was essential not only to identify the immediate effects of the construction of the Turkestan-Siberian railway but also to understand the long-term consequences and interactions of various factors. Moreover, given the city's contemporary development, the study had to consider current trends and future prospects, necessitating the integration of historical analysis with modern data and methods (Attokurova & Adylbekova, 2022).

M. Kozybaeva (2023) highlights the pivotal role of railway construction in developing the transport and communications infrastructure of cities in Northern Kazakhstan, connecting them to major industrial centres within the country. Since 2008, the network of high-speed rail (HSR) lines in China has expanded significantly, a development that, according to many experts, has stimulated economic growth. M. Jin *et al*. (2020) tested this hypothesis by analysing the impact of HSR on economic inequality in China between 2002 and 2016 using a spatial econometric model. Their findings confirmed that HSR indeed contributes to local economic growth, although the spillover effect was found to be insignificant. Conversely, J. Jiao *et al*. (2020) concluded that the economic impact of HSR is more closely linked to improvements in accessibility and connectivity of the railway network rather than simply the presence of HSR infrastructure. Accessibility and connectivity between neighbouring cities exert a mutual influence on their economic growth.

The study by M.B. Bouraima *et al*. (2020) identified that the primary threats to railways are competition from road transport and periodic government intervention. The authors identified outdated and non-functional infrastructure, as well as chronic underfunding, as the main weaknesses of railways. However, they noted that potential market growth and large-scale long-distance rail freight transport are key opportunities and strengths. Meanwhile, Y. Liang *et al*. (2020) discuss the contentious issue of whether HSR can stimulate regional economic growth along its route, particularly when connecting less developed and developed regions, suggesting a need for further research in this area.

A.N.H. Ibrahim *et al*. (2020) argue that while rail-based public transport is a more advanced and preferable mode of transportation, capable of addressing congestion and pollution problems, its adoption rates remain low due to various factors. Among these, they highlight that passengers often opt for more reliable and convenient alternatives or are dissatisfied with the quality of service provided.

While the authors examined various aspects of railway infrastructure and its impact on economic growth and urban development, their research has left certain crucial questions underexplored. The social and cultural impacts of railways have not been examined in detail. Issues such as how railways affect population mobility, access to education and healthcare, and cultural exchange between regions have been overlooked. The environmental consequences of railway development also require deeper analysis. It is essential to consider the impact of railways on the environment, including landscape changes, effects on local flora and fauna, and greenhouse gas emissions. The long-term economic sustainability of railway development is another important aspect that has not been sufficiently addressed. There is a need to understand how railways influence economic diversification and resilience in the face of economic crises.

This study aimed to conduct a comprehensive assessment of the impact of the Turkestan-Siberian railway on the development of the city of Bishkek. The primary objectives of the research included analysing the phases of construction and commissioning of the railway. In particular, the study investigated the transformations of the architecture of the railway station in Bishkek in connection with the development of the railway; the influence of various architectural styles and epochs on the formation of railway structures in Bishkek was also evaluated.

MATERIALS AND METHODS

A variety of sources and methods were employed to investigate the impact of the Turkestan-Siberian railway on the development of Bishkek (formerly known as Frunze, Pishpek), ensuring a comprehensive analysis of the topic. The materials used included historical documents, archival records, maps, and reports. Primary sources comprised reports on the construction of the Turkestan-Siberian railway, data on the city's urban planning and architectural features, and documents about the industrial and urban development of Bishkek at various points in time. Cartographic materials, such as historical and contemporary maps of the city illustrating changes in its layout, as well as diagrams of railway lines and stations, were also crucial sources (Khitakhunov, 2024). These materials were studied in the library, which provided access to the necessary documents and archival records.

The historical method enabled the analysis of documents and archival materials to identify key stages in the development of railway infrastructure and its impact on urban planning. A comparative analysis of different periods in the city's development helped to understand how its structure changed under the influence of the railway. Cartographic analysis was used to visualise changes in urban planning and railway line routing, as well as for geographical modelling of the railway's impact on the location of industrial and residential areas in the city. The socio-cultural analysis allowed for the study of the railway's influence on the city's socio-economic development, including migration processes, the development of trade and industry, and the cultural and architectural changes caused by the development of railway infrastructure. The theoretical-architectural method was employed to investigate the architectural features of railway stations and adjacent areas, their role in shaping the urban environment, and to analyse urban planning decisions related to the placement of railway facilities in the city's master plan.

A variety of tools and technologies were employed in the study. Geographic Information Systems were used to analyse spatial data and visualise changes in urban planning, as well as to create maps and diagrams illustrating the impact of the railway on Bishkek's development. Statistical methods were applied to analyse demographic and economic data, enabling the identification of correlations between railway development and changes in urban structure. Computer modelling facilitated the simulation of various scenarios for the development of urban infrastructure, considering historical data, and forecasting future changes in the urban environment under the influence of transport infrastructure.

The study was subject to several limitations that must be considered when interpreting the results. Data availability was one such constraint: some archival materials and documents may have been inaccessible or incomplete, limiting the comprehensiveness of the analysis. Modern data on the city's development may have been restricted due to the closure of certain information sources. The accuracy of historical data could also vary, for example, historical documents may have contained inaccuracies or distortions, affecting the reliability of the conclusions; therefore, critical analysis and comparison of various sources were necessary to obtain an objective picture. The complexity of factors further complicated the analysis. Urban development is influenced by a multitude of factors, including economic, political, social, and cultural aspects, making it difficult to isolate the influence of the railway alone. The need to account for the interaction of various factors was crucial for a comprehensive understanding of the development processes.

RESULTS

The construction of the Turkestan-Siberian railway (1926-1931) connected Siberia, Central Asia, and the centre of the country, accelerating transportation (Khitakhunov, 2024). The idea of a Siberia-Turkestan railway emerged in the 19th century. The Crimean War highlighted the importance of railways, and in 1857 a decree was issued to create a railway network. In 1877, the Syzran-Orenburg line was built, but it was decided to extend the route to Tashkent via the Trans-Caspian railway. Although the Altai region could supply grain and coal, the delivery was costly due to the lack of direct communication with Central Asia (Bakytbek *et al.*, 2020)

At the beginning of the 20th century, surveys for the Arys-Verny railway began. In 1906, an interdepartmental committee allocated funds for the construction of the section from Barnaul to Semipalatinsk-Arys (Alotaibi *et al.*, 2022). In 1912, the industrialist A.I. Putilov became involved in the project, completing the line to Burnoe station in 1924. In 1927, a central authority for the construction of the Turkestan-Siberian railway was established in Moscow, and the railway was officially opened on 31 December 1930 (Filatova, 2012).

The route through the Trans-Ili Alatau Mountain range sparked considerable debate. After lengthy discussions, the Chokpar variant was adopted, reducing construction costs by 23 million roubles. Simultaneously, the Semirechensk railway was reconstructed, and the Pishpek-Tokmak line was built (Faísca & Januário, 2024). The Frunze railway division began operations in 1924, serving Bishkek's industrial enterprises. The opening of the railway line facilitated the city's development and led to the merger of Bishkek-1 station with the city. Residential and industrial buildings emerged along the station, many of which have retained their 1920s architectural style (Palin *et al.*, 2021).

During the 1920s and 1930s, the Kyrgyz railway network developed as part of the unified railway system of the Soviet Union. It consisted of two sections, both single-track, non-electrified, broad-gauge (1,520 mm) lines. In the north, a 323-kilometer section, including stations such as Lugovaya (Kazakhstan), Kara-Balta, Bishkek, and Balykchy, was the southern branch of the Turkestan-Siberian railway, linking Central Asia with Siberia via present-day Kazakhstan. This section was managed from Almaty (Kazakhstan) (Fig. 1). In the south, a 101-kilometer network was constructed, comprising four short branches in Osh, Jalal-Abad, Kyzyl-Kyya, and Tash-Kömür, which connected to the Trans-Aral railway running from Tashkent to Orenburg (Russia), linking Central Asia with European Russia and the Turkestan-Siberian railway at Arys (Kazakhstan). These southern branches were managed from Tashkent

(Uzbekistan). During the 1930s, the area between the city and the station saw the development of industrial and residential buildings for Interhelpo, contributing to the merger of Bishkek-1 station with the city (Niu *et al.*, 2021).

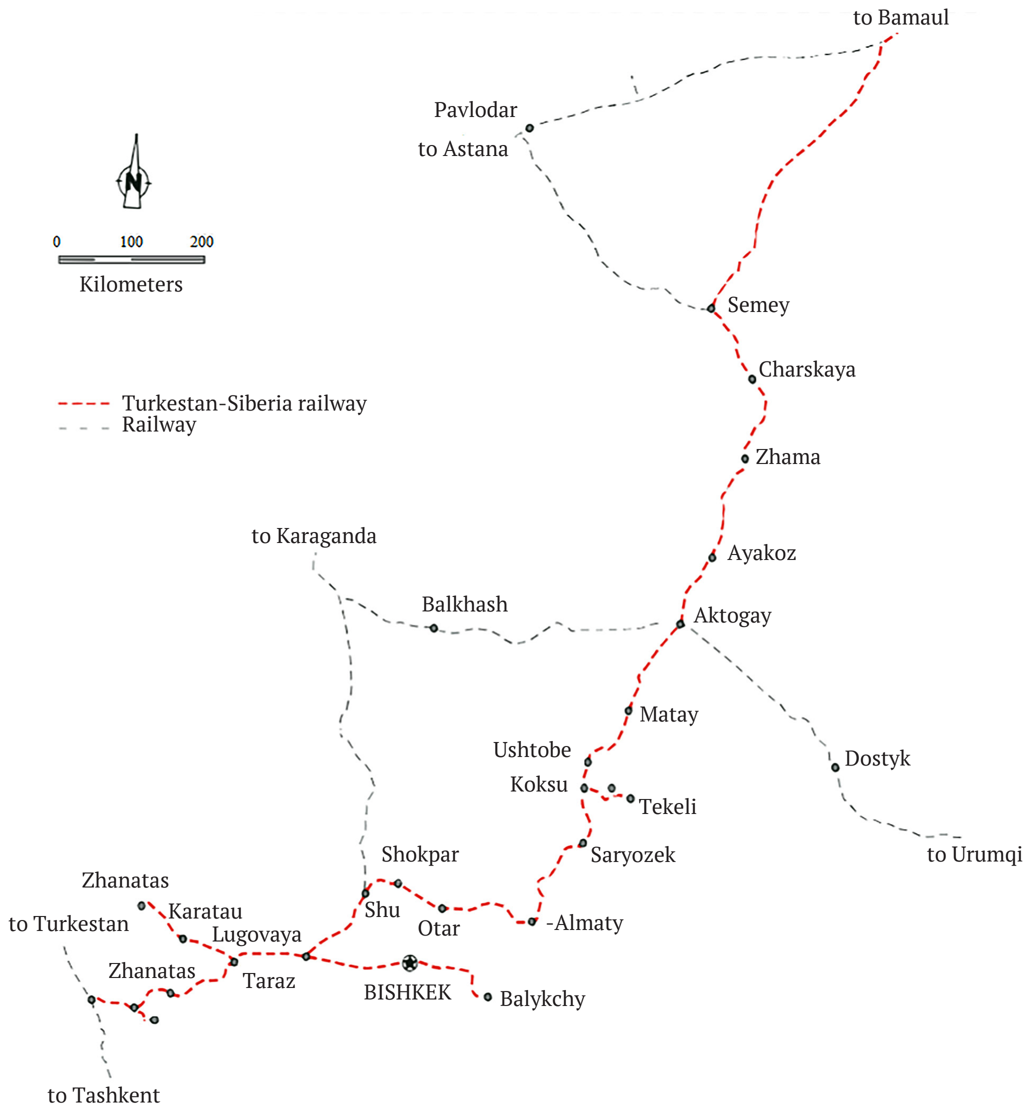

Figure 1. Scheme of Turkestan-Siberian railway

Source: F. Niu *et al.* (2021)

Following the dissolution of the Soviet Union in 1991, the Kyrgyz Republic inherited a railway infrastructure comprising 2,500 freight wagons, 450 passenger carriages, and 50 locomotives. To manage and operate the railway network within the country, a new state-owned enterprise, "Kyrgyz Temir Zholu", was established, taking over the functions of the former Soviet railway centres in Almaty and Tashkent. Trains operating on Kyrgyz railways now had to cross international borders to connect to the main lines in Kazakhstan and Uzbekistan. All transportation between the northern and southern parts of the Kyrgyz railway network was carried out via the railway networks of these two neighbouring states.

In 2024, warehouse facilities, various wholesale bases of organisations, and industrial enterprises extend along the railway station. The residential buildings are predominantly single-storey, and the surrounding courtyards feature characteristic railway workers' houses designed in a pre-revolutionary style that persisted into the 1920s, as can be seen in Taraz, where the railway also arrived in the 1920s (CAREC, 2021). Elsewhere in the city, this district was generally not perceived as being connected to the railway station, despite it being an interesting landmark with pre-revolutionary architectural features. The surrounding area is still known as Bishpek, which remained the name of the station until 1991, while the current Bishkek-2 was previously known as Frunze station (Fig. 2). Within the station grounds, there was a garden. The waiting room floor was adorned with colourful tiles featuring various patterns and ornaments.

Figure 2. Pishpek station

Notes: photo taken in 1924
Source: S. Horák (2022)

Along the railway routes crossing the city, passenger, freight, and sorting stations have developed, alongside numerous engineering, technical, and civil structures. Bishkek's railway junction developed into a complex structural and planning scheme, occupying vast urban areas. Advances in railway technology, such as increased speeds and load capacities, coupled with a lack of territorial reserves, led to the irrational placement of certain parts of Bishkek. As a result, the railway and its associated infrastructure, along with the nearby urban development, found themselves in extremely constrained and congested conditions (Acker & Triggianese, 2021).

Bishkek's railway junction, a complex and multifaceted system, played a pivotal role in shaping and developing the city's infrastructure. The passenger station served numerous routes, connecting Bishkek with other regions and countries, thereby fostering increased population mobility and tourism. The freight and sorting stations ensured efficient logistics and goods transportation, stimulating industrial and commercial growth. The railway junction's engineering and technical infrastructure, encompassing depots, repair workshops, warehouses, and administrative buildings, guaranteed the seamless operation of the entire system (Wang *et al.*, 2020a).

Advances in railway technology, manifested in increased speeds and load capacities, necessitated the expansion and modernisation of railway infrastructure. However, a lack of available land and dense urban development constrained these expansion possibilities. Consequently, some sections of the railway infrastructure were ineffectively situated, creating challenges for urban planning and transport logistics. Nevertheless, the development of railway transport had a significant impact on the formation of the urban environment, facilitating the integration of different districts and improving transport accessibility (Musayev *et al.*, 2022).

The shaping of the city's urban structure under the influence of railway transportation enabled more precise planning and implementation of urban development policies. The utilisation of scientific data and historical urban analysis facilitated informed decision-making in the creation of new projects and the reconstruction of existing facilities. This allowed for the creation of a balanced and harmonious urban environment, fostering the sustainable development of Bishkek and its integration into regional and international transport networks.

The emergence of Bishkek as an industrial centre of the Kirghiz Soviet Socialist Republic (SSR) was influenced by the evacuation of industrial enterprises and labour resources during the Second World War, as well as the presence of a railway transport infrastructure of union significance within the city. The need for the rapid restoration of evacuated large industrial enterprises and the construction of new facilities resulted in the haphazard formation of industrial zones in Bishkek along the railway corridor, which subsequently shaped the development of residential and public areas of the city beyond the primary provisions of the master plan (Jelen *et al.*, 2021). The incessant expansion of urban areas has led to a lack of comprehensive architecture and planning in urban development. The unplanned allocation of land for residential housing to serve the labour needs of industrial enterprises resulted in the persistence of a spatial arrangement where industrial zones were situated between residential areas, separated by railways. Consequently, as Frunze continued to develop, its urban structure became even more fragmented.

The development of new industrial and residential districts with low-rise housing of undistinguished aesthetic quality perpetuated the "flat" character of urban development. This contributed to problems related to the cost-effectiveness of the city's engineering services (Wang *et al.*, 2020b). The connection of central districts to the main railway line facilitated a significant expansion of residential development, resulting in the construction of large hotel complexes, such as the Ala-Too and Pishpek hotels, near the railway. Additionally, substantial public, commercial, and cultural buildings, as well as shopping centres, were erected along Mira and Lev Tolstoy Avenues. This development also prompted the reconstruction of the planning structure in nearby districts, including the construction of overpasses on Sovetskaya and Alma-Atinskaya Streets, Mira Avenue, and the widening of Timur Frunze Street.

The current and prospective development of the agglomeration has been driven by the railway remaining one of the primary modes of mass transport, facilitating both long-distance travel and commuter flows of the workforce. As a result of the ongoing development of the track and warehousing facilities at the railway hub, alongside the construction of access routes to new enterprises, there has been an increased demand for the organisation of the city's transport infrastructure. This has necessitated a significant rise in capital investment for its reconstruction.

The escalating freight traffic on the railway and the impossibility of physically relocating the railway line within the city have had a profound impact on the overall functioning of the city's transport hub. As a result, the construction of bypass roads, complete with additional infrastructure, has become necessary. The emergence of Pishpek and the formation and development of its planning structure were directly linked to the construction of the Turkestan-Siberian railway. The city's growth was driven by a confluence of geographical, economic, geological, and strategic factors that facilitated the transformation of a small district town into the large, multi-industrial transport hub of Frunze.

The chosen research topic facilitated clarification of the city's typology at various stages of its development and elucidated the trajectory of its changing urban specialisation, influenced by the railway complex as a stable foundation for the city's urban-typological development. The first typological characteristic of Pishpek was the fortress built at the intersection of caravan routes. The next stage of its development can be identified as a commercial and fair crossroads, featuring spontaneous constructions. By the end of the 19th century, the status of the settlement was changed to that of a county town. The political changes in the country in 1917 led to an influx of migrants and the establishment of the "Interhelpo" commune, which proposed the creation of a new sun city in the steppe (Uralbayev & Yermekbayev, 2021).

The station was established during the construction of the railway branch from Lugovaya to Pishpek, which led to the creation of a settlement adjacent to the station. On the eve of the 1940 war, Pishpek had evolved into a significant railway station on the Turkestan-Siberian railway. The increase in freight traffic necessitated the urgent establishment of new enterprises in the area. In the development of the master plan for Pishpek, the "Hippodamian" planning system was selected, which was more progressive compared to the medieval layouts characteristic of Central Asian cities (Fig. 3). This rectangular quarter structure was devised by the ancient Greek architect and urban planner, Hippodamus of Miletus (485-405 BC). In the 5th century BC, he designed cities such as Rhodes (Turkey), Thurii (Italy), and Alexandria (Egypt) in Greek-colonised territories, as well as the Athenian port of Piraeus. In these projects, Hippodamus embodied his philosophical idea of a strictly geometric organisation of urban space, a principle that remains relevant even today (Khitakhunov, 2024).

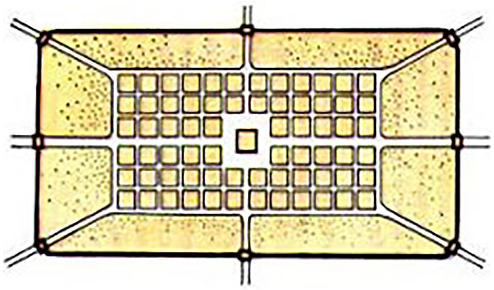

Figure 3. The chessboard Hippodamian street system, 1917
Source: Ya. Mazmanov (2020)

During the 1920s and 1930s, significant industrial enterprises were established in Frunze, laying the foundation for the modern western industrial zone. One notable example of urban planning from this period is the "Workers Township", a project realised by Czechoslovakian communist workers who had founded the "Interhelpo" cooperative in Frunze. The name "Interhelpo" translates from Ido (Esperanto) as "mutual aid". This cooperative, operating in the city from 1923 to 1943, was involved in constructing power stations and foundries, becoming the progenitor of Kyrgyz industry and a leading force in the republic's industrialisation during the pre-war period (Alymbaev, 2024). The "Workers Township" project embodied the dream of realising the utopia envisioned by the Italian Renaissance scholar Tommaso Campanella in his work "City of the Sun" (Figs. 4, 5).

Figure 4. The City of the Sun, 1920
Source: Ya. Mazmanov (2020)

Figure 5. Bishkek. Workers Township, 2024
Source: Ya. Mazmanov (2020)

In 1926, a railway line connecting Lugovaya station to the city of Frunze was constructed. That same year, the city's streets were classified into three types: central, intermediate, and peripheral. The 1930s saw a surge in construction activity, although the city remained provincial in character. Following the establishment of the Kirghiz Soviet Socialist Republic (SSR) in 1936, Frunze became its capital, necessitating significant changes in the city's architecture. In 1938, a series of large-scale state initiatives in architecture and urban planning were implemented, laying the foundation for a new phase in the development of the capital of the Kirghiz SSR. The first general plan for Frunze was developed, prepared by the workshop of the architect I.V. Zholtovsky and oriented towards the city's economic development within a planned economy. Among the authors of the plan were architect N.I. Smirnov, engineering economist G.D. Babad, and consulting academician I.V. Zholtovsky. Additionally, state regulatory documents governing urban planning were introduced, and an architectural and planning department was established, headed by the city's chief architect, responsible for shaping urban policy and overseeing the implementation of the general plan. Furthermore, the Union of Architects of Kyrgyzstan was founded, a public organisation coordinating architectural activity in the region (Alymbaev, 2024).

These measures, alongside the strengthening of the construction sector and the establishment of the first enterprises in the building industry, led to significant changes in urban development. Construction based on the first master plan commenced in 1940 and continued after the Second World War. The city retained a rectangular quarter layout, expanding to the east, west, and south, with the construction of buildings rising to two or three stories. Architectural ensembles began to emerge in Frunze. Between 1946 and 1950, several notable structures were built, including the opera and ballet theatre designed by architects A.I. Laburenko and P.P. Ivanov, residential buildings and a hospital complex on Moskovskaya Street designed by P.P. Ivanov, the ensemble of Soviet Square featuring the building of Kyrgyz State University, which was conceived by architects E.G. Pisarskaya, P.P. Ivanov, and V.E. Nusov, as well as a complex of buildings for the Academy of Sciences designed by Y.V. Bilinsky and A.D. Bocharov, among other projects.

The second general plan for the city of Frunze, developed in the post-war years and approved by the Council of Ministers of the Kirghiz SSR in 1956, differed little from the first. It incorporated provisions that had not been implemented due to the war and represented an adjustment of these. However, the population estimate in the new plan was lower than the actual figure, which diminished the value of the analytical component. This necessitated the development of a new general plan for the city of Frunze, although the overall layout of the city remained virtually unchanged. Table 1 provides a systematic overview of the key changes in the city's architecture and infrastructure associated with the development of the railway network.

Table 1. Impact of the railway on the architecture and infrastructure of Pishpek

Aspect	Description
Changes in the architecture of railway stations	Stations became more functional and spacious, featuring elements of industrial style.
Use of new materials	The adoption of modern building materials to enhance strength and durability.
Planning of new districts	The development of new districts and industrial zones in proximity to railway lines.
Development of transport logistics	The integration of railway transport into the urban environment to improve logistical connections.
Impact on urban panelling	The master plans of the city were oriented around the location of the railway infrastructure.

Source: compiled by the authors

The development of the railway in Bishkek during the mid-20th century played a pivotal role in transforming the city from an administrative and cultural centre into a major industrial hub. The railway not only provided transport links to other regions but also stimulated the creation of a powerful industrial base, which became the foundation for the city's economic growth and development. Along the railway lines, factories and plants began to be constructed at a rapid pace, fundamentally altering Bishkek's architectural landscape.

The industrial zone that emerged around the railway station quickly became one of the city's key districts. The proximity of the railway provided convenient transportation links, making this area ideal for the location of large industrial facilities. Among the first and most significant establishments in this zone was the machine engineering plant, which became a symbol of Bishkek's industrialisation.

Constructed between the 1950s and 1960s, the plant was designed to meet the contemporary standards for industrial buildings. Key design criteria included scale, functionality, and durability, reflecting the need for production facilities capable of operating at full capacity for extended periods. Occupying a substantial area, the plant was equipped with all necessary utilities and infrastructure to ensure uninterrupted production.

The architecture of the machine engineering plant, like other industrial buildings of that era, was characterised by strict and laconic forms. Functionality was paramount: buildings had to be robust, practical, and conducive to the production process. As a result, the plant buildings had simple rectangular or square forms, allowing for efficient use of the internal space. Concrete and steel were the primary materials used in construction (Babachenko *et al.*, 2022). These materials provided the necessary structural strength, resistance to external elements, and durability. Industrial buildings were characterised by high ceilings and large window openings, ensuring sufficient natural light and ventilation for optimal production processes.

The façades of these buildings typically lacked intricate decorative elements. The primary focus was on simplicity and practicality. The only decorative features might be relief patterns on concrete panels or the use of colour accents to highlight specific structural elements. This simplicity and minimalism became a hallmark of industrial architecture of that period, reflecting broader trends in Soviet architecture which emphasised functional and durable buildings. The construction of the machine engineering plant and other industrial facilities near the railway station significantly altered Bishkek's urban infrastructure. The emergence of such large industrial enterprises led to the creation of new jobs, which in turn attracted a population influx to the city. This necessitated the construction of new residential areas, schools, hospitals, and other social infrastructure.

Industrial zones that developed around the railway line became pivotal elements of the city's economy. They employed a significant portion of the population and contributed to the growth of related sectors such as transport, logistics, and services. Furthermore, the expansion of industry in the city led to the establishment of new educational institutions, and training specialists for work in factories. The rapid industrialisation also had a significant impact on the city's environment. The proliferation of factories led to increased air and water pollution, becoming a major concern for city authorities. In response, measures were subsequently taken to improve the ecological conditions, including the modernisation of production processes and the implementation of wastewater treatment facilities.

Bishkek's industrial heritage, forged in the mid-20th century, remains a significant part of the city's history. Many factories continue to operate, contributing to the city and regional economies. Concurrently, these industrial zones are undergoing modernisation, leading to improved environmental conditions and the creation of new jobs. The railway, as a catalyst for industrial development, continues to be reflected in Bishkek's architectural landscape and social fabric, underscoring the importance of this infrastructure project in the city's history.

In the second half of the 20th century, as Bishkek's population grew due to the expansion of the railway, there was a pressing need for new residential areas to accommodate the increasing number of inhabitants. One significant project of that era was a residential complex built in the vicinity of the railway station. This complex, which became an integral part of the urban landscape, was conceived as a model of contemporary urban planning and a realisation of innovative architectural ideas.

The residential complex near the railway station was designed according to the principles of late Modernism, a style widely adopted in Soviet architecture of that period. The core concept of the project was to create a comfortable and functional environment where housing and public facilities were integrated into a unified architectural and urban space. The complex comprised several apartment buildings, constructed according to standard designs typical of Soviet architecture in the 1960s and 1970s. These buildings were made of reinforced concrete and brick, ensuring their durability and longevity. The high-rise buildings, typically five to nine storeys tall, were designed to maximise the use of urban space, allowing for a large number of apartments to be accommodated within a relatively small area.

The architecture of the residential complex was typical of late Modernism: the buildings had simple, geometrically clean lines, minimalist façades, and functional layouts. The primary focus was on comfort and practicality. Each building featured large windows to maximise natural light, and balconies, which served as both an architectural feature and an additional space for residents. The building façades, primarily constructed from brick and reinforced concrete, were finished with plaster and facing panels. A restrained colour palette, such as light shades of grey and beige, was employed, giving the complex a sober and contemporary appearance. The façades were also characterised by the horizontal lines and rhythmic repetition of window openings typical of the period, emphasising the laconic and functional nature of the architectural solution.

The residential complex constructed near the railway station, in the style of late Modernism, successfully embodies the principles of Soviet architecture from the 1960s and 1970s. Through the use of standardised designs, reinforced concrete, and brick, the complex ensures durability and functionality, which were key aspects of that era. Its architecture, with its simple geometric forms and minimalist facades, reflects the core ideas of convenience and practicality, aligning with the tenets of late Modernism.

However, considering modern comfort standards and urban planning regulations, this residential complex may not fully meet contemporary expectations. Although spacious windows and balconies provide ample natural light and extra living space for residents, the limitations of standardised designs and restrained architectural solutions may fall short of more innovative and adaptable approaches in modern construction. Nevertheless, the use of a restrained colour palette and the underlying emphasis on functionality remain relevant, making the complex suitable for comfortable living but not ideal in terms of contemporary demands for residential spaces.

The development of Frunze's urban transport infrastructure was largely influenced by the presence of the railway, which limited the number of level crossings and overpasses. Key structures such as the Frunze-2 station, Dzerzhinsky Boulevard, the eastern industrial zone, and the combined heat and power plant became central elements around which large-scale construction took place. These facilities contributed to the creation of unique architectural and spatial solutions, such as the Vokzalnaya Square complex, the railway workers' park in Pishpek, and the panoramic view of Sovetskaya Street visible from the pedestrian bridge of the overpass.

The Turkestan-Siberian railway had a profound impact on the development of Bishkek, acting as a catalyst for its economic growth and urbanisation. The construction of railway infrastructure stimulated trade and industry, facilitated migration and altered the city's demographic makeup. The railway also influenced architectural and urban changes, including the expansion of the city's boundaries and the formation of new districts. In the future, railway infrastructure will continue to play a pivotal role in the city's further modernisation and development.

The architecture of Bishkek's railway stations has been significantly modernised since the advent of the railway. The buildings have become more functional and expansive, exhibiting elements of industrial style through the use of new building materials and technologies, which ensure the strength and durability of the structures. The railway has facilitated the expansion of urban territory and the formation of new districts. Urban development has actively progressed in the eastern, western, and southern directions, made possible by the advancement of railway infrastructure. The establishment of new industrial zones in close proximity to the railway lines has improved transport logistics and promoted the integration of rail transport into the urban environment. The study has indicated that the modernisation of the existing railway infrastructure is essential for enhancing its functionality and integrating it into the overall city transport system. Railway facilities, possessing architectural and historical significance, require a careful approach to their preservation and adaptation to contemporary conditions.

The findings of this research should prove beneficial in addressing urban planning and architectural challenges facing the city. In the future, when undertaking reconstruction projects, the research materials can provide valuable insights for creating a comprehensive transport hub, supported by terminal and warehousing infrastructure. Given Bishkek's advantageous geographic location and its administrative significance within the region, understanding how the city's urban structure has been shaped by railway transport will allow for more precise adjustments to the city's urban planning policies.

DISCUSSION

The construction of the Turkestan-Siberian railway played a crucial role in the economic development of Bishkek, transforming the city and significantly influencing its growth. The railway acted as a catalyst, initiating processes that ultimately led to an increase in population and an expansion of the industrial sector. These changes inevitably affected the city's architecture, which began to undergo substantial transformations. This was particularly evident in the station buildings, which became a vital component of the new urban infrastructure. Their architecture evolved to be more expansive and functional, reflecting the city's need for an efficient transport system. New building materials and technologies, such as iron and steel, were actively incorporated into the designs of the stations, ensuring their durability and strength. This development allowed the stations to become symbols of the industrial progress that accompanied Bishkek's growth during that period. Such changes mirrored broader processes of modernisation that encompassed the city as a whole.

Analysis of existing research has shown that a similar impact of railway transport on urban architecture can be observed in other regions. For instance, in the study by A. Cardoso de Matos *et al*. (2020) focusing on the Iberian Peninsula, the significant role of railway stations in transforming the urban environment is also highlighted. In major cities such as Lisbon and Seville, railway stations have become key elements of industrial architecture, mirroring the processes occurring in Bishkek. Here, as in the capital of Kyrgyzstan, new materials and technologies, such as iron, steel, and glass, were introduced, leading to considerable changes in urban morphology and landscape. However, despite the similarities in the processes of change, there are also notable differences. In Bishkek, the emphasis was placed on integrating the railway into the urban environment and developing industrial zones, whereas on the Iberian Peninsula, the focus was on architectural changes that reflected the cultural and historical characteristics of the region. This contrast underscores the diversity of approaches to urban modernisation, which is contingent upon local conditions and traditions.

The development of the railway in Bishkek also had a significant impact on the demographic processes within the city. Improved transport accessibility attracted a large number of migrants, contributing to population growth. This influx of new residents necessitated the expansion of residential and industrial zones, which, in turn, stimulated further urban development (Danchuk *et al*., 2019). New districts began to emerge around the railway lines, forming the basis for Bishkek's urban growth. These changes were driven by the need to adapt the urban infrastructure to new economic realities. The railway not only enhanced transport connections but also facilitated the creation of new jobs, attracting many individuals seeking economic opportunities (Gavkalova & Kyrychenko, 2023). This laid the groundwork for a new urban structure focused on industrial development and the integration of various city districts.

Similar urban transformations can be observed in other regions where railway development has played a pivotal role in urban growth. For instance, a study by A. Rjoub & R.K. Al-Shawabkeh (2018) on the impact of the Hejaz railway on the development of Mafraq in Jordan, also demonstrates how railways facilitated urban growth. However, despite similarities with Bishkek, Mafraq placed a greater emphasis on preserving architectural heritage, while Bishkek focused more on industrial growth and modernisation. This difference highlights the diversity of approaches to urbanisation, dependent on the specific cultural and historical conditions of a region. In both cases, the railway acted as a catalyst for development, but the directions and priorities of these changes varied according to local circumstances.

Equally significant was the impact of the railway on cultural changes in Bishkek. The influx of migrants led to the formation of a new social landscape where diverse cultures and traditions intersected and interacted. This diversity contributed to the enrichment of the city's cultural life, as new social connections and interactions stimulated the development of urban culture. The railway served as a bridge, connecting various cultural and ethnic groups, leading to the formation of a unique urban identity (Matsiuk *et al.*, 2023). These changes were driven by the need to adapt to new living and working conditions brought about by the railway.

Similar processes can be observed in other regions where railways have been instrumental in cultural transformation. For instance, a study by E. Aksoy & N. Gültekin (2007) on the modernisation of Turkish cities highlights the role of railway complexes in these processes. In Turkey, as in Bishkek, the railway became a significant factor in cultural change. However, unlike Bishkek where the changes were more comprehensive, in Turkey modernisation was primarily focused on stylistic changes in architecture. Railway stations and public buildings constructed during the modernisation period became symbols of new trends, integrating traditional and contemporary architectural elements. These changes reflected a desire for renewal and modernisation that became characteristic of cities developing along railway lines.

The architectural changes in Bishkek, prompted by the development of the railway, also involved the integration of new building materials and technologies. This was essential for ensuring the durability and resilience of structures that needed to withstand increased loads and meet the new demands of the urban environment. In this context, the research by E. Kido (2016), focusing on modern railway stations in Japan and Europe, provides valuable comparative insights. It discusses the coordination of architectural and engineering solutions to achieve aesthetically balanced and functional outcomes. In both Japan and Europe, as in Bishkek, architectural changes were driven by the necessity to adapt to new growth conditions. However, in Japan and Europe, the emphasis was placed on technical excellence and aesthetic diversity, reflecting a desire to create harmonious and functional urban spaces. In contrast, the changes in Bishkek were primarily dictated by economic and social realities that required the modernisation of urban infrastructure to support sustainable growth (Dooranov *et al.*, 2024).

A comparison of research on Bishkek and other regions indicates that approaches to the development of railway infrastructure varied according to local characteristics and historical context. For instance, in the study by Ž. Jurković *et al.* (2021), focus on the sustainable development of the city of Osijek in Croatia, there is an emphasis on integrating railway corridors into contemporary planning while preserving cultural and historical heritage. In Osijek, as in Bishkek, the railway became a crucial component of urban infrastructure; however, the approaches to its development and integration into the urban environment differed. In Croatia, the primary focus was on preserving cultural heritage and harmonising new transport corridors with historical buildings. In contrast, Bishkek's emphasis was on the historical and socio-economic analysis of the railway's impact on the city's development. Both studies highlight the necessity of a comprehensive approach to planning railway infrastructure, yet the focal points vary according to the region under investigation.

In Bishkek, railways have contributed to population growth, industrial development, improved transport accessibility and infrastructure, as well as cultural and demographic changes. The impact of railways on urban processes has highlighted the need for strategic planning and investment in transport infrastructure to ensure sustainable development. The railway has acted as a catalyst for change, initiating modernisation processes that have affected all aspects of urban life. The development of railways in Bishkek, as in other regions, has led to significant changes in the urban environment. In each case, these changes had their own unique characteristics, determined by the geographical, cultural, and historical context. However, common to all studies is the recognition of the importance of railway infrastructure as a key element contributing to the modernisation and development of cities. The railway has become the foundation for the formation of new urban structures, where industrial zones and transport corridors played a central role. This change was made possible by the introduction of new technologies and building materials, which allowed for the adaptation of urban infrastructure to new growth conditions. The railway in Bishkek has become a symbol of progress, opening up new opportunities for economic and social development, underscoring its important role in the city's history.

CONCLUSIONS

The construction of the Turkestan-Siberian railway, along with the establishment of stopping points and access routes to industrial facilities, dictated the forced directions of urban development, often affecting areas less suitable for residential construction than those occupied by railway infrastructure. The railway also facilitated the growth of existing industries and the establishment of new industrial enterprises, ensuring their uninterrupted operation through the delivery of raw materials and the transport of finished products. Consequently, nearly all industrial facilities associated with the Frunze station were situated along the railway corridors. This resulted in the fragmentation of the urban structure, a lack of clear zoning, an expansion of urban land, deterioration of transport and engineering services, challenges in forming the planning structure and development of coastal areas, as well as a worsening of the environmental situation.

The analysis of the impact of the railway hub on the urban structure of the city revealed a dual relationship between the development of the railway and the growth of industrial districts. The expansion of the railway hub facilitated industrial growth, while conversely, the rise of industry complicated the railway infrastructure within the city limits. The railway also had a significant influence on the formation of the intra-city transport infrastructure of Frunze, the main routes of which were determined by the limited number of crossings and overpasses over the railway lines. The construction of facilities such as the Frunze-2 station, Dzerzhinsky Boulevard, the eastern industrial zone, and the combined heat and power plant contributed to the emergence of large-scale developments. This led to the creation of interesting architectural and spatial solutions, such as the Vokzalnaya Square complex, the railway workers' park in Pishpek, and the panoramic view of Sovetskaya Street visible from the pedestrian bridge of the overpass.

The research findings underscore the need to pay special attention to Bishkek's railway junction to create a more advanced urban structure, as railway functions have long been taken into account as an urban planning factor. It is important to maintain the capital's status as a major transport and distribution centre in the future. Future research could delve into a detailed analysis of the railway infrastructure's impact on the environment, including changes to ecosystems, air quality, and noise pollution levels. Additionally, it could explore the potential of modernising railway infrastructure using advanced technologies such as automation and digitalisation to enhance the efficiency and environmental friendliness of the transport system.

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CONFLICT OF INTEREST

None.

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Вплив залізниці на розвиток Бішкеку

Анотація. Метою даного дослідження був детальний аналіз впливу залізниці на розвиток міста Бішкек. У дослідженні використовувалися історико-аналітичні та географічні методи, аналіз архівних документів, картографічних матеріалів та наукових публікацій для з’ясування впливу залізниці на зростання Бішкеку. Результати дослідження показали, що будівництво Туркестано-Сибірської залізниці відіграло ключову роль у формуванні міської структури Бішкека. Залізниця сприяла економічному зростанню міста, збільшенню населення та промисловому розвитку. Навколо залізничних станцій і шляхів виникли нові житлові та промислові райони, що призвело до значного розширення міської території. Крім того, залізниця покращила транспортну доступність міста, сприяючи розвитку торгівлі та міжрегіональних зв’язків. Вплив залізниці також позначився на архітектурі міста, що характеризується появою будівель і споруд, характерних для залізничної епохи. З часом роль залізниці в житті міста дещо зменшилася, проте її історичний вплив залишається значним. Дослідження показало, що залізниця сприяла не лише економічному розвитку, але й культурним змінам у Бішкеку. Поява залізничного вузла призвела до посилення міграції та зміни демографічної структури міста, залучення нових мешканців і трудових ресурсів. Залізниця також сприяла розвитку інфраструктури та комунальних послуг, таких як електрифікація та водопостачання, що покращило якість життя в місті. Зрештою, залізниця стала вирішальним фактором інтеграції Бішкеку в регіональні та міжнародні транспортні мережі, підвищивши його стратегічне значення в регіоні. Залізниця відіграла важливу роль у становленні та розвитку Бішкека, здійснюючи багатогранний вплив на його економіку, соціальну структуру та містобудування. Історичний досвід розвитку залізничної інфраструктури міста може слугувати основою для планування його майбутнього розвитку

Ключові слова: архітектура залізничного вокзалу; міжрегіональне сполучення; містобудування; міський каркас; транспортна мережа

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Technology of granulated ceramic aggregate for concrete based on clay of Atyrau deposit of Western Kazakhstan

Abstract. The purpose of this study was to investigate the technology of granular ceramic aggregate based on clay of Atyrau deposit, with a focus on improving the mechanical and thermal properties of concrete to achieve best efficiency and sustainability in construction. The methods employed in this study included chemical analysis, X-ray phase analysis, electron microscopy. Using these methods, the physical-mechanical and chemical-mineralogical characteristics of the ceramic aggregate were determined. The study presents solutions to the problem of providing the construction industry of the West Kazakhstan region. It highlighted the key characteristics of the material, its structural features, and its effect on concrete properties. The study presented the errors occurring during the application of granular ceramic aggregate technology and identified the reasons for their occurrence. The functioning of the technology was analysed,

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which is critical for determining its efficiency, its potential for development, and for identifying possible improvements in the operation of the respective industries. The evaluation of the performance of concrete with granular ceramic aggregate, the rationale for the use of this material, the limitations in use, and the impact of these limitations on the quality of the final product were discussed. The study proposed recommendations aimed at optimising the application process of granular ceramic aggregate, improving the reliability of concrete, and considering a range of factors affecting production and operational aspects

Keywords: construction; natural resources; exploitation; component; engineering system

INTRODUCTION

The study of granular ceramic aggregate technology for clay-based concrete represents an essential stage in the development of the construction industry. This is conditioned by the potential improvement in the mechanical properties of concrete. The use of clay as an aggregate brings environmental sustainability, reducing dependence on artificial materials. Alumina (a key component of clay) may be available and cheaper than conventional building materials. The unique properties of clay, such as good thermal and acoustic insulation, offer opportunities for creating energy efficient buildings and improving living conditions. Research into this subject can lead to the development of new materials and construction methods, contributing to the continuous improvement of the industry.

The problematic of researching the technology of granular ceramic aggregate for clay-based concrete lies in the need to determine the best method of creation and implementation of this material in the construction sphere (Kolesnikova *et al.*, 2023). Researchers face challenges such as determining suitable physico-chemical characteristics of clay, developing an efficient granulation technology, analysing the effect of aggregate on concrete properties, and assessing the economic and environmental feasibility of the technology.

According to S. Montayev & M. Ryskaliev (2020), ceramic porous aggregates, which are natural or artificial porous stone materials with a bulk density not exceeding 1,200 kg/m^3, find application in modern construction in the creation of lightweight concrete. These lightweight aggregates are usually produced by thermal treatment of the clay raw material, followed by screening or crushing and subsequent grading. Ceramic materials have thus been successfully introduced into concrete production, occupying their specialised niche (Kutsenko & Kutsenko, 2022). This study did not investigate the effect of different heat treatment temperatures of clay raw materials on the properties of ceramic porous aggregates. S. Montayev & D. Majit (2021) propose a simplified technology to produce ceramic aggregate with low bulk density. The essence of the method is thermal treatment of clay shale at a temperature impact of 700-800°C,which leads to cracking of grains and reduction of bulk density by 1.5 times compared to conventional methods. This study did not investigate the effect of changes in the structure of ceramic aggregate on its mechanical properties.

N. Bekkaliev *et al.* (2021) focus on the problems associated with the shortage and excessive cost of crushed stone used in construction, especially in reinforced concrete structures and road construction. To solve this problem, it is proposed to use road construction expanded clay aggregate, a material based on clay processing, which can replace crushed stone and be used as a thermal insulation material (Tassybekov *et al.*, 2020). The authors also propose to integrate industrial wastes such as metallurgical slags and ashes from combined heat and power plants (CHP) into the production of road construction expanded clay aggregate. This study did not investigate the effect of proportions of industrial wastes such as ash from CHP on the physical and mechanical properties of road construction expanded clay aggregate.

Ye. Ryltsev (2017) presented a method of production of ceramic porous aggregate using oil sludge addition to montmorillonite clay. This not only improves the quality of the aggregate, but also contributes to the utilisation of waste and the replenishment of the raw material base with new materials (Khrystych, 2023). The economic benefit of this method is the reduction of raw material and production process costs (Astakhova & Astakhov, 2024). This study did not investigate in detail the effect of oil sludge additive on the environmental resistance and environmental sustainability of ceramic aggregate. A. Hotovkin (2023) conducted experiments to create expanded clay by introducing loess-like loams into bentonite clays. The results demonstrate the transition of loams from non-swelling to medium-swelling clays. Increasing the content of bentonite clay from 20 to 50% was accompanied by a decrease in the average density of samples and an increase in granule strength by 2.5-3 times. This study did not analyse the effect of different proportions of components on the structural features of expanded clay, such as its porosity and granule shape.

The purpose of this study was to comprehensively analyse the influence of a range of factors such as heat treatment temperature, structure changes, industrial waste proportions, on the properties of ceramic aggregate, considering its physical and mechanical characteristics. The objectives of this study were to analyse the physical and chemical properties of clay from the above-mentioned deposit, including mineral composition and particle structure, to develop and optimise granulation technology for the production of ceramic aggregate, and to evaluate the effect of aggregate on the mechanical properties of concrete and its stability.

MATERIALS AND METHODS

The study of granular ceramic aggregate technology was conducted using various methods. Functional method in the study of this topic contributed to a more profound understanding of the properties of clay Atyrau deposit and optimise its use in the technology of granular ceramic aggregate for concrete. The synthesis method helped to form the best material composition and improve its properties to increase the strength and stability of concretes; to highlight key findings, draw general conclusions, and generalise the findings. The systematisation method helped in organising the data, identifying relationships and creating a unified model for better learning and optimising the material. The comparison method in the study helped in identifying the most effective technology options, determining the best parameters and selecting the best solutions to create a quality and competitive material. The chemical analysis method helped to determine the composition of the raw materials, identify interactions between components, and control the quality of the material produced, thus improving production efficiency and ensuring compliance with standards. The method of X-ray phase analysis in the study contributed to the identification of crystalline phases in the material, determination of structural characteristics and phase composition, which is key to understanding the formation of the material structure and its properties. The electron microscopy method facilitated visual analysis of the microstructure of the material, revealing its morphological features, particle sizes, and distribution of components, and provided a detailed understanding of the internal structure of the aggregate.

The study of granular ceramic aggregate for clay-based concrete was carried out in Zhangir Khan West Kazakhstan Agricultural University. Loam from Atyrau deposit was selected as the main raw material, while ash from Ekibastuz State District Power Plant (SDPP) was used as a modifying component (Fig. 1).

Figure 1. Ekibastuz State District Power Plant
Source: compiled by the authors

Clay samples were taken directly from the quarry and standards including the State Standard of the Republic of Kazakhstan (ST RK) No. 992-96 (1996) were used to evaluate their properties in laboratory conditions. After transporting the ash and clay samples, analyses were carried out to determine their physical and mechanical properties and chemical and mineralogical composition. Firstly, the raw materials were dried in an electric desiccator at 70-80°C until a final moisture content of 5-7% was achieved. The dried clay components were then pulverised in a laboratory ball mill until they passed through a sieve with 1 mm aperture size. The obtained powdered raw materials were dosed using electronic scales and transferred into a metal spherical bowl for further mixing with water. Initially, the raw materials were mixed in a spherical bowl until a homogeneous texture was obtained. Then water was added to the obtained mixture in the volume of 20-28% of the weight of dry material. After the introduction of water, the raw material mixture was subjected to stirring until a homogeneous ceramic mass was obtained. This mass was used to produce pellets of different sizes: 5-10 mm, 10-20 mm, 20-40 mm. The formed pellets were then subjected to drying in a desiccator at 70-80°C until constant weight was achieved. After drying, the pellets underwent a firing process in a rotary kiln at 1,000°C. After firing, the pellets were tested for physical and mechanical properties. The samples obtained after firing were thoroughly calcined granules coloured light red.

These studies were carried out to assess the suitability of raw materials for the production of ceramic aggregate (expanded clay aggregate for road construction) and ceramic paving stones. X-ray phase analysis was carried out on a DRON-3 diffractometer using SiCa radiation in the angle range of 80-640, with a method sensitivity of 1-2%. Clay powders passed through a 0.315 sieve were subjected to X-ray phase analysis. Chemical and mineralogical composition of the raw components under study was determined using scanning electron microscope JSM-6390LV with energy-dispersive microanalysis system, X'Pert PRO MPD X-ray diffractometer and inductively coupled plasma mass spectrometer ICP-MS Agilent 7500cx from JEOL, Japan.

The methods employed made it possible to determine the physical and mechanical characteristics, chemical composition and structure of the materials, which is important for assessing their suitability in the technology of production of ceramic materials. This comprehensive study has contributed to a better understanding of the properties of the raw material components and the optimisation of the technological processes in the production of granular ceramic aggregate.

RESULTS

To provide high quality building materials and improve the performance of concrete mixtures, clay-based granular ceramic aggregate technology is being actively developed. This innovative process involves the use of specially treated clay as the main component to create granules that are subsequently incorporated into concrete (Moreno-Maroto *et al.*, 2023).

The study of clay of Atyrau deposit revealed a range of characteristics that determine its properties. Chizhsky drying sensitivity coefficient (Cd): the estimation of this parameter is within 63-66. The drying sensitivity coefficient is an index reflecting the change in the volume of clay material during drying and allowing to judge its plasticity and moulding ability (Bandura *et al.*, 2024). These studies indicate a plasticity number of 10-11. The plasticity number is a measure of the plasticity of clay and is defined as the difference between the yield strength and the compressive strength (Lotero *et al.*, 2021; Shumakov *et al.*, 2024). The range of average clay density values is 1,210-1,240 kg/m^3. Average density is a measure of the mass of clay material in a unit volume (Ghonaim & Morsy, 2023). Chemical and mineralogical composition: clay of Atyrau deposit differs by absence of montmorillonite component. Instead, mixed-layer formations with hydrous mica and kaolinite are present. This indicates the composition of the clay and its mineral composition (Mahmoodi *et al.*, 2023). Different ones have been found in clay, each characterised by its lattice parameters (d/n) (Table 1).

Table 1. Lattice parameters of crystalline phases of Atyrau deposit

Quartz	Feldspar	Calcite	Hematite
d/n = 4.23·10^{-10} m	d/n = 3.18·10^{-10} m	d/n = 3.02·10^{-10} m	d/n = 1.839·10^{-10} m
d/n = 3.34·10^{-10} m		d/n = 2.018·10^{-10} m	d/n = 1.686·10^{-10} m
d/n = 1.974·10^{-10} m	d/n = 2.286·10^{-10} m	d/n = 1.912·10^{-10} m	d/n = 1.590·10^{-10} m
d/n = 1.813·10^{-10} m			
d/n = 1.538·10^{-10} m			

Source: B. Kanagaraj *et al*. (2023)

These data provide information on the structure and composition of the crystalline components of clay, which can be vital for understanding its properties and potential applications in various fields. The Atyrau loam data include high-resolution images of the clay microstructure (Fig. 2), showing particle morphology, structural features, and particle sizes. The clay of the sample under study is characterised by a certain chemical composition (Table 2).

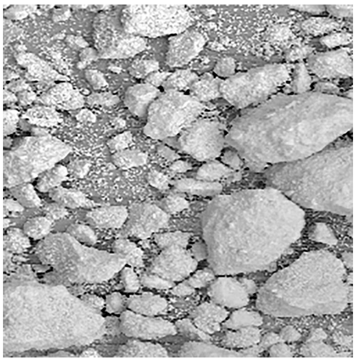

Figure 2. Scanning electron microscopy image of Atyrau loam

Source: compiled by the authors

Table 2. Weight percentages of the elements of the clay sample under study

Element	%
oxygen (O)	52.79
sodium (Na)	0.96
magnesium (Mg)	2.15
aluminium (Al)	7.58
silicon (Si)	18.62
sulphur (S)	0.23
chlorine (Cl)	0.64
potassium (K)	1.92
calcium (Ca)	9.84
titanium (Ti)	0.28
iron (Fe)	5

Source: compiled by the authors

These data provide information on the chemical composition of clay, which is a key aspect when investigating its properties and possible applications in various fields including construction, ceramics, and other industries. As a result of scientific and experimental studies, the main physical and mechanical characteristics of ash were determined. The particle size analysis of ashes shows the content of different fractions depending on the particle size. Particles larger than 0.25 mm represent 5.98%, while particles within 0.05-0.01 mm are represented by a fraction of 43.07%. The specific surface area of ash, a significant parameter, indicates the surface of its particles and ranges within 3,200-3,700 g/cm^2. The true density of ash, which reflects its mass per unit volume, is within 1.75-1.84 g/cm^3. Bulk density, which is the mass of ash per unit volume when bulked, ranges within 675-740 kg/m^3. The data on the chemical composition of the ash (Table 3), which includes significant amounts of silica, aluminium oxide, calcium, are essential for determining the characteristics of the ash, its properties, and possible applications such as construction, cement, or other building materials.

Table 3. Chemical composition of ashes obtained from Ekibastuz SDPP

Name of raw material	Oxide content, wt. %												
	SiO_2	Al_2O_3	TiO_2	CaO	MgO	Fe_2O_3	P_2O_5	F	SO_3	CO_2	Na_2O	K_2O	para
Ekibastuz SDPP ash	57.7	24.5	-	1.1	1	4.1	-	-	0.13	-	1.57	-	8.7

Source: compiled by the authors

Each of the chemical elements in the composition of Ekibastuz SDPP ash can influence the production technology of granular ceramic aggregate for clay-based concrete (Table 4).

Table 4. Influence of elements on material properties

Element	Influence
SiO_2 (silica)	Affects strength and stability. Supports the formation of strong structures in ceramics.
Al_2O_3 (aluminium oxide)	Takes part in the formation of crystal structures, affecting mechanical properties. May also affect colour and thermal stability.
CaO (calcium oxide)	Can serve as a binder and improve the properties of ceramic material. Affects strength and stability.
MgO (magnesium oxide)	Affects mechanical properties and thermal stability. Can be used to regulate rheological characteristics.
Fe_2O_3 (iron oxide)	May affect the colour range and structure of the material. A small amount can be positive for mechanical properties.
Na_2O and K_2O (sodium and potassium oxides)	Affect the chemical and physical properties of clay, can activate the ash binder.
P_2O_5 (phosphorus oxide), SO_3 (sulphur oxide), F (fluorine)	May affect glass transition properties and improve material strength.
CO_2 (carbon dioxide)	Affects carbonisation characteristics, which may be essential in the firing process.

Source: compiled by the authors

These elements can be adjusted in the granular ceramic aggregate production technology to achieve best properties for clay-based concretes (Lu *et al.*, 2023). The research area related to the development of ceramic composition for the creation of ceramic aggregate (expanded clay aggregate for road construction) and ceramic paving stones is defined by the maximum permissible concentrations of the components expressed in per cent by mass. In this area of research, the concentration limit ranges were established as follows: loam from Atyrau deposit – from 70 to 90%, and Ekibastuz SDPP ash – from 10 to 30%. Three different ceramic compositions were considered and each of them is characterised by certain percentages of raw materials (Table 5).

Table 5. Characteristics of ceramic compositions

No. of structure	Bulk density, kg/m^3	Compressive strength, MPa	Water absorption, %	Heat transfer coefficient, W/mK
1	1,230	8.7	26.4	0.41
2	970	9.3	31.1	0.28
3	860	12.8	34.4	0.21

Notes: firing temperature – 1,000°C

Source: compiled by the authors

During the analysis of changes in physical and mechanical properties of experimental samples depending on the composition of raw materials the following regularities were revealed: introduction of ash from Ekibastuz SDPP within 10-30% leads to an increase in the strength characteristics of samples of expanded clay aggregate for road construction. When fired at 1,000°C, an increase in strength of up to 12.8 MPa is noted. While the average density of the samples decreases, ranging within 860-1,230 kg/m^3. These results of scientific and experimental studies also indicate the acceleration of sintering and crystallisation processes in ceramic masses with the addition of ash from Ekibastuz SDPP (Cantero *et al*., 2021). From the results of X-ray phase analysis and electron microscopic analysis it follows that the samples contain the following crystalline phases: quartz, needle-shaped crystals of mullite, as well as melted grains of feldspar and hematite. There is an increase in the glassy phase content due to partial melting of clay minerals. The formation of crystalline and glassy phases at 1,000°C favours the formation of porous and robust microstructure of pellet samples. The change in the average density values of the samples is associated with the formation of porous structure due to the burnout of coal residues present in the ash. This conclusion is confirmed by analysing the microstructure of pellet samples made both without ash addition and with ash addition up to 30%. Samples produced without the addition of ash have a dense structure with small micropores. Whereas the pellet samples with ash addition up to 30% exhibit a characteristic complex porous structure due to sintering. Based on the obtained findings, the development of the technological scheme of production of expanded clay aggregate for road construction based on clay rock processing with the use of corrective additives involves a detailed investigation of technological stages (Table 6).

Table 6. Technological stages of ceramic production

Stage	Description
Extraction and preparation	Search and study of clay rock deposits; assessment of clay raw material quality; laboratory analyses; extraction using mechanical or hydraulic methods; transport of clay raw material to the production site.
Sorting and classification	Mechanical sorting and removal of impurities; classification of clay raw materials by particle size.
Addition of correcting agents	Adding corrective additives to the clay mass to correct chemical composition and improve properties; fine-grained additives to improve the flowability of the mixture.
Mixing and moisturising	Mixing of clay mass with additives in special agitators; moistening of the mixture to achieve optimum consistency.
Moulding	Pressing or extrusion of the mixture to create moulded products (slabs, tiles).
Drying	Pre-drying of formed products at controlled temperature and humidity.
Roasting	Subjecting products to firing in furnaces with a certain temperature and time regime to give strength and resistance to external influences.
Glazing (as required)	Application of glaze on the surface of products to improve decorative and protective characteristics; additional firing step to fix the glaze.
Quality control	Conducting tests for strength, water absorption, geometric dimensions, and other characteristics; rejecting products that do not meet standards.
Packaging and storage	Packaging of finished products according to customer requirements; storage in warehousing conditions.
Shipment	Organisation of transportation and shipment of expanded clay aggregate for road construction to customers or construction sites.
Environmental measures	Implementation of waste recycling and reuse system; compliance with environmental protection standards.

Source: compiled by the authors

It is vital to emphasise that the specific processes and parameters will depend on the specifications of the clay raw material, the requirements of the expanded clay and the corrective additives used. In addition, local standards and regulations should be considered when designing the process flow diagram.

DISCUSSION

As a result of the study of clay from the Atyrau deposit in Western Kazakhstan, it was found that these materials are suitable to produce granular sintered ceramic aggregate for concrete. The use of large tonnage secondary resources such as Ekibastuz SDPP ash improves the physical, mechanical, and technological properties of ceramic aggregates. X-ray diffraction and electron microscopic analyses showed the presence of crystalline phases including quartz, mullite, feldspar, and hematite, and an increase in glass phase content when the clay minerals were melted at 1,000°C. This favours the development of a porous and durable microstructure of the granules. The use of Ekibastuz SDPP ash in the ceramic mass also favourably affects the thermal conductivity of the sintered ceramic material, which can increase energy efficiency in the construction of buildings and structures.

N.T. Sithole & T. Mashifana (2020) analysed the crystal phases of clay samples using X-ray diffraction. X-ray microanalysers were used to determine the lattice parameters of quartz, feldspar, calcite, and hematite. The findings of the researchers were as follows: quartz – $d/n = 4.05 \cdot 10^{-10}$ m, feldspar – $d/n = 3.42 \cdot 10^{-10}$ m, calcite – $d/n = 3.10 \cdot 10^{-10}$ m, hematite – $d/n = 1.75 \cdot 10^{-10}$ m. Lattice parameters of crystalline phases of clay from the study of N.T. Sithole & T. Mashifana (2020) and Atyrau deposits have differences. Quartz and calcite have larger lattice parameters compared to clay from the Atyrau deposit, while feldspar and hematite have finer lattice parameters. These differences may indicate different formation conditions and history of these clays, which requires further geological investigation to fully understand their origin and properties. Additional studies may include analyses of impurities, sample formation conditions, and the effect of temperature and pressure on lattice parameters.

G. Bumanis *et al*. (2022) investigated the chemical composition of oil shale, because its strength makes it an ideal material for wall cladding, flooring, and other building elements. The researchers provided weight percentages of the following elements: oxygen (O) – 48.2%, sodium (Na) – 1.15%, magnesium (Mg) – 2.8%, aluminium (Al) – 6.4%, silicon (Si) – 22.1%, sulphur (S) – 1.05%, chlorine (Cl) – 0.75%, potassium (K) – 1.5%, calcium (Ca) – 10.2%, titanium (Ti) – 0.4%, iron (Fe) – 6.55%. Slate has a higher silicon content, which may have a positive effect on its hardness and resistance to high temperatures (Kruglov *et al*., 2023). On the other hand, clay is distinguished by its higher aluminium content, which may give it increased ductility and ability to form ceramic products. The high iron content of oil shale can give it a distinctive colour and affect its strength properties (Nguyen, 2023; Nenastina *et al*., 2024). Apart from chemical analysis, studies may include physical properties (ductility, hardness), thermal properties (heat capacity), structural studies (X-ray diffraction analysis), mechanical properties (strength), environmental aspects (environmental stability) and technological capabilities (processing processes, compatibility with other materials).

L. Jones & R. Urbano Gutiérrez (2023) investigated the properties of granite, as it is widely used for facing facades of buildings, laying tiles, creating countertops, as well as for the construction of bridges, roads, and other infrastructural objects due to its strength, resistance to wear and tear, and aesthetic appearance. The researchers performed a chemical analysis which showed the following results: oxygen (O) – 60.32%, sodium (Na) – 3.1%, magnesium (Mg) – 0.78%, aluminium (Al) – 10.15%, silicon (Si) – 20.85%, sulphur (S) – 0.23%, chlorine (Cl) – 0.45%, potassium (K) – 2.6%, calcium (Ca) – 1.92%, titanium (Ti) – 0.4%, iron (Fe) – 2.3%. Both granite and clay samples contain oxygen (O) and silicon (Si) in appreciable amounts. The presence of aluminium (Al) in both samples, but in different concentrations, which may affect their mechanical properties. Granite contains a high percentage of oxygen and aluminium, which is inherent in granitic rocks that are often used in construction (Linchenko *et al*., 2022). Clay has higher iron (Fe) and calcium (Ca) content, which makes it more suitable for ceramic industry (Soralump *et al*., 2023). Additionally, the geological origin, mineralogical composition, moisture absorption, electrical properties, biological effects, development of new compositions and evaluation of the economic viability of clay and granite can be investigated.

N.P. Martins *et al*. (2021) conducted a study on sedimentary clays. The particle size analysis shows that particles larger than 0.25 mm account for 8.50% and particles within 0.05-0.01 mm account for 38.20%. The specific surface area of clay ranges within 3,000-3,500 g/cm^2. The true density ranges within 2-2.2 g/cm^3 and the bulk density varies from 800 to 900 kg/m^3. Comparative analysis with ash results shows that clay has higher percentage of coarse particles (more than 0.25 mm) and less percentage of particles within 0.05-0.01 mm as compared to ash. The specific surface area of clay is also slightly less than that of ash. The true and bulk densities of clay exceed the corresponding values for ash. J. Migunthanna *et al*. (2022) investigated the chemical composition of ash obtained from coal fired power plant, because it can be effectively used as an additive for building materials which helps in improving the mechanical and thermal properties such as strength and stability. The results are presented as weight percentages of the following elements: SiO_2 – 62%, Al_2O_3 – 20.2%, TiO_2 – 1.5%, CaO – 0.8%, MgO – 0.9%, Fe_2O_3 – 5.5%, P_2O_5 – 0.2%, F – 0.05%, SO_3 – 0.3%, CO_2 – 2.1%, Na_2O – 1.1%, K_2O – 4%. Comparative analysis of chemical composition of ash obtained from Ekibastuz SDPP and ash from coal-fired power plant (CFPP) revealed the following differences and similarities. Both sources have high SiO_2 content, indicating a considerable presence of silicon in both ashes. CaO content is similar in both compositions, while MgO, Na_2O, and K_2O contents are almost absent. While Ekibastuz SDPP ash contains a higher percentage of Al_2O_3, CFPP ash has a higher Fe_2O_3 content. It is also noted that TiO_2, P_2O_5, F, SO_3, and CO_2 are present only in CFPP ash, which may affect its properties and applications. These differences emphasise the need to consider the chemical composition of ash while evaluating its potential use in various industries, especially in the context of construction and material production.

G.S. dos Reis *et al*. (2021) proposed a technological scheme for the production of ceramic tiles from clay and waste sludge from the ceramic industry. Extraction and preparation of raw materials, including prospecting and exploration, quality assessment, and laboratory analyses. Sorting and classification, including removal of impurities and classification of raw materials. Addition of enhancing additives such as hydrogen compounds to improve ductility. Mixing and moistening to achieve best mixture consistency. Moulding through pressing or extrusion. Drying and subsequent firing in special kilns. Glazing and, if necessary, re-firing to fix the glaze. Quality control including tests for strength, water absorption, and geometric dimensions. Customised packaging, storage, and dispatch. Environmental measures, including waste management systems and compliance with environmental standards, are also a significant step.

The discussion of clay-based granular ceramic aggregate revealed the prospects for the use of this material in the construction industry. The discussion helped to emphasise its potential as a functional and effective component for concretes, with certain properties that contribute to improve the mechanical and environmental performance of construction materials. This material not only provides opportunities for sustainable utilisation of natural resources, but also ensures the stability and high strength of the final concrete structures.

CONCLUSIONS

The findings of the study of clay of Atyrau deposit confirm its suitability for use in the technology of granulated ceramic aggregate, which can improve the properties of concrete mixtures. Analysing the characteristics of clay, including its plasticity, crystalline structure and chemical composition, provides important information on potential applications in construction and industry. Ekibastuz SDPP ash was investigated for its fractional composition, specific surface area, true and bulk density.

Chemical analysis highlighted the high content of SiO_2, Al_2O_3, and CaO, which makes this ash a promising component for granular ceramic aggregate in construction. Analysis of physical and mechanical properties of the obtained granules at three different compositions showed a significant influence of the proportions of loam and Ekibastuz SDPP ash on their density, strength, water absorption, and thermal conductivity. As a result of the conducted study of raw materials for granular ceramic aggregate, the main stages of its production were identified. These steps include drying, grinding, dosing, mixing, granule formation, drying, and firing at high temperature. The physical and mechanical properties of the finished samples confirm the differences in the characteristics for the three different compositions, which reflects the influence of the percentage of loam and Ekibastuz SDPP ash on the final material properties. As a result of analysing the physical and mechanical properties of ceramic samples with the addition of Ekibastuz SDPP ash varying from 10 to 30%, it was found that the use of this additive increases the strength properties of samples of expanded clay aggregate for road construction after firing at 1,000°C. Therewith, the average density of the samples decreases, forming a porous structure, which indicates the processes of sintering and crystallisation in ceramic masses when using ash.

The findings obtained show changes in the microstructure of the samples, reflecting the effect of the additive on the formation of porous and durable granule structure. Clay is favoured in construction because of its high plasticity, thermal insulation, environmental sustainability, and decorative possibilities. Compared to slate and granite, clay offers ease of moulding, effective thermal insulation, naturalness, and aesthetically pleasing design. Further research can be directed towards the optimisation of the production process of clay-based granular ceramic aggregate, analysis of its effect on the mechanical properties of concrete, and the search for new methods to improve the performance of concrete structures using this material.

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CONFLICT OF INTEREST

None.

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Технологія гранульованого керамічного заповнювача для бетона на основі глин Атирауського родовища Західного Казахстану

Анотація. Метою цього дослідження було вивчення технології гранульованого керамічного заповнювача на основі глини Атирауського родовища, з акцентом на поліпшення механічних і термічних властивостей бетону для досягнення найкращої ефективності та стійкості в будівництві. Методи, використані в цьому дослідженні, включали хімічний аналіз, рентгенофазовий аналіз, електронну мікроскопію. За допомогою цих методів були визначені фізико-механічні та хіміко-мінералогічні характеристики керамічного заповнювача. У дослідженні представлені шляхи вирішення проблеми забезпечення будівельної галузі Західно-Казахстанської області. Виділено ключові характеристики матеріалу, його структурні особливості та вплив на властивості бетону. У дослідженні представлені помилки, що виникають при застосуванні технології гранульованого керамічного заповнювача, і виявлені причини їх виникнення. Проаналізовано функціонування технології, що є критично важливим для визначення її ефективності, потенціалу для розвитку та виявлення можливих покращень у роботі відповідних галузей. Обговорено оцінку експлуатаційних характеристик бетону з гранульованим керамічним заповнювачем, обґрунтування застосування цього матеріалу, обмеження у використанні та вплив цих обмежень на якість кінцевого продукту. В результаті дослідження були запропоновані рекомендації, спрямовані на оптимізацію процесу застосування гранульованого керамічного заповнювача, підвищення надійності бетону та врахування низки факторів, що впливають на виробничі та експлуатаційні аспекти

Ключові слова: будівництво; природні ресурси; експлуатація; компонент; інженерна система

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An analysis of the transport impact of finish building on-ramps and off-ramps from the Dnipro embankment to the Darnytskyi Bridge in Kyiv

Abstract. This study was aimed at assessing the effectiveness of design solutions for the development of Kyiv's transport infrastructure based on transport modelling and analysis of possible socio-economic effects. To do this, a four-step algorithm for modelling transport demand was used, based on data from sociological surveys, territory plans, and forecasts for 2030. The results of the study showed significant changes in the functioning of the Kyiv transport network as a result of the implementation of the proposed design solutions. The transport modelling helped to estimate quantitative indicators such as traffic volumes on major highways, as well as qualitative changes such as reduced congestion, shorter travel times, and cost savings. One of the key results was that the opening of new exits and entrances to the Darnytskyi Bridge on the left bank contributed to a slight increase in bridge capacity, but the biggest

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effect was seen on the approaches to the bridge. The additional approaches have increased traffic volumes, which indicates improved transport accessibility for drivers using this transport hub. The results related to environmental performance were also important. The reduction in congestion resulted in a reduction in CO_2 emissions, which is a significant contribution to improving the environmental situation in the city. In terms of cost-effectiveness, the results demonstrated significant savings in transport losses, confirming that the implementation of the proposed measures has a positive impact on transport infrastructure, as well as reducing financial losses associated with travel. Thus, the results of the study confirmed that the proposed design solutions have a positive impact on the development of the transport network, increasing capacity and reducing negative environmental impact, which opens up opportunities for creating a more efficient transport system that meets the requirements of sustainable development and improves the overall quality of life of Kyiv residents

Keywords: street and road network; transport modelling; traffic capacity; node congestion; infrastructure development scenarios; social impacts

INTRODUCTION

Ukrainian cities, including the capital, Kyiv, are facing transport issues arising from the rapid increase in car ownership (Semchenko, 2020). The growth of the private car fleet is driven by both the rising demand for personal transport and the relative availability of used cars from Europe and the USA, influenced by national policies. These factors, combined with urban planning policies that typically aim to meet citizens' demands for unrestricted car use, have led to a significant increase in the load on the road network (RN) in Ukrainian cities. The consequences include a deterioration in the level of service (LOS) of the RN, an increase in harmful emissions, higher energy losses, a decline in transport accessibility, and reduced resilience of the transport systems in Ukrainian cities.

The situation is particularly critical in Kyiv. In 2021, the Ukrainian capital ranked third among 404 cities worldwide for congestion levels, according to the Traffic Index (2021), with traffic delays reaching 56%. This indicates that a significant portion of Kyiv's RN, constructed in the 1960s and 1980s, along with RN overall density, is inadequate to meet the growing demand for transportation. Moreover, due to limited resources for maintaining and developing the RN, the city is gradually losing its capacity to modernise, and even maintain, its existing transport infrastructure, further exacerbating the problem of deficiencies (Sidliarenko, 2023). Given these challenges, it is crucial to make decisions aimed at improving the efficiency of the RN. One key area is the modernisation and expansion of important transport hubs and junctions. Conducting a cost-benefit analysis of such projects can facilitate decision-making that aligns with legal requirements and urban planning goals, enabling the achievement of the highest level of cost-effectiveness.

A crucial factor in enhancing the efficiency of RNs is a comprehensive study of the impact of various design solutions on traffic flows using transport modelling. In the research by O. Stepanchuk *et al*. (2022), the effectiveness of transport modelling methods was highlighted, emphasising that such technologies can significantly improve the overall efficiency of RN utilisation. In the study by V. Perlov & I. Kyrytsya (2023), transport modelling was used for planning and modernising the RN in Vinnytsia, where positive effects of applying such technologies were identified. Furthermore, the article of G. Boeing & W. Riggs (2024) examined the impact of transport systems on traffic optimisation, demonstrating that the use of transport modelling methods can significantly optimise RNs, reducing traffic delays and improving overall network performance. Thus, these results confirm that the application of transport modelling is essential and relevant for the effective management of RN development.

Moreover, transport modelling can provide deeper insights into the impact of specific design solutions on the performance of RNs. In the research conducted by E. Suryani *et al*. (2020), the effectiveness of implementing new design solutions based on transport modelling of various traffic management scenarios was analysed, revealing that optimising traffic management at intersections and road sections can lead to increased capacity of key sections of the RN. The study of E. Zadobrischi *et al*. (2020) focused on the impact of modernising RN elements on the overall efficiency of the transport system, and as a result, revealed that such updates can contribute to a significant transport effect. In the study by W. Wu *et al*. (2020), the emphasis was on the implementation of intelligent transportation systems, where, using transport modelling, it was found that the integration of innovative technologies can improve the overall level of road safety on the RN and yield a transport effect. Nevertheless, even considering the positive results, it is necessary to take into account the limitations and challenges associated with the implementation of such design solutions and, consequently, projects.

Another crucial factor to analyse is the impact of different strategies on RN efficiency through the use of transport modelling. The study of M. Ogryzek *et al*. (2020) conducted detailed transport modelling of scenarios involving both the reconstruction of existing roads and the construction of new transport routes, demonstrating that the reconstruction of key intersections can increase the overall capacity of the RN. The research of C.-Y. Wu *et al*. (2021) focused on assessing the impact of new transport technologies on achieving transport efficiency, revealing through transport modelling those new technologies contribute to reducing congestion duration at intersections on the RN. The article of P. Wang *et al*. (2020) used transport modelling to investigate the transport effect of measures to restrict the use of private transport, including the development of cycling infrastructure and increasing the amount of public transport. However, despite these results, it should be noted that when implementing new design solutions in an existing RN, it is necessary to consider not only technical but also socio-economic aspects, ensuring a balance between efficiency and the system's resilience, which requires further monitoring and adjustment as projects are developed.

This study aimed to assess the transport impact of design solutions for intersections on the RN, using the left-bank on-ramps and off-ramps of the Darnytskyi Bridge in Kyiv as a case study. To achieve this goal, several key tasks were defined and implemented, including an analysis of the impact of the proposed design solutions on the overall efficiency of the RN, including changes in capacity, and delay times, as well as an assessment of socio-economic and environmental impacts such as savings in transport losses and expected reductions in CO_2 emissions, allowing for a comprehensive evaluation of the consequences of implementing changes to the RN.

MATERIALS AND METHODS

The research was conducted of the Department of Urban Construction at the Kyiv National University of Construction and Architecture (KNUCA), which specialises in the analysis and development of urban planning solutions. A digital twin of Kyiv's mobility, developed by the university, was used for the analysis. One of the key tools used for transport modelling was the academic version of the PTV Visum software. To forecast the development of Kyiv's regional network (RN) and its suburbs under conditions of uncertainty, a two-stage expert survey was conducted in the field of urban planning. The survey aimed to gather insights and professional assessments on potential development paths, considering the current challenges and resources available. The experts who participated in the survey had significant professional experience in urban and transport planning, ranging from 10 to 25 years, which ensured a high level of expertise in evaluating the feasibility and implications of proposed projects.

The survey was conducted in Kyiv, Ukraine, in 2024, using an absentee format to accommodate the participants' schedules while maintaining ethical and procedural integrity. During the first stage, five experts participated, primarily representing academic institutions and consulting firms. Their involvement focused on identifying critical issues and proposing preliminary solutions. In the second stage, six additional experts joined the survey, including specialists from local government bodies and design organisations. This diversified the perspectives and enriched the analysis by incorporating practical and institutional knowledge alongside academic insights. To ensure transparency and adherence to ethical standards, all participants were informed in advance about the principles of ensuring their anonymity. They received comprehensive information about the study's objectives, the procedures for using the data they provided, and the potential risks associated with their participation. Ethical standards were strictly observed throughout the research process. The study conformed to the recommendations of the American Sociological Association's Code of Ethic (1997), Guidance Note of the European Commission "On Ethics and Data Protection" (2021), and adhered to the ethical principles outlined by the academic institution overseeing the research.

During the first stage, experts were asked to identify infrastructure projects and urban development projects in Kyiv and its suburbs that were likely to be implemented or in the final stages of implementation by 2030. Projects were classified into three categories: infrastructure (including the construction or redevelopment of highways, bridges, intersections, and streets), public transport (new routes and rapid transit lines), and development (new residential areas, business centres, industrial enterprises, shopping and entertainment facilities, educational institutions, and cultural institutions). Given that experts provided a more detailed list of projects in the first two categories, it was decided to focus on these areas. In the second stage of the study, the assessment of the likelihood of implementation only concerned infrastructure projects and public transport development projects.

The finalised list from the second stage was provided to 6 experts to assess the likelihood of implementation for each project. The experts were asked to assess the likelihood of the implementation of the following projects by 2030 on a scale from 1 to 7, where 1 indicates the project will definitely not be implemented, and 7 indicates the project will definitely be implemented by 2030. To assess the development of the RN by 2030, the analysis area was divided into over 500 transport zones. For each of these transport zones, data on population and other socio-economic indicators were collected based on materials from the Kyiv General Plan (2020). This data was used to calculate transport demand, which in the digital twin of Kyiv's mobility is implemented using a fourstep algorithm.

The first step in the transport modelling involved a representative sociological survey, based on which the main purposes and volumes of daily trips between transport zones were determined, as well as the distribution of trips by different modes of transport. The analysis also considered data on the duration and distance of trips, which allowed for the calculation of transport demand for each step of model creation. Four main matrices of inter-zonal trips were then formed: for private transport, public transport, pedestrians, and cyclists. Subsequently, the matrices, except for the pedestrian one, were distributed across the RN. For calibration, data from passenger flow surveys on public transport routes and data on traffic volume at key intersections and segments of the RN were used.

The transport demand model used in this study included data from 2019, i.e., the period before COVID-19 and the full-scale war in Ukraine. In the calculations of the forecast scenarios for 2030, a constant value of projected transport demand was used for all scenario variants. Additional important factors were the limitations and assumptions considered when constructing the digital twin, as well as in the process of calculating the transport effect of implementing the proposed scenarios for the development of the RN.

RESULTS

The development of a digital twin of Kyiv's mobility and its suburban area has revealed that one of the primary issues in urban mobility is the uneven planning and development of urban territories. Kyiv exhibits a significant imbalance in the spatial distribution of population and jobs. According to Figure 1, the left-bank districts of the city – Desnianskyi, Darnytskyi, and Dniprovskyi – account for 36% of the city's population (approximately 1.05 million people), yet these areas host only 18% of the total number of workplaces (Sustainable urban transport for Kyiv..., 2016), as illustrated in Figure 2. This mismatch creates significant challenges for the RN, hindering movement and increasing delays.

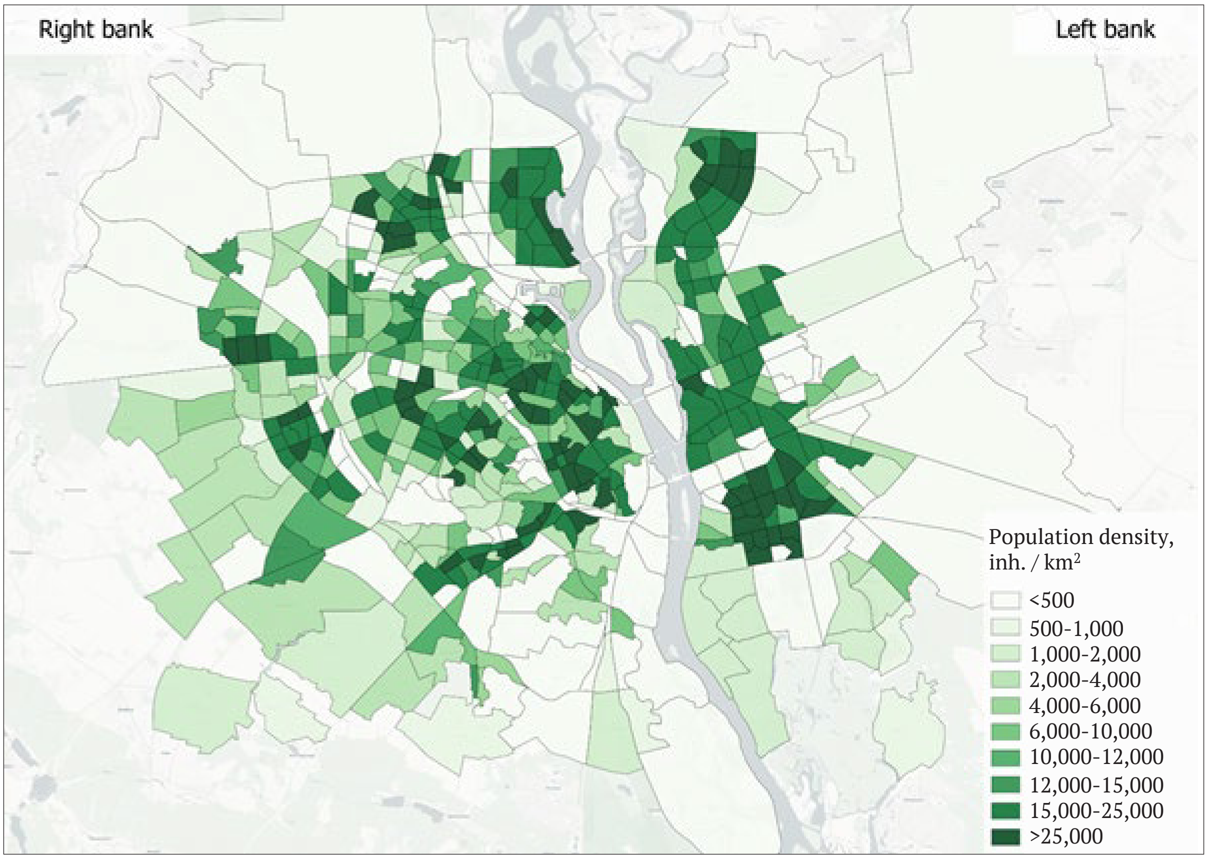

Figure 1. Distribution of population in the spatial settlement structure of Kyiv and its suburban area
Source: developed by the authors based on Sustainable urban transport for Kyiv: Towards a sustainable and competitive city built upon the legacy system and innovations (2016)

Movement between both banks of the Dnipro River in Kyiv is facilitated by both private and public transport. The capital has a fairly extensive public transport system, but its capacity and quality of service remain insufficient to fully meet the city's demand for transportation and effectively curb the growth of car ownership. In 2016, approximately 320 buses, 430 trolleybuses, and 212 trams operated on Kyiv's routes. However, according to a World Bank report (Sustainable urban transport for Kyiv..., 2016) published the same year, to optimise the transport network and adequately meet transport demand, it was necessary to invest in the purchase of at least an additional 230 buses, 420 trolleybuses, and 72 trams to supplement the existing fleet. Despite expert recommendations and the declared priority of developing public transport in Kyiv's strategic plans, the city's public transport system has not undergone significant improvements since 2016. One of the significant blows to public transport was COVID-19 (Gkiotsalitis & Cats, 2021). During the quarantine restrictions, transport operated in a reduced mode and with a limited number of passengers, leading to the loss of some users who previously preferred public transport.

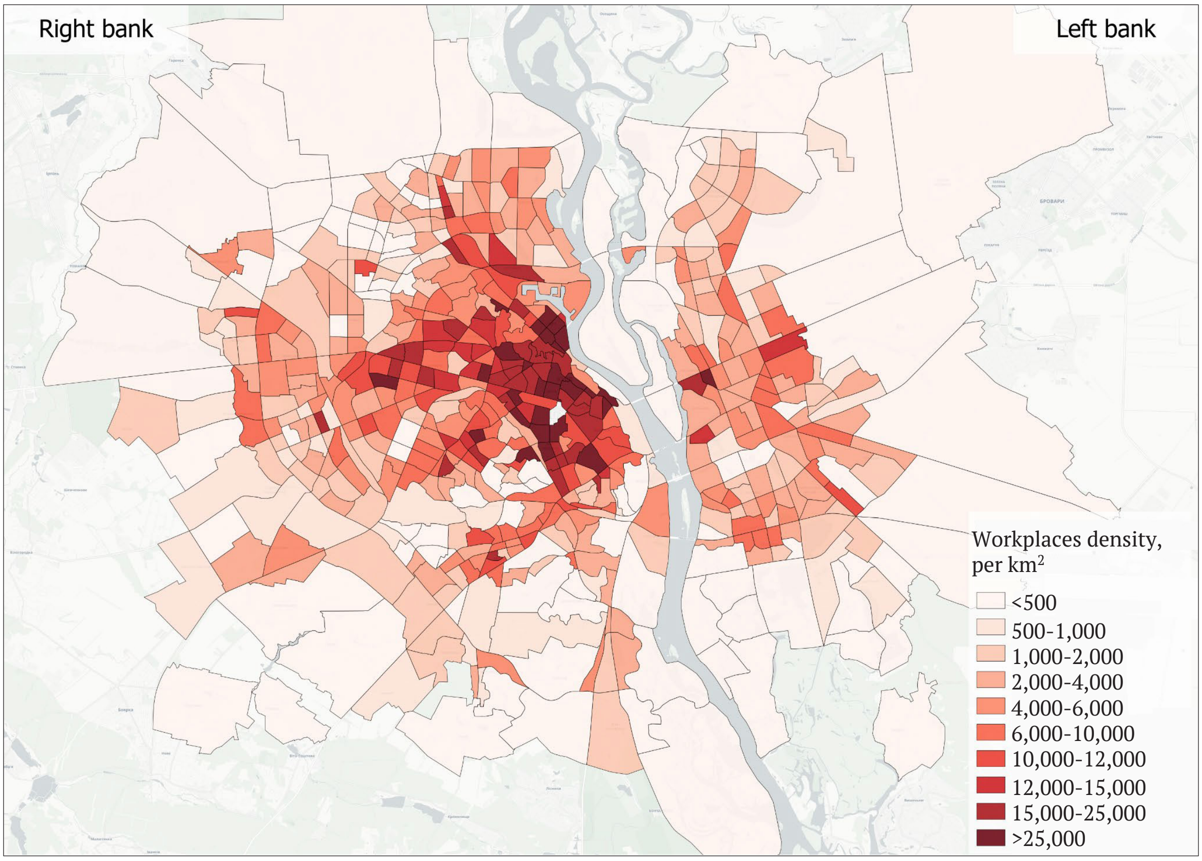

Figure 2. Distribution of workplaces in the spatial settlement structure of Kyiv and its suburban area
Source: developed by the authors based on Sustainable urban transport for Kyiv: Towards a sustainable and competitive city built upon the legacy system and innovations (2016)

Since the beginning of the full-scale Russian invasion of Ukraine in 2022, the situation for public transport has deteriorated even further. The number of vehicles on public transport routes has decreased significantly. For example, in September 2022, only 180 buses, 165 trolleybuses, and 97 trams were operating on the routes, which is 44, 62, and 54% less, respectively, than in 2016 (Ivanets, 2022). This reduction significantly decreased the reliability and accessibility of public transport for Kyiv residents, which, in turn, could be one of the reasons for the increase in car ownership and the more frequent use of private cars for urban trips. The lack of stable and high-quality public transport pushes residents to choose personal transport (Li & Xu, 2020), which puts additional pressure on the RN and worsens the overall transport situation in the capital (Kramskyi *et al.*, 2023).

In 2017, the Decision of the Kyiv City Council No. 7/4071 (2018) was developed and officially approved in 2018. This document envisages the construction of over 1,000 km of bicycle routes throughout the city. However, as of 2021, the total length of existing bike paths and lanes in Kyiv was only 202.2 km (Bicycle infrastructure in Kyiv, 2022), of which 27.8 km falls on public transport lanes where cycling is experimentally permitted. However, despite the stated length of the cycling network, its main problem remains its connectivity. As of 2024, Kyiv has only one fully-fledged cycling route "Residential Area Troieshchyna-Centre". Other sections of cycling infrastructure are mostly made up of separate and unconnected fragments (Fig. 3). Most bike lanes or paths have appeared as a result of major repairs to individual streets and do not form a single network, which significantly complicates safe and convenient cycling in the city.

Due to the lack of adequate transport supply, including the insufficient development of public transport and cycling infrastructure, as well as the uneven distribution of the population within Kyiv and its suburban area, the demand for private car trips is growing (Ceder, 2021). This leads to the overload of existing bridge crossings over the Dnipro River (Fig. 4), which creates significant problems for the RN.

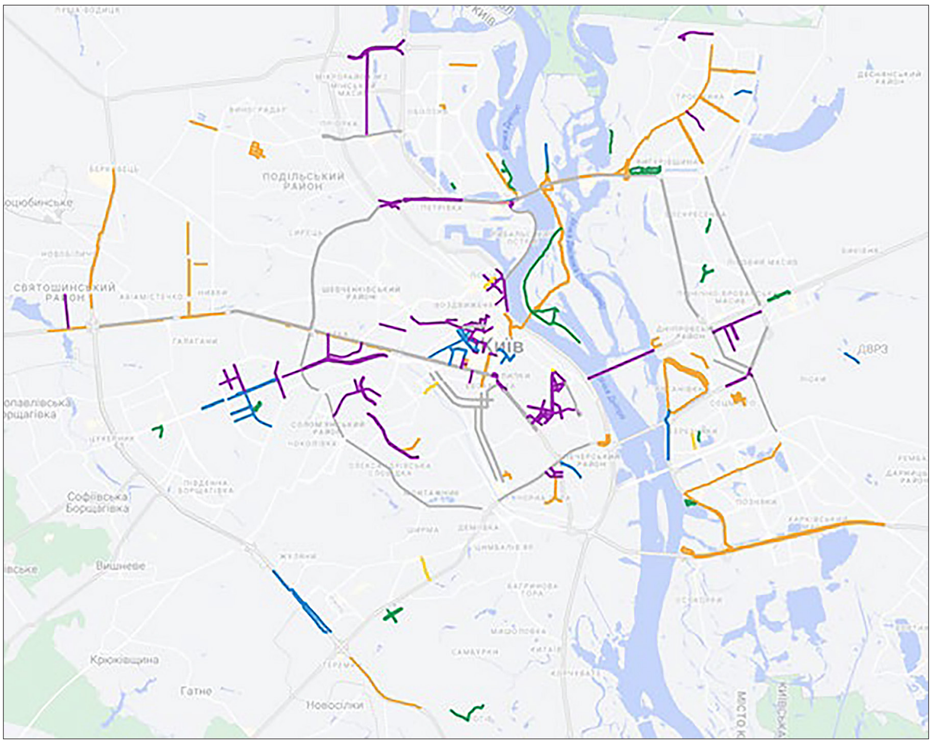

Figure 3. Map of bicycle lanes and cycle paths in Kyiv as of 2022

Source: developed by the authors

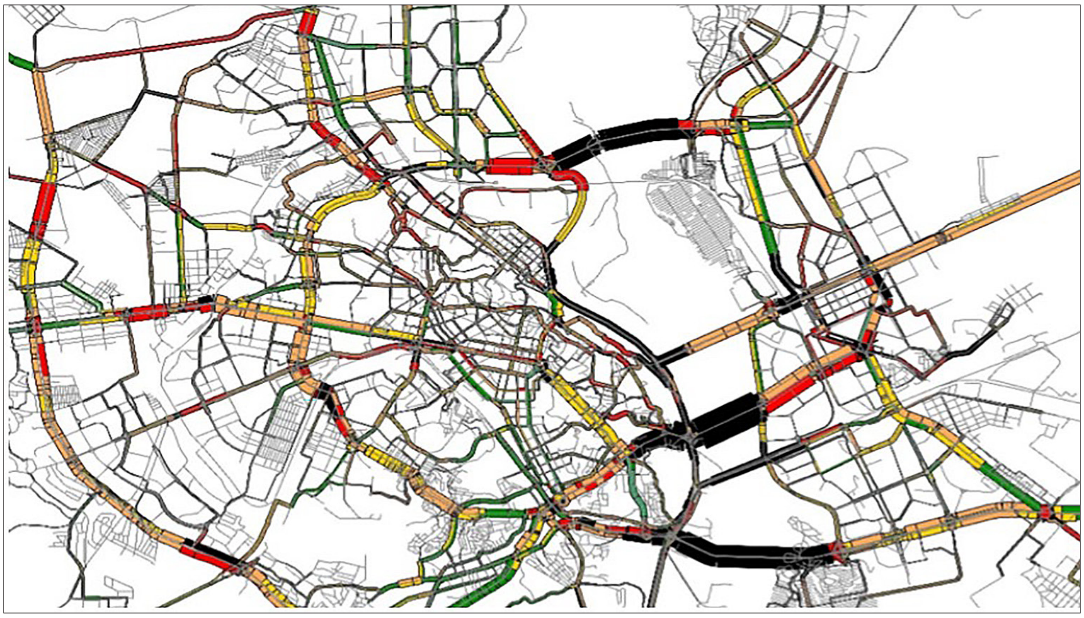

Figure 4. Map of the volume/capacity ratio on the Kyiv RN

Source: developed by the authors based on M. Osetrin *et al*. (2015)

Overloaded bridges become "bottlenecks" in the RN, affecting its overall efficiency. In case of emergencies, such as the sudden closure or repair work on any of these structures, the resilience of the RN is significantly reduced. This, in turn, jeopardises not only the safety but also the defence capability of the Ukrainian capital, as the reliable functioning of the RN is critical for ensuring the mobility of the population, logistics of goods, and prompt response to various challenges.

Of the five operational road bridges across the Dnipro River in Kyiv, two bridges – the Metro Bridge and the Paton Bridge – are in a non-operational state (Ministry of Infrastructure…, 2023). This creates an additional load on the other bridges and significantly affects the overall capacity of the RN. In such a situation, when assessing the effectiveness of design solutions, special attention should be paid to bridge crossings as critical elements for the resilience of the RN. The efficiency of these bridges largely depends on the quality of the functioning of pre-bridge intersections on the RN. They are key points that play a decisive role in the distribution of traffic flows (Osetrin & Tarasiuk, 2014), and their operation is determined by factors such as transport demand, location, and purpose of the intersection (Bekenovet *al.*, 2020). One of the important objects of Kyiv's RN is the Darnytskyi Road and Railroad Bridge, along with its approaches. This bridge performs a crucial transport function as it connects the left and right banks of the capital, providing for the movement of both road and rail transport. The road part of the Darnytskyi Bridge has 3 lanes in each direction, as shown in Figure 5.

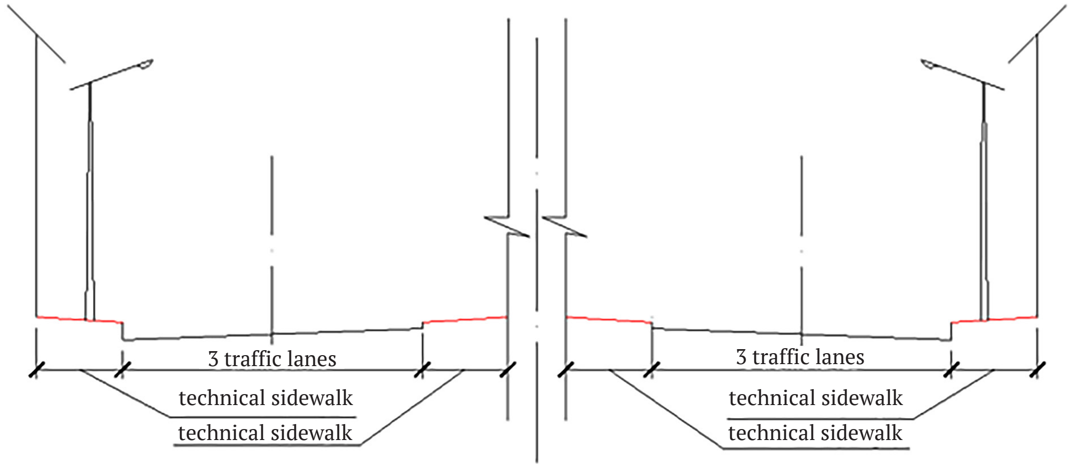

Figure 5. The cross-section of the road section of the Darnytskyi Road and Railroad Bridge in Kyiv
Source: developed by the authors

On the right bank of the Dnipro River, to effectively connect the Darnytskyi Road and Railroad Bridge to the RN, an interchange with flyover was built, which provides access to the Naddniprianske Highway. This interchange is an important part of the RN, which allows for reducing delays as a result of the assignment of traffic flows. On the left bank, the main approach to the Darnytskyi Bridge is Petro Radzinia Street, which connects to the intersection of Pryvokzalna Street and Kharkivske Shose, providing the main transport link for cars moving towards or from the bridge. In addition, to integrate the Darnytskyi Bridge into the existing RN, part of Sortuvalna and Yuriy Shumskyi Streets were additionally built, improving access to the bridge and the capacity of its approaches. In Figure 6, these new sections created for better connection of the Darnytskyi Bridge with the RN are marked in blue. In red, in turn, are the key exits of the Darnytskyi Bridge, which play an important role in ensuring the movement of cars between different parts of the bridge.

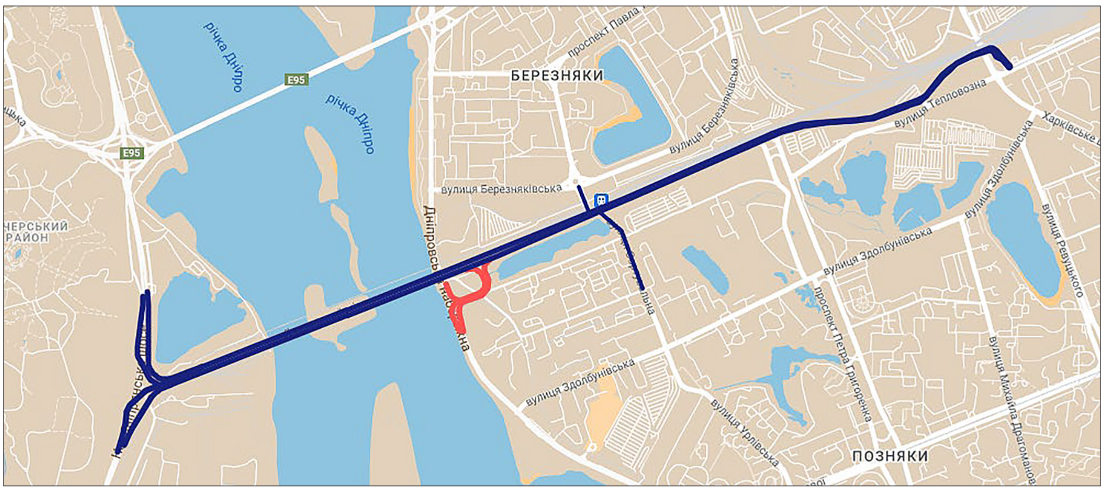

Figure 6. Darnytskyi Bridge with right-bank and left-bank approach routes
Source: developed by the authors

The foundational urban planning document in Ukraine is the General Plan of a city, which defines the strategy for the development of a settlement, including its transport infrastructure, development planning, and socio-economic development. This document is a crucial tool for regulating the development and the evolution of urban space and also determines the main directions of spatial planning for the city over a long period. For Kyiv, a General Plan (2020) was approved which was valid until 2020. However, as of 2024, this document has already lost its relevance and does not take into account modern challenges, such as population growth, increased levels of car ownership, and the need for modernisation of transport infrastructure (Buil *et al.*, 2016). In this regard, there has been a need to develop a new General Plan that could reflect the current realities and formulate the prospects for the city's development in the future. As of 2024, attempts are underway to create a new General Plan for the city of Kyiv, which will cover the period up to 2040. However, the process of developing this document faces several difficulties, and therefore it has not yet been approved. The absence of an up-to-date General Plan significantly complicates the planning and development of urban infrastructure, including the RN, as there are no clear guidelines for making design solutions regarding the future development of the capital (Nenastina *et al.*, 2024).

In the section concerning the RN, the draft of the new General Plan for Kyiv continues to follow the principles laid down in previous versions. The main concept is focused on the extensive development of transport infrastructure, which involves large-scale investments in the expansion of the RN. In particular, the project envisages the construction of multi-level intersections, which, according to the developers, should contribute to the optimisation of traffic flows and reduce delays at key intersections on the city's RN. In addition, significant attention is paid to transforming many existing streets into continuous-flow highways, which is expected to increase the speed of movement around the city. This decision is aimed at improving connectivity between city districts and ensuring greater capacity for vehicles. One of the most ambitious elements of the project is the planned construction of three new bridges across the Dnipro River, aimed at significantly easing traffic between the right-bank and left-bank districts of the capital. These new bridges should become important transport arteries, capable of reducing the overload of existing bridges and providing additional routes for motorists (Fig. 7).

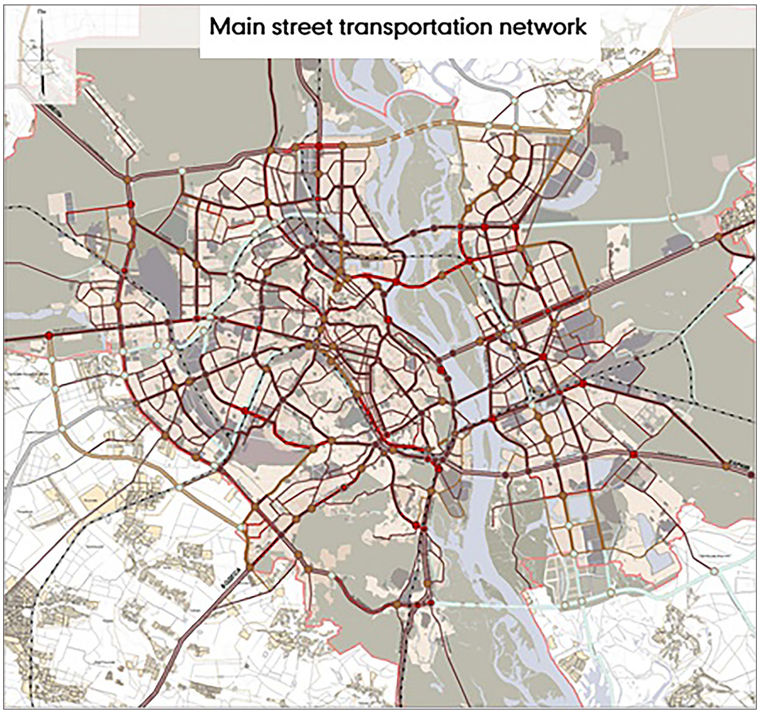

Figure 7. Development of the urban RN as outlined in the draft of Kyiv's new General Plan
Source: developed by the authors based on the Kyiv General Plan (2020)

It should be noted that the implementation of all the measures envisaged in the draft of the new General Plan for the city of Kyiv and its suburban area is unlikely. A significant number of the declared projects require large investments and long implementation periods, which calls into question their full implementation. Given these limitations, within the framework of this study, it was decided to consider a more realistic scenario for the development of the RN. For this purpose, as noted before, a two-stage expert survey in the field of urban planning was conducted, which made it possible to assess potential development paths, taking into account the expert assessment of current resources and capabilities. The results of this assessment of the probability of implementing urban planning projects are partially presented in Table 1.

Table 1. Partial results of expert assessment on the feasibility of urban development projects for Kyiv

Category	Project	Experts share	Average score
Bridges	Off-ramps from Darnytskyi Bridge	1	5.9
	Reconstruction or restoration of the Metro Bridge	1	4.6
	Restoration of the Paton Bridge	0.8	4.5
	Completion of the Podilskyi Bridge	0.7	4.4
Highways/streets	Finish building of Medova Street (near Zhulyany Airport)	0.8	5.3
	Dovbusha Street extension from DVRZ to Brovarskiy Avenue	0.5	3.8
Pedestrian	Pedestrianisation of Kontraktova Square	0.8	5.3
	Pedestrian bridge at Obolon	0.5	4.6
	Bessarabska passage	0.5	4.2
	Reorganisation of Lvivska Square	0.5	3.8
	Replacement of 30 underground crossings with surface-level crossings	0.5	3.7
Public transport	Extension of the metro line to Vynohradar	0.8	5.3
	Urban electric railway line Vyshhorod-Obolon-Pochaina	0.8	4.1
	The new urban railway station at Obolon	0.7	4
	The new urban railway station at Lybidska	0.5	3.8
	Extension of the Borshchahivka rapid tram line to Vokzalna station (via Petliura Street)	0.5	3.8
	Opening of the Lvivska Brama metro station	0.5	3.7
	Development of a rapid transit line from Troieshchyna to the city centre	0.5	3.5
Intersections	Bohatyrska/Poliarna intersection	0.7	4.4
	The intersection at Vernadskyi/Palladina (near Akademmistechko)	0.7	3.7
Squares	Reconstruction of Halytska Square (Peremohy Square)	0.7	4.2

Source: developed by the authors

To include in the digital twin of Kyiv's mobility (projected state), those projects that received the support of most experts were selected. Of all the proposed projects, only two – the construction of off-ramps for the Darnytskyi Bridge and the reconstruction of the Metro Bridge – received the consolidated support of all survey participants. All experts without exception expressed confidence that these projects would be implemented within the specified timeframe. The location of all objects supported by experts, including these two critical projects, is shown in Figure 8.

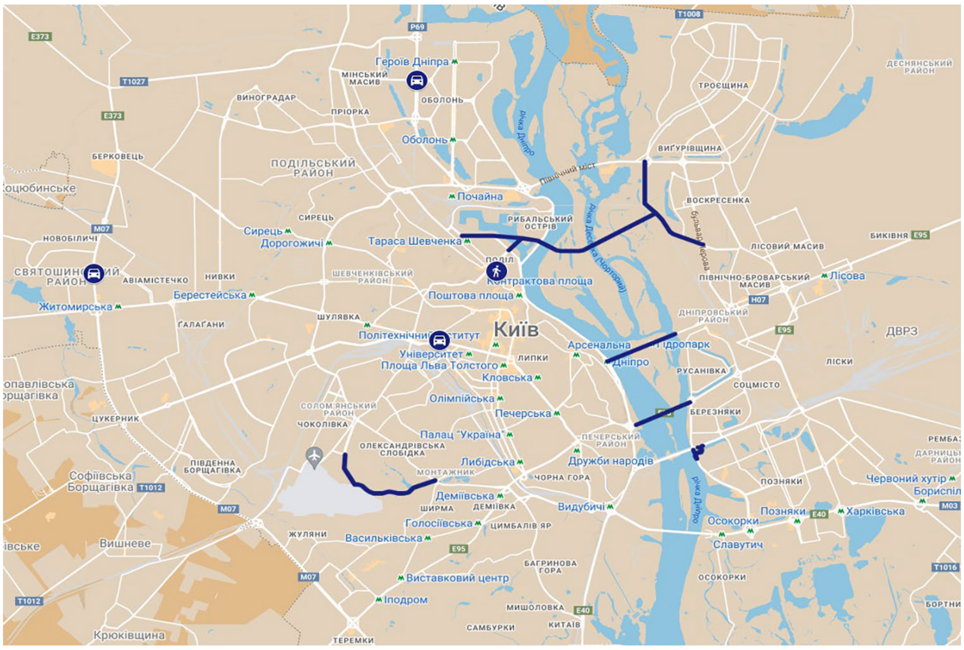

Figure 8. Projects with a high probability of implementation by 2030 according to the assessment of surveyed experts
Source: developed by the authors

During the calculation of forecast scenarios in the digital twin of Kyiv's mobility, an assignment of the expected transport demand, which was forecast for 2030, was carried out. It is important to note that this transport demand remained constant for all considered scenarios, which allowed for the comparability of results and the assessment of the impact of various infrastructure projects under the same conditions. In addition, to create a baseline version of the digital twin of Kyiv's mobility and to calculate the transport effect of each of the forecast scenarios, several assumptions were used, a list of which is presented in more detail in Table 2.

Table 1. Assumptions for the creation of the baseline version of Kyiv's digital mobility twin

Assumption	Value
The base year for mobility data within the analysis area	2019
Projected population in the analysis area for 2030	4,478,738
The projected level of motorisation in the analysis area for 2030	556 vehicles per 1,000 people
The average occupancy of a private car	1.7
Analysis period	Average annual daily period
Cost of 1 hour in 2022, UAH	127.1
Average CO_2 emissions from a private car, g/km	130

Source: developed by the authors based on Main Department of Statistics of Kyiv (2024), European Environmental Agency (2024)

Within this study, 14 forecast scenarios were formed for transport modelling. These scenarios were created by comparing 7 basic development options for the RN in 2030 in two versions: the first – without off-rams from the Darnytskyi Bridge to the Dnipro embankment, and the second – with their commissioning. Scenario 1 is the baseline and includes all projects selected based on the results of the expert survey, as well as forecast data on the socio-economic development of Kyiv in 2030. This scenario serves as a basis for comparison with other options. Scenario 2 is based on the data of Scenario 1 but additionally assumes the commissioning of new exits from the Darnytskyi Bridge to the Dnipro embankment, which could potentially significantly change the transport demand in this part of the RN. Scenarios 1 and 2 are demonstrated in more detail in Figure 9.

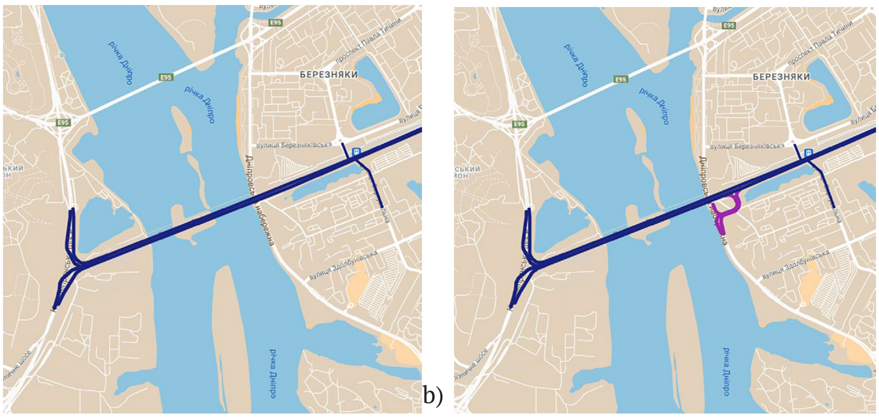
a) b)

Figure 9. Baseline forecast of transport modelling for the study

Notes: a) – Scenario 1; b) – Scenario 2

Source: developed by the authors

Comparing forecast Scenarios 1 and 2 enables an assessment of the impact of introducing exits for the Darnytskyi Bridge on the overall efficiency of the RN. This comparison provides a clear indication of how new crossings in the RN could enhance the throughput of the RN, reduce delays, and optimise the distribution of traffic flows, which is critical for the city's future development (Medina-Salgado *et al.*, 2022). The following forecast scenarios allow for a detailed evaluation of the impact of introducing exits for the Darnytskyi Bridge, assuming the construction of a new tunnel on the right bank of the Dnipro River. This helps identify how the integration of new elements into the RN may influence traffic distribution and the overall effectiveness of the RN.

Forecast Scenario 3 is based on the data of forecast Scenario 1 but includes additional changes. Specifically, this scenario assumes the commissioning of a tunnel through Busova hora, which will exit onto the intersection of M. Boichuka and Zaliznychne Shoes streets. In addition, within the framework of this scenario, it is also planned to reorganise traffic on Saperno-Slobidska and Zhylianska streets, which will allow to reduce delays and improve the connection between the main highways. Forecast Scenario 4 expands the previous one, providing for the simultaneous commissioning of both the tunnel on the right bank and the exits for the Darnytskyi Bridge on the left bank. This allows for an analysis of the combined transport effect of both elements of the RN, which can increase the throughput of the RN, reduce delays, and optimise the distribution of traffic flows in the city. More details of forecasted Scenarios 3 and 4 are shown in Figure 10.

The following forecast scenarios, presented in Figure 11, are based on the data of forecast Scenario 1 and involve the sequential closure of bridges across the Dnipro River, both without and with the opening of the Darnytskyi Bridge exits, respectively.

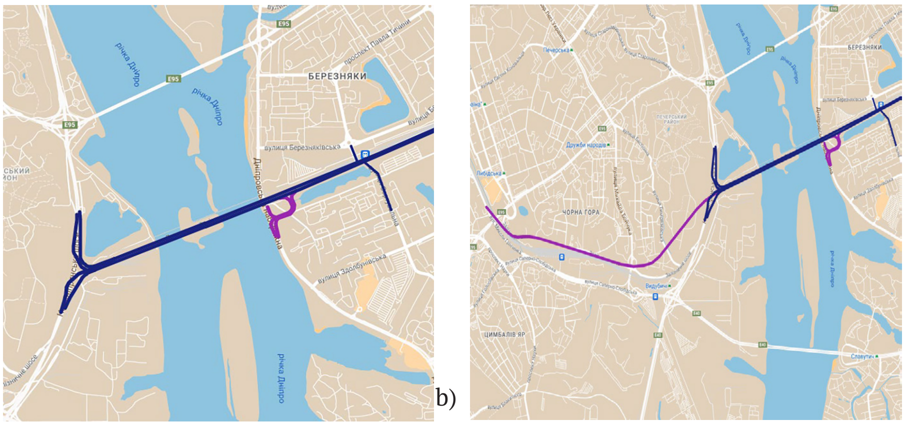

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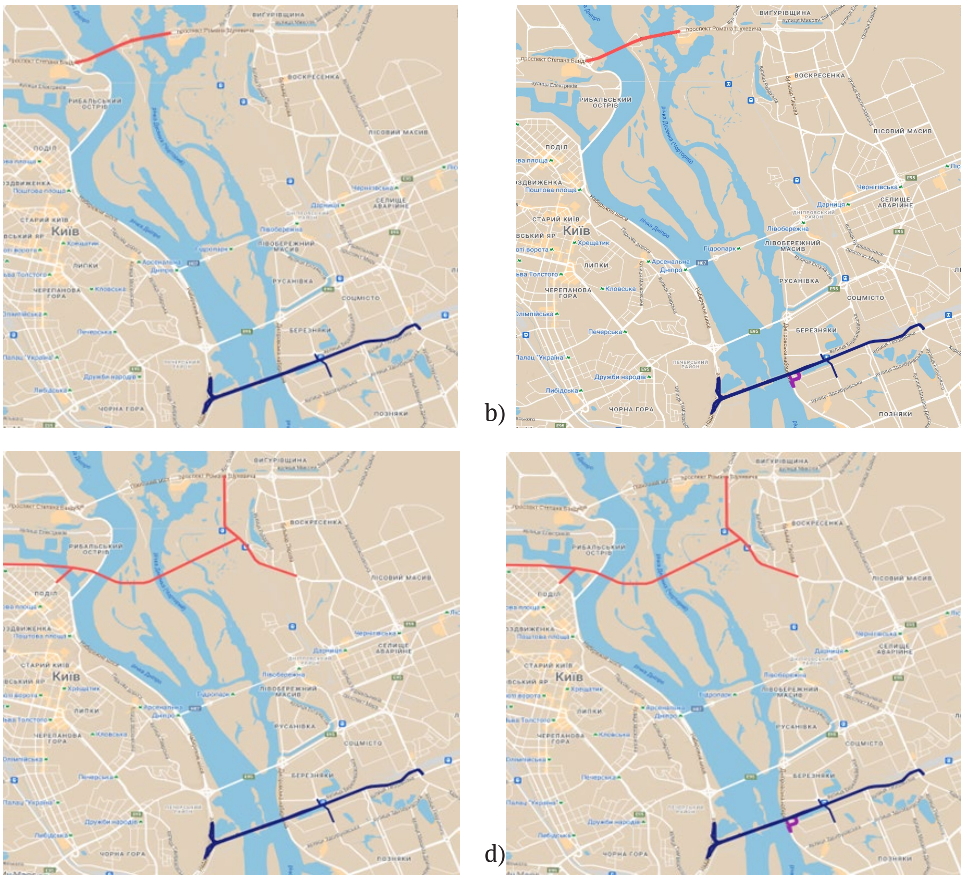
Figure 10. Forecasted transport modelling for the study

Notes: a) – Scenario 1; b) – Scenario 2

Source: developed by the authors



a) b) c) d)

Figure 11 . Forecast Scenarios 5-14 of transport modelling for the study

Notes: a), b) – forecast Scenarios 5 and 10 (closure of the Pivnichnyi Bridge); c), d) – forecast Scenarios 6 and 11 (closure of the Podilskyi Bridge)

Source: developed by the authors

Figure 11. Continued

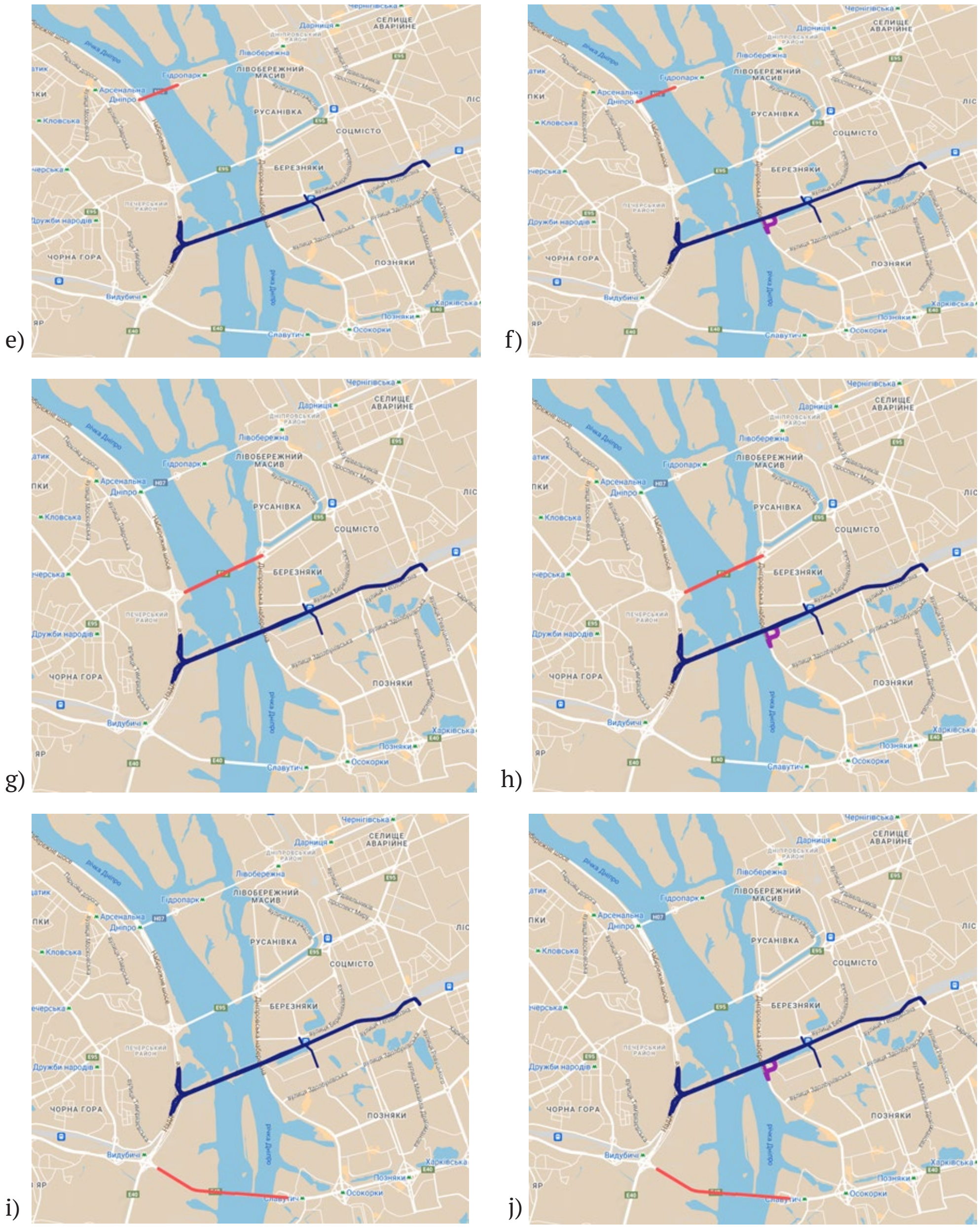


Figure 11 . Forecast Scenarios 5-14 of transport modelling for the study
Notes: e), f) – forecast Scenarios 7 and 12 (closure of the Metro Bridge); g), h) – forecast Scenarios 8 and 13 (closure of the Paton Bridge); i), j) – forecast Scenarios 9 and 14 (closure of the Pivdennyi Bridge)
Source: developed by the authors

Forecast Scenarios 5-14 aim to provide a detailed assessment of the impact of introducing off-ramps for the Darnytskyi Bridge on the resilience of the RN. These forecast scenarios consider various options for the implementation and modernisation of intersections on the RN, allowing for an analysis of how additional exits for the Darnytskyi Bridge can affect the overall stability and reliability of the RN in the event of potential emergencies or repair work. The results of the calculations carried out in the digital twin of Kyiv's mobility and its suburbs are presented in the form of cartograms illustrating the volume of private transport and the load on the RN. These maps clearly visualise the level of traffic loads as a result of assignment for different forecast scenarios. An example of visualisation for the baseline scenario is shown in Figures 12 and 13. The performance indicators for the RN across all forecasted scenarios are presented in Table 3.

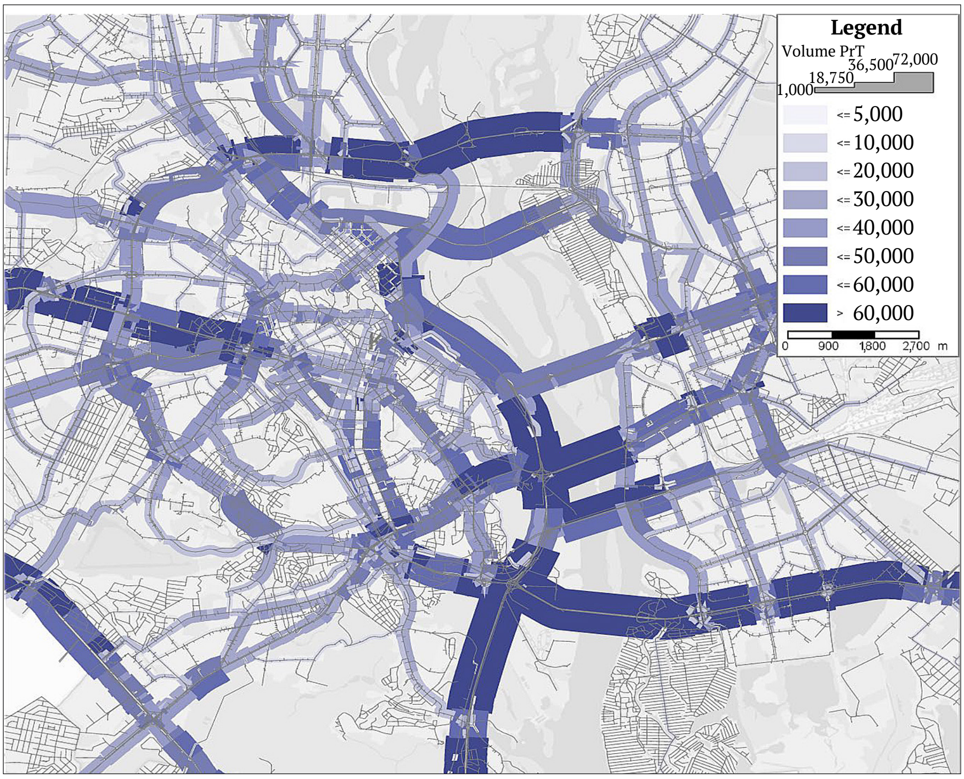


Figure 12. Traffic volume map for the RN of Kyiv city for the base scenario
Source: developed by the authors

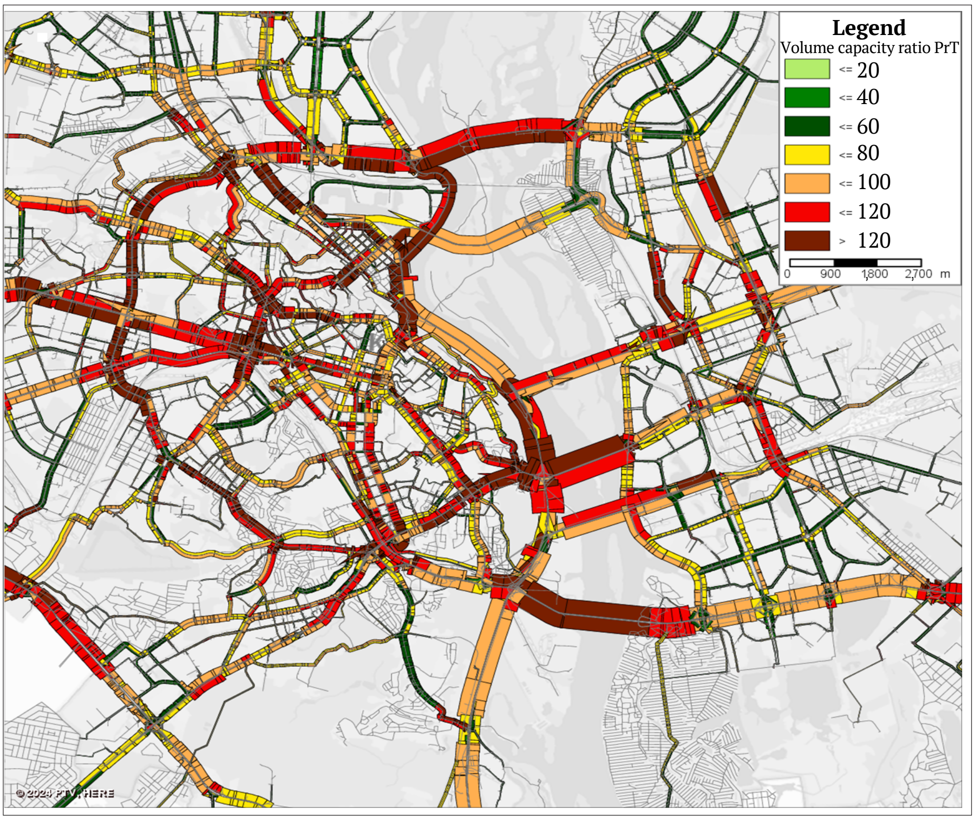


Figure 13. Map of the volume/capacity ratio for the RN of Kyiv city for the base scenario
Source: developed by the authors

Table 3. Performance indicators for the RN of Kyiv city for forecasted scenarios

Compared scenarios		Change in daily mileage of private transport, km	Change in travel time for correspondences, hours	Change in average trip duration, sec	Change in annual transport loss, UAH	Change in CO_2 emissions, kg
1	2	-9,461	-5,642	-7.90	261,741,000	1,514
3	4	-9,924	-7,791	-10.91	361,436,000	1,590
5	10	-5,136	-5,380	-7.53	249,586,270	822
6	11	-8,878	-4,693	-6.57	217,715,310	1,421
7	12	-10,802	-6,775	-9.48	314,302,410	1,730
8	13	-47,979	-25,307	-35.43	1,174,029,690	7,680
9	14	-24,229	-11,130	-15.58	516,337,400	3,880

Source: developed by the authors

The assessment of changes in CO_2 emissions into the city's atmosphere is based on the product of the projected changes in the daily mileage of private transport, which are predicted within the framework of the calculated scenarios, and the average amount of CO_2 emissions from one vehicle per kilometre of its mileage (Liu *et al.*, 2023; Yang *et al.*, 2023). For an accurate calculation of annual transport losses, changes in the time of correspondence realisation and the value of time, determined by the average wage within the study area, are taken into account. For example, in 2022, the average salary in Kyiv was 127.1 UAH/hour (Minfin, 2022). In addition, it is assumed that on average a passenger car in Ukraine emits about 160 grams of CO_2 per kilometre of mileage (Buberger *et al.*, 2022).

The opening of the off-ramps from the Darnytskyi Bridge to the Dnipro embankment (without considering other changes in the RN) does not directly affect the capacity of the bridge itself. However, it significantly changes the capacity of the approaches to the bridge on the left bank. Changes in transport demand that arise as a result of these changes for all forecast scenarios were compared to the baseline forecast scenario and are presented in Table 4.

Table 4. Changes in traffic intensity in Kyiv compared to the baseline forecast scenario

Compared scenarios		Scenario name	Change in Darnytskyi Bridge load, %	Load of Darnytskyi Bridge off-ramps, %			
			On the left bank	The off-ramp from the bridge	To Berezniaky	To Osokorky	On-ramps to the bridge
1	2	Baseline + offramps	1.8%	42.5%	28.8%	51.9%	9.5%
3	4	Tunnel + offramps	3.3%	57.8%	56.8%	53%	6.6%
		Bridge closures					
5	10	Pivnichnyi	1.4%	51%	39.1%	57.8%	7.4%
6	11	Podilskyi	1.5%	49.6%	37.5%	56.7%	7.5%
7	12	Metro	2.5%	54.9%	46.5%	57.7%	6.3%
8	13	Paton	7.7%	96.7%	128%	55.8%	2.9%
9	14	Pivdennyi	7%	65.9%	13.3%	112%	12.2%

Source: developed by the authors

Thus, in the baseline forecast scenario with the addition of off-ramps, the load on the Darnytskyi Bridge increases by 1.8%, indicating a slight increase in transport demand. However, the off-ramps demonstrate significant variation in load. Specifically, the off-ramps from the bridge to Berezniaky and Osokorky have loads of 42.5 and 28.8% respectively, while the on-ramp to the bridge has a load of 9.5%. In the forecast scenario with the tunnel and offramps, the load on the Darnytskyi Bridge increases by 3.3%, and the load on the off-ramps also increases. Specifically, the off-ramps to Berezniaky and Osokorky have loads of 56.8 and 53% respectively, while the on-ramp to the bridge decreases to 6.6%. When considering forecast scenarios with the closure of other bridges, the results show more variations in the impact on the load of the Darnytskyi Bridge. The closure of the Pivnichnyi Bridge leads to an increase in the load on the Darnytskyi Bridge by 1.4%, while the closure of the Podilskyi and Metro bridges causes an increase of 1.5 and 2.5% respectively. The most significant impact on the load of the Darnytskyi Bridge is observed in the scenario with the closure of the Paton Bridge (7.7%) and the Pivdennyi Bridge (7%).

The load on the off-ramps in the case of the closure of the Paton Bridge and the Pivdennyi Bridge reaches critical levels, in particular, the off-ramps from the Darnytskyi Bridge to Berezniaky and Osokorky have loads of 128 and 112% respectively. This indicates a potential overload of infrastructure in such scenarios, which requires additional measures to improve capacity. Thus, the obtained results provide valuable information for further planning and optimisation of the RN, including the possibility of adapting infrastructure to ensure effective operation under conditions of traffic assignment.

DISCUSSION

Within this study, the use of transport modelling in a digital twin allowed for a detailed assessment of the impact of design solutions on Kyiv's RN. Thanks to the capabilities of transport modelling, it was possible to forecast changes in demand and assignment on the RN and predict their transport effects, impact on the RN's capacity, and environmental aspects. Transport modelling allowed for the evaluation of the transport effect of implementing design solutions, such as the construction of off-ramps for the Darnytskyi Bridge, as well as analysing potential forecast scenarios for the assignment of traffic flows. Moreover, this research helped identify critical points that require additional intervention or correction of design solutions. The use of a digital twin made it possible to evaluate various options for the development and reconstruction of intersections on the RN, providing a scientific basis for making management decisions and increasing the efficiency of transport infrastructure under conditions of uncertainty (Matsiuk *et al.*, 2023). In the study by J. Li *et al.* (2021), transport modelling was also used to evaluate the effectiveness of urban transport system planning, allowing for the consideration of numerous RN development scenarios. The study of D. Alobaydi *et al.* (2020) focused on researching the impact of increasing the capacity of intersections on the RN and changes in traffic flows on the RN's capacity using transport modelling methods, which allowed for achieving a transport effect. In the study by R. Lovelace *et al.* (2020), in turn, attention was paid to analysing the transport effect of introducing new intersections on the RN using transport modelling, focusing on improving mobility and reducing travel time for the population. Thus, this study, compared to the mentioned research, covers a more comprehensive approach, combining transport demand modelling with the analysis of the transport effect, making it more scalable and suitable for broader practical application.

A crucial part of the research was the formation of 14 forecast scenarios, allowing for a detailed study of potential changes in the distribution of traffic flows and the identification of the transport effects of design solutions, particularly the off-ramps for the Darnytskyi Bridge to the Dnipro embankment in Kyiv. The research results showed that the implementation of the off-ramps for the Darnytskyi Bridge would significantly impact the distribution of traffic flows and reduce delays on the RN. A comparison of the forecast Scenario 1 (baseline) with the forecast Scenario 2, which envisages the implementation of the specified design solutions, showed that the new off-ramps could significantly impact delays on the RN and improve its capacity. The introduction of a tunnel through Busova hora and the reorganisation of traffic on major streets within the framework of forecast Scenario 3 may also have a positive impact on reducing delays and improving connections between major highways. Forecast Scenario 4, which combines both of these elements, may have even greater benefits, providing a comprehensive approach to the development of the RN. Forecast Scenarios 5-14 enabled an assessment of how different implementation options for new intersections on RN can affect the resilience and stability of the RN. In the research of Z. Liu *et al.* (2022), a similar approach to analysis was used, including the creation of various scenarios to assess the dynamic stability of a multimodal public transport network for sustainable transport development. In the study of P.-C. Xu *et al.* (2024), a similar methodology was applied to assess social aspects, creating scenarios to analyse the impact of new transport solutions on public transport accessibility. In the article of W. Yue *et al.* (2021), transport modelling was used to study traffic efficiency, developing scenarios to assess the impact of new infrastructure solutions on highway congestion levels. However, this research, in comparison to the mentioned studies, is unique in that it is focused on the specific conditions of the city of Kyiv and includes a comprehensive approach to transport modelling of traffic flows, allowing for obtaining more detailed and specific information about the impact of specific design solutions on the capital's RN.

The results of the analysis of various forecast scenarios, presented in this study, have provided an opportunity to comprehensively assess the impact of different RN development options on key performance indicators. Forecast scenarios that included new off-ramps for the Darnytskyi Bridge, as well as other infrastructure changes, showed a significant reduction in daily vehicle kilometres travelled, indicating a decrease in delays and improved conditions for drivers. In particular, forecast Scenario 13, which envisaged the greatest number of changes, demonstrated the most significant results in all key indicators: daily vehicle kilometres travelled decreased by 47,979 km, correspondence completion time decreased by 25,307 hours, and the average trip duration decreased by 35.43 seconds. This was accompanied by a significant reduction in annual transport losses and CO_2 emissions, confirming the high efficiency of the design solutions of this forecast scenario. Forecast Scenarios 2 and 4 also showed a significant transport effect, reducing daily vehicle kilometres travelled by 9,461 and 9,924 km, respectively, as well as reducing correspondence completion time and trip duration. Although forecast Scenario 4 showed the most significant positive effect in all aspects, forecast Scenario 2 also demonstrated a significant reduction in annual transport losses and CO_2 emissions. Other forecast scenarios, such as 10, 11, 12, and 14, also showed positive results, albeit less significant compared to the most comprehensive scenarios. While they still provided reductions in transport costs and improvements in environmental indicators, the differences compared to the most effective scenarios were smaller. In the study of X. Xiao & H. Duan (2020), a comprehensive approach to transport modelling of traffic flows was also used, including an assessment of the effectiveness of implementing new intersections on the RN and changes in urban infrastructure. In the article of L.M. Hilty & R. Meyer (1996), in turn, the impact of different transport infrastructure development scenarios on environmental indicators, in particular, pollutant emissions, was studied. However, compared to the mentioned studies, this research is distinguished by the fact that it includes a detailed assessment of the impact not only of infrastructure changes but also of scenarios that take into account the real socio-economic conditions of the city, as well as their long-term consequences for the RN.

Additionally, this study provided detailed results on the impact of various forecast scenarios on the traffic load of the Darnytskyi Bridge and its off-ramps. Forecast Scenario 2 showed a moderate impact on the traffic load of the Darnytskyi Bridge and its off-ramps. The introduction of new off-ramps led to a significant increase in the load on offramps to the left bank (42.5%) and to Berezniaky (28.8%), as well as a significant increase in the capacity of the bridge entrance (up to 9.5%). This forecast scenario provided a reduction in the load on the main traffic flows but did not significantly change the overall traffic load picture. Forecast Scenario 4 demonstrated greater changes in the traffic load of the RN. The introduction of the tunnel along with the off-ramps led to a significant increase in the load on the off-ramps, in particular in the directions to Berezniaky (56.8%) and Osokorky (53%). Forecast Scenarios 5-12 with bridge closures showed varying levels of impact on the traffic load of the Darnytskyi Bridge. For example, forecast Scenario 10 (Pivnichnyi Bridge closed) and forecast Scenario 11 (Podilskyi Bridge closed) demonstrated a moderate increase in the load on the off-ramps up to 7.4 and 7.5%, respectively, while forecast Scenario 12 (Metro Bridge closed) showed a high load on the new off-ramps up to 54.9%. Forecast Scenarios 13 (Paton Bridge closed) and 14 (Pivdennyi Bridge closed) showed a significant increase in traffic load, especially on the off-ramps, up to 128 and 65.9%, respectively. Overall, the analysis showed that forecast scenarios with bridge closures can create additional load on other sections of the RN, while forecast scenarios with new off-ramps and tunnels can more effectively distribute traffic flows and reduce the load on some intersections of the RN. In the study by P. Bindzar *et al*. (2021), a transport modelling method was also used to assess the impact of new intersections on the load on highways. The research of M.Z. Serdar *et al*. (2022) aimed to assess the impact of various infrastructure reconstruction scenarios on the overall capacity of the RN. In the article by R. Suryadithia *et al*. (2021), in turn, the possibility of integrating new transport technologies that improve the efficiency of the transport system was considered. However, the results of this study, compared to the results of the mentioned works, differ in that it offers more accurate and specific data on the impact of the proposed design solutions on traffic flows and socio-economic aspects in the conditions of the Darnytskyi Bridge in Kyiv, which allows for a clearer understanding of the potential benefits and risks of implementing the design solutions.

Such studies are crucial for the effective planning and development of the RN. They allow for a detailed assessment of the impact of various design solutions on traffic flows, socio-economic indicators, and environmental aspects. The creation of digital twins and the use of transport modelling methods enables accurate forecasting of the consequences of introducing new elements to the RN, helps to optimise costs and improves the efficiency of the transport system. The results of such studies also assist in the formation of strategies for sustainable development, which is critical for ensuring a high quality of life in megacities.

CONCLUSIONS

Through the use of transport modelling, this study conducted a detailed analysis of the impact of design solutions on the functioning of Kyiv's RN. This allowed for the consideration of several factors, such as the intensity and composition of traffic flow, design solutions, and traffic organisation. Based on the obtained data, quantitative and qualitative indicators of the RN's performance were formed, including the intensity of movement of various participants, time costs, distance travelled, and environmental indicators.

The evaluation of design solutions, particularly the off-ramps for the Darnytskyi Bridge, showed that the implementation of these design solutions will lead to an increase in traffic demand on the bridge towards the left bank by 1.8%. This is also accompanied by a reduction in transport losses, which will amount to 261.7 million UAH per year, and a decrease in CO_2 emissions by 1,500 kg per day. These results confirm that the implementation of design solutions with off-ramps can positively impact the transport situation in the city, specifically by reducing costs and improving environmental indicators, thus creating a positive transport effect. The study also established that the additional commissioning of a tunnel on the right bank to the Darnytskyi Bridge, along with the completion of off-ramps from the Dnipro embankment, has an even greater impact on the performance indicators of the RN. In this scenario, the demand for the bridge towards the left bank increases by 3.3%, indicating a higher efficiency of the implemented solutions. The annual savings in transport costs in this case will amount to over 361.4 million UAH, and the reduction in CO_2 emissions will reach 1,590 kg per day. This demonstrates a better transport effect for the RN.

Overall, the conducted research confirms that the implementation of the proposed design solutions can significantly improve the efficiency of Kyiv's RN, particularly in terms of reducing transport losses and environmental impacts, which underscores the importance of planning and implementing design solutions considering all possible impacts on the city. It is important to note that the approach applied to the evaluation of design solutions for urban RNs is focused on indicators obtained from a digital twin exclusively within the framework of transport modelling, which may affect the accuracy and detail of the assessment. For further research in this direction, it should be considered to integrate detailed transport modelling, which allows for a more detailed study of the impact of design solutions at the level of individual elements of the RN, which will enable a more accurate assessment of the transport effect.

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CONFLICT OF INTEREST

None.

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Аналіз техніко-економічної ефективності добудови з’їздів/заїздів з Дніпровської набережної на Дарницький міст у м. Києві

Анотація. Дане дослідження було спрямоване на оцінку ефективності проєктних рішень для розвитку транспортної інфраструктури Києва на основі транспортного моделювання та аналізу можливих соціально-економічних ефектів. Для цього було використано чотирикроковий алгоритм моделювання транспортного попиту, що базується на даних соціологічних опитувань, планів територій та прогнозних показниках на 2030 рік. Результати проведеного дослідження показали суттєві зміни у функціонуванні транспортної мережі Києва в результаті впровадження запропонованих проєктних рішень. Завдяки застосуванню транспортного моделювання вдалося оцінити кількісні показники, такі як інтенсивність транспортних потоків на основних магістралях, а також якісні зміни, такі як зменшення заторів, скорочення часу поїздок та економію витрат. Одним із ключових результатів стало те, що відкриття нових з’їздів та в’їздів на Дарницький міст на лівому березі сприяє незначному зростанню пропускної здатності мосту, однак найбільший ефект був помітний на під’їздах до нього. Завдяки додатковим підходам зросла інтенсивність руху, що свідчить про поліпшення транспортної доступності для водіїв, які користуються цим транспортним вузлом. Також важливими були результати, пов’язані з екологічними показниками. Внаслідок зменшення заторів було досягнуто зниження викидів CO_2 у повітря, що є значним внеском у поліпшення екологічної ситуації в місті. Щодо економічної ефективності, результати продемонстрували значну економію транспортних втрат, підтверджуючи, що впровадження запропонованих заходів має позитивний вплив на транспортну інфраструктуру, а також зменшуючи фінансові втрати, пов’язані з поїздками. Таким чином, результати дослідження підтвердили, що запропоновані проєктні рішення мають позитивний вплив на розвиток транспортної мережі, підвищуючи пропускну здатність та зменшуючи негативний вплив на довкілля, що відкриває можливості для створення більш ефективної транспортної системи, яка відповідає вимогам сталого розвитку та підвищує загальну якість життя мешканців Києва

Ключові слова: вулично-дорожня мережа; транспортне моделювання; пропускна здатність; завантаженість вузлів; сценарії розвитку інфраструктури; соціальні наслідки

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Features of architectural environment formation: A case study of public spaces in the regional context of Northern Kazakhstan

Abstract. The purpose of the study was to analyse the changes in approaches to the design and organisation of urban environment by comparing architectural solutions of the past and the present. The study examined key elements of the urban environment, including parks, squares, embankments, squares and boulevards, and their role in improving the quality of life of the local population. The methodology included analysing climatic conditions such as temperature fluctuations, precipitation levels and wind activity, as well as their influence on the choice of building materials and architectural solutions. The main results showed that the use of modern heat and moisture resistant materials is important to ensure the durability of facilities in the harsh climate of the region. The paper analyses the formation and development of public spaces in the cities of Northern Kazakhstan with a focus on architectural solutions and spatial organisation of urban environment. Modern approaches to design, including integration of natural elements into the urban environment, creation of pedestrian zones and improvement of transport accessibility are studied. The efficiency of multifunctional spaces was assessed, and examples of reconstruction of public spaces in such cities as Kokshetau, Pavlodar, Petropavlovsk, Kostanai and Astana were analysed. The results of the study showed that the introduction of environmentally friendly materials and technologies contributes to the creation of a sustainable and comfortable urban environment. The paper concludes on the importance of creating inclusive spaces that take into account the needs of different population groups, thus improving the quality of life in the harsh climate of the region. The results obtained can be used to develop recommendations for improving public spaces in similar climatic zones

Keywords: multifunctional zones; integration of natural landscapes; sustainable development; inclusive environments; urban infrastructure; climate adaptation; cultural heritage

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INTRODUCTION

The formation of the architectural environment in the regional context of Northern Kazakhstan represents a complex challenge, requiring the consideration of both climatic and socio-economic factors. The region is characterised by harsh climatic conditions, including extreme winter temperatures, strong winds, and significant seasonal fluctuations in weather patterns. These natural features directly influence the choice of building materials, architectural forms, and technologies employed in the design of public spaces. Ensuring the sustainability and durability of structures becomes a key priority when creating an urban environment that provides comfort and safety for residents throughout the year. The study of architectural environment formation in Northern Kazakhstan has gained particular relevance in the context of changes occurring from 1991, when Kazakhstan gained independence, to 2024. Over this period, the urban environment has undergone significant evolution – from typical Soviet-era developments to modern solutions prioritising harmony with the natural surroundings and meeting emerging needs for the creation of comfortable public spaces (Schults *et al.*, 2016).

Existing studies provide theoretical insights and practical recommendations, contributing significantly to the development of this subject. In particular, the research of S. Donchenko & K. Samoilov (2020) on urban planning complexes in Almaty offer valuable perspectives on the processes of modernisation and the integration of architectural solutions, which are also relevant for cities in Northern Kazakhstan. The approaches described by G. Abdrassilova (2023) in her study of Soviet-era residential buildings emphasise the importance of preserving architectural heritage during the modernisation of urban spaces, a consideration that is equally pertinent to other regions with similar architectural features. The study by M. Kikimbayev (2023) on the creation of new public spaces illustrates contemporary design practices and their importance in establishing cultural and social hubs in the region.

S. Mamedov (2020) examines the principles of architectural and planning development of residential complexes within the changing social structure of cities in Northern Kazakhstan. The study highlights those transformations in the social structure directly influence architectural solutions, ensuring the functionality and aesthetic appeal of residential and public spaces. The research by A. Kornilova & A. Zeynullina (2021), which explores factors affecting the organisation of recreational zones in residential districts, complements this analysis by focusing on the selection of materials and technologies adapted to regional characteristics. The study emphasises that architectural solutions in Northern Kazakhstan must consider not only climatic factors but also social dynamics, such as population growth and increasing demands for quality urban environments. This approach is particularly important in the planning of public spaces, which must be both comfortable and multifunctional. G. Karabaev (2020) describes the use of spatial-structural modules as a means of optimising the design of public spaces in Northern Kazakhstan, where climatic conditions necessitate flexible and adaptive solutions to create sustainable and durable architectural structures. Existing research provides essential theoretical and practical foundations for the study of architectural transformations in the region. However, insufficient attention has been given to the formation of the architectural environment within the context of historical and cultural evolution, particularly concerning Northern Kazakhstan. The absence of a comprehensive approach that integrates the study of historical architectural solutions with contemporary trends represents a significant scientific challenge.

This study analysed the transformation of the architectural environment of public spaces in Northern Kazakhstan from a historical perspective. The research focused on comparing past and present architectural approaches to identify key trends influencing the development of urban spaces.

MATERIALS AND METHODS

A comprehensive approach to data collection and analysis was employed to achieve the research objective. The study focused on the landscape organisation of cities such as Kokshetau, Pavlodar, Petropavlovsk, Kostanai and Astana. Particular attention was given to analysing the development of public spaces, the reconstruction of historical sites, and the integration of modern architectural solutions into the urban environment, considering the region's climatic conditions. Specifically, the research examined projects involving the redevelopment of squares, the creation of new pedestrian zones, and the enhancement of riverfront areas. Evaluating the accessibility of public spaces for all population groups, including individuals with reduced mobility, played a crucial role, as it represents a key aspect of improving inclusivity within the urban environment.

The research methodology included an analysis of urban planning documentation, which facilitated the collection of information on the current state and reconstruction of public spaces in each of the cities studied. Particular emphasis was placed on the restoration of historical sites from the 19th and 20th centuries, as well as projects for the creation of new recreational areas such as parks, squares, and embankments. The architectural solutions and approaches employed in reconstruction and construction projects were examined, with special attention to the harsh climatic conditions of Northern Kazakhstan. The study utilised various materials, including the Resolution of the Government of the Republic of Kazakhstan No. 722 (2022) and the Master Plan of Astana City up to 2035 (Makhmetova *et al.*, 2022). International reports were also considered, such as the Climate Risk Country Profile: Kazakhstan (2021) and the Kazakhstan – country climate and development report (World Bank, 2021). Additionally, reports on strategic environmental assessments for the General Plan of Kokshetau until 2040 (n.d.) and the Profile of a smart sustainable city Nur-Sultan, Kazakhstan (2020) were incorporated.

The study included an analysis of modern construction materials such as metal, glass, and environmentally friendly composites used in the design of new structures. Particular attention was given to materials with high resistance to thermal deformation, which is essential in a continental climate characterised by sharp temperature fluctuations. The research also examined the implementation of energy-saving technologies, including thermal insulation materials, ventilation systems, and rainwater harvesting systems, which contribute to reduced energy consumption and the creation of a comfortable microclimate within buildings. Geographic Information System (GIS) technologies, specifically Quantum GIS (QGIS), were employed to visualise changes in public spaces. Using QGIS, zoning maps of public spaces and green areas were created for each city, enabling the representation of spatial changes and the impact of new projects on the urban environment. The maps were based on topographic data, ensuring precision in depicting the terrain and urban structure.

The research also developed a model framework for improving public spaces in Northern Kazakhstan, which included the creation of principles and approaches for designing more comfortable, environmentally sustainable, and accessible recreational and social interaction areas, tailored to the region's specific conditions. The model aimed to enhance the efficiency of urban land use and integrate modern technologies, allowing for the consideration of the needs of various population groups and ensuring the balanced development of infrastructure.

RESULTS

Public spaces in the cities of Northern Kazakhstan encompass a wide range of areas designed to meet the social, environmental, and cultural needs of residents. Parks and squares play a pivotal role, serving not only as recreational areas but also as essential ecological components of the urban environment. In a continental climate with extreme temperature fluctuations, the presence of green spaces and open areas contributes to improved microclimates. In summer, these spaces provide natural cooling through tree shade and evapotranspiration. They also mitigate the impact of pollutants, as green areas contribute to air purification and increased humidity levels, which is particularly important for cities located on the plains of Northern Kazakhstan, where climatic inversions often lead to stagnant polluted air.

Squares and boulevards serve as vital public hubs where pedestrian routes intersect and cultural and social events are organised. These spaces function as important transportation and communication nodes, providing access to key points within the city and fostering social interaction. In Northern Kazakhstan, where the climate can be harsh for a significant part of the year, squares are designed with the need for climate adaptation in mind. For instance, the presence of wind and snow-protected areas, combined with well-planned lighting and infrastructure, makes these public spaces more comfortable and accessible for use throughout the year.

Embankments and pedestrian zones constitute another significant category of public spaces, offering not only recreational opportunities but also enhancing the quality of the urban environment. These areas are a crucial part of the infrastructure of cities in Northern Kazakhstan, where natural conditions can vary from harsh winters to hot summers. Along these promenades, walking paths, resting areas, and spots for nature observation are created, contributing to a higher quality of life for residents. A key aspect is the integration of these spaces with the surrounding landscape, preserving the region's natural beauty and harmoniously incorporating them into the urban fabric. Embankments often become venues for city festivals, sporting events, and public gatherings, highlighting their importance as social and cultural hubs of urban life.

The climate of Northern Kazakhstan, characterised by its extreme continental conditions, significantly influences the selection of materials and design approaches. In such environments, thermal resistance and the ability of building materials to withstand extreme temperature fluctuations are of paramount importance. Winters in the region are marked by severe frosts, reaching as low as 48°C in the northeaster part, necessitating the use of materials with high frost resistance and the ability to withstand abrupt temperature changes. Conversely, summers can be very hot, with temperatures reaching 41°C, demanding materials with thermal stability to prevent deformation and damage caused by high temperatures. A key design approach in these conditions is considering the thermal properties of materials. To ensure efficient energy use and maintain a comfortable indoor climate, modern thermal insulation materials are employed to minimise heat loss in winter and overheating in summer. Ventilated facades also play a crucial role, allowing buildings to "breathe" and preventing moisture accumulation in the building structure (Zhangabay *et al.*, 2023).

Winds, frequently reaching speeds of 10-15 m/s, particularly in spring, impose additional constraints on material selection and design solutions. Constructing buildings in windy regions necessitates the use of materials and technologies that can withstand high wind loads. The prevalence of strong winds dictates the need for reinforced roof and facade structures to prevent damage and ensure the long-term stability of buildings (Bugaevsky *et al.*, 2020). In northern latitudes, the protection of buildings against wind erosion must also be considered, especially in areas with lower precipitation where soils can be susceptible to wind-driven erosion (Table 1).

Based on the provided climatic data, the influence of climatic conditions on material selection and design approaches in Northern Kazakhstan is linked to the need to consider extreme climatic conditions, including temperature fluctuations, precipitation, and humidity levels. Average monthly temperatures in Petropavlovsk range from 15°C in January to 20°C in July, indicating significant seasonal temperature variations. This necessitates the use of materials with high resistance to thermal deformations to prevent damage in both winter frosts and summer heat. Frost-resistant materials and effective thermal insulation solutions become essential for ensuring the longevity of buildings.

Table 1. Climate data for Petropavlovsk based on 30-year average figures

Month	Average monthly air temperature, °C	Average monthly precipitation, mm	Average monthly relative humidity, %
January	-15	13	81
February	-13.5	12	81
March		-5	15
April	6	24	66
May	14	28	59
June	18	46	62
July	20	68	66
August	18	49	67
September	11	29	71
October	3	25	76
November	-7	19	81
December	-13	13	82

Source: created by the authors based on the General Plan of Kokshetau until 2040 (n.d.)

The average monthly precipitation increases significantly during the summer months (reaching 68 mm in July), necessitating careful consideration of water-resistant and corrosionresistant materials to protect against moisture. Reliable waterproofing of structures and efficient rainwater drainage systems are crucial, especially during periods of heavy rainfall. Concurrently, the average relative humidity, fluctuating between 59% in May and 82% in December, impacts the durability of building materials, demanding the use of moisture-resistant coatings and corrosionresistant structures (World Bank, 2021).

In major cities of Northern Kazakhstan, such as Kokshetau, Petropavlovsk, and Astana, there is a growing trend towards improving the quality of the urban environment and enhancing residents' quality of life. For instance, in Kokshetau, the administrative centre of the Akmola Region, the focus is on creating spaces for public interaction and recreation, driven by its significance in transportation and tourism infrastructure. A key aspect of shaping public spaces in Kokshetau is preserving the natural landscape and integrating it into the urban fabric. Surrounded by picturesque forests and lakes, the city necessitates the incorporation of natural elements into the design of public areas. Parks, squares, and green spaces have become an integral part of the urban infrastructure, not only enhancing aesthetic appeal but also improving the ecological situation amidst rapid urbanisation (Brovina & Sallaku, 2024). Additionally, Kokshetau is actively developing multifunctional public spaces, such as squares and pedestrian zones, which play a vital role in the city's social life. These spaces are becoming venues for cultural and community events, such as festivals and exhibitions, fostering cultural engagement among residents and attracting tourists. A crucial element of these spaces is accessibility for all population groups, including those with reduced mobility, contributing to a more inclusive urban environment (General Plan of Kokshetau..., n.d.). The role of transportation infrastructure in the organisation of public spaces should also be noted. As a major transportation hub, Kokshetau requires special attention to ensure connectivity between public places and the city's main transport arteries. This necessitates the provision of comfortable pedestrian and cycling routes, enabling residents and tourists to move freely around the city and interact with various public spaces.

In the mid-1950s, spaces such as the Park of Culture and Recreation were established in Kokshetau, reflecting their importance in shaping the urban environment (Table 2). These areas, designed in the style of Soviet architecture with elements of classical design, are characterised by ordered forms and clear compositional lines. At that time, building materials such as brick and concrete were prevalent, reflecting an emphasis on durability and affordability. Functionally, these zones served as places for recreation and mass events, contributing to the development of the city's social life. However, in subsequent decades, they lost part of their infrastructure and green spaces, necessitating their renovation and adaptation to modern conditions.

Table 2. Analysis of new projects and reconstructions of public spaces in Kokshetau

Street/Object	Purpose	New projects/Reconstructions	Materials used
Park of Culture and Recreation	Recreation and public events	Renovation with restoration of green areas, creation of pedestrian routes	Natural materials (wood, stone)
Nazarbayev Avenue	Transport artery	Renovation with the improvement of transport infrastructure and landscaping	Asphalt, concrete, landscaping elements
Abylai Khan Avenue	New neighbourhood construction	Expansion with new residential and commercial buildings	Modern construction materials (concrete, glass)
Entrance Highway	Transport highway	Modernisation, expansion of pedestrian zones	Road surfaces, landscaping
Park on the shore of Lake Kopa	Coastal recreation area	Creation of forest park zones and a new business centre	Eco-friendly materials, glass, metal

Source: created by the authors based on the General Plan of Kokshetau until 2040 (n.d.)

Between 2015 and 2023, the reconstruction and creation of new public spaces in Kokshetau, including the refurbishment of entrance highways and the development of new districts, demonstrate a shift towards more integrated and multifunctional design. These projects consider not only social but also environmental, cultural, and transportation aspects. For instance, the General Plan of Kokshetau until 2040 (n.d.) envisions the creation of a business centre on the shores of Lake Koba, incorporating green spaces and boulevards. In this context, modern materials such as glass and metal are used to create lightweight structures adapted to the region's climate. A comprehensive study of architectural objects and public spaces in Pavlodar highlights their historical layering, where buildings from different eras coexist harmoniously. A crucial aspect is the preservation of the cultural and architectural value of old public spaces while modernising them using contemporary technologies and materials.

The organisation of public spaces in Pavlodar aims to harmonise natural and urban elements. Contemporary public spaces include the reconstruction of embankments, the creation of parks, boulevards, and squares, which cater to residents' needs for recreation and cultural leisure. Particular attention is paid to preserving the natural landscape within the city and adapting these spaces to modern standards of convenience and multifunctionality (Table 3).

Table 3. Analysis of renovations and modern public space projects in Pavlodar

Street/Object	Original purpose	New projects/Reconstructions	Materials used
Pavlodar Regional Museum of History and Local Lore	Trading house of merchant Artemy Derov	Renovation into a museum, preservation of the façade in the style of Siberian modernism	Brick, stucco, wrought iron grilles
Cathedral of the Annunciation	Religious building	New building constructed in 1999	Gilded domes, stone
Main Post Office	Main postal office	Renovation without altering major elements, tower with clock	Concrete, asphalt
Mashkhur Jusup Mosque	Religious building, built in 2001	Modernisation, addition of madrassas and cultural spaces	Modern materials, shanyrak, glass
Pavlodar Regional Drama Theater named after Chekhov	Trading house of merchant Surikov, later a cinema and infantry school	Renovation into a theatre, preservation of historical appearance	Brick, restoration of Soviet-style elements

Source: created by the authors based on D. Demidenko (2021)

The development of public spaces in Pavlodar demonstrates a balance between preserving cultural heritage and introducing innovative architectural solutions. Significantly, many of these reconstructions aim to create multifunctional spaces that meet contemporary standards of comfort and accessibility. An analysis of Petropavlovsk's architectural development reveals a multi-layered urban structure where historical buildings seamlessly coexist with modern architectural projects and reconstructions. Older parks and streets, such as Constitution Street (formerly Lenin Street), are essential elements of the city's architectural heritage, showcasing changes in styles, building materials, and functional characteristics. On this street, buildings constructed in the 19th and 20th centuries, including merchant houses, stand out for their use of traditional materials like brick and wood. These buildings not only served as residences but also functioned as commercial and community spaces, forming the core of the urban environment (Table 4).

Table 4. Analysis of new projects and reconstructions of public spaces in Petropavlovsk

Street/Object	Purpose	New projects/Reconstructions	Materials used
Siberian Trading Bank Building	Commercial bank, later administrative building	Central Department Store (CDS), façade renovation	Brick, modernised elements
Romanov School	Educational institution, later a school and technical college	Humanities and Technical College, preservation of historical appearance	Brick, restoration of original elements
House of Merchant Strelov	Trading house, later military enlistment office and general goods store	Museum, preservation of architectural monument	Brick, historical materials
Hotel "Kyzyl Zhar"	Hotel, once the city centre	Hotel modernisation, room and infrastructure updates	Modern building materials, glass, metal
Memorial to Military and Revolutionary Glory	Burial site for victims of the Civil War	Creation of memorial complex, addition of commemorative elements	Memorial materials, marble

Source: created by the authors based on Once upon a time: How Petropavlovsk has changed in 269 years (2021)

Petropavlovsk's architectural styles encompass elements of Siberian Modernism, as well as later Soviet architectural forms. Examples of merchant architecture, such as the House of Merchant Strelov, highlight meticulous attention to detail, including decorative wrought-iron grilles and stucco, indicative of rich finishes and high-quality construction. Such buildings reflect the multifunctional nature of the urban architecture of that time, combining residential and commercial functions. Contemporary trends in Petropavlovsk's architecture focus on preserving historical heritage while incorporating modernisation. For instance, the reconstruction of the "Kyzyl Zhar" Hotel, a significant building from the 1970s, showcases the use of modern building technologies and materials such as glass and metal, allowing the building to adapt to new conditions while retaining its original functions. Additional functional zones, such as restaurants and fitness centres, are created within modernised buildings, enhancing their appeal to both residents and tourists (Once upon a time: How Petropavlovsk..., 2021).

The development of public spaces in Petropavlovsk is focused on creating convenient and multifunctional zones for relaxation and leisure. The reconstruction of Constitution Street, one of the largest pedestrian zones in Kazakhstan, which took place between 2018 and 2020, exemplifies this approach. This car-free street has become a central venue for urban events and tourist activities, contributing to the city's cultural life. It is also important to note the modernisation of historically significant buildings, such as the former Siberian Trade Bank, which was renovated in 2019 and now serves as a central department store in 2024. New public space development projects include measures to improve transport accessibility, making the urban environment more comfortable for residents and visitors. The interaction between new public spaces and the natural environment, such as the streets along the Ishim River, helps to preserve the city's unique natural features. Thus, Petropavlovsk maintains a balance between preserving its historical appearance and introducing modern architectural solutions, creating a comfortable and attractive environment for living and leisure.

An analysis of Kostanai's urban development highlights the significance of historical, natural, and contemporary factors in shaping the city's architectural environment. The specific characteristics of construction along the Tobol River played a crucial role in the development of urban spaces, defining the structure of the city's-built environment. Early buildings were constructed from brick and wood, typical of 19th-century architecture. Notable examples include the real school and merchant houses, which reflect the classical architectural style and the use of local materials. These structures not only served as residences but also formed public spaces, becoming important elements of the city's central districts. In the 20th century, particularly during the period of intensive Virgin Lands campaign, Kostanai experienced significant population growth, leading to a substantial increase in high-rise construction. Among the buildings constructed between 1950 and 1970, the railway station and central department store are notable examples of functional Soviet architectural style. These buildings used materials such as concrete and glass, reflecting the construction approaches of that era. In contemporary times, the city's public spaces are developing with a focus on creating a comfortable environment for residents, including renovated residential complexes and squares (Table 5).

Table 5. Analysis of new projects and reconstructions of public spaces in Kostanai

Street/Object	Purpose	New projects/Reconstructions	Materials used
Central Square	Administrative centre of the city	Renovation to create a pedestrian zone, landscaping	Asphalt, concrete, decorative elements
"Airport" Microdistrict	New development on the site of Lake Tarelochka	Infrastructure renovation, creation of residential complexes	Modern materials, plastic, concrete

Table 5. Continued

Street/Object	Purpose	New projects/Reconstructions	Materials used
“Bereke” Microdistrict	New development in the north-western part of the city	Addition of recreational areas, improvement of drainage system	Asphalt, concrete, metal
“Yubileiny” Microdistrict	Mixed zone with industrial facilities	Improved transport accessibility, construction of residential and commercial buildings	Glass, metal, plastic
Square in front of the “Chemist”	Cultural centre of the city	Renovation of the square to create a public space	Concrete, decorative elements, glass

Source: created by the authors based on the Development Strategy of Kostanay till 2050 is being elaborated (2019)

Contemporary projects for developing new microdistricts, such as “Airport”, “Bereke”, and “Yubileiny”, focus on creating housing complexes that take into account the region’s natural and climatic conditions. The use of modern materials, such as glass, metal, and plastic, enables the construction of energy-efficient and durable buildings, meeting the demands of modern urban development. However, issues such as flooding and infrastructure shortages remain pressing and require further attention (Development Strategy of Kostanay…, 2019). A contemporary approach to reconstructing and creating public spaces aims to improve transport accessibility and integrate new developments into the city’s natural landscape, thus preserving its unique character. Therefore, the development of Kostanai’s architectural environment is based on preserving historical heritage and introducing modern architectural solutions, contributing to the creation of a comfortable and attractive urban environment for both residents and visitors.

Urban development in Kostanay is focused on preserving historical landmarks, renovating public spaces, and creating new residential complexes that meet contemporary architectural and environmental standards. A key element is the functional zoning of microdistricts (Fig. 1), which allows for diverse resident needs to be accommodated and ensures accessibility to residential, social, educational, and recreational areas. This contributes to the creation of a harmonious and comfortable urban environment, essential for the sustainable development of the city.

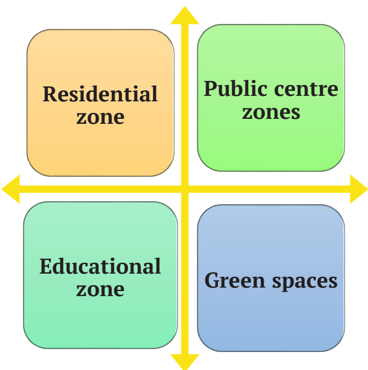

Figure 1. Functional zones in the urban development of Kostanai
Source: created by the authors based on the Development Strategy of Kostanay till 2050 is being elaborated (2019)

The residential zone plays a pivotal role in ensuring a comfortable living environment, accommodating a diverse range of housing types from multi-family apartments to single-family homes. Optimal building density and its distribution to other zones provide convenience for residents, minimising strain on the city’s transportation network and improving accessibility to key infrastructure. This is particularly crucial for the effective planning of new residential areas.

Public centre zones encompass a range of commercial, cultural, and administrative facilities, providing various services. The even distribution of such centres across microdistricts is crucial, as it fosters the development of all city areas and reduces the strain on the central district. This ensures a balanced distribution of social activities and enhances the overall quality of the urban environment. Educational zones, including schools and kindergartens, provide accessible education within walking distance, particularly beneficial in the region’s northern climate. Locating these institutions near residential areas reduces travel time, creating a more comfortable living and learning environment. Green spaces with recreational facilities are vital for improving the city’s ecological conditions, providing opportunities for relaxation and sports activities. They contribute to better air quality, noise reduction, and comfortable outdoor recreation year-round, which is especially important in Kostanay’s harsh continental climate. Thus, a comprehensive approach to Kostanay’s development, incorporating modern architectural design and functional zoning, fosters a sustainable and attractive urban environment.

Astana’s public spaces offer a unique blend of historical and contemporary architectural approaches, reflecting the city’s evolution from a Soviet settlement to the modern administrative centre of Kazakhstan. Preserving the architectural heritage of the Soviet period, including the influence of its urban planning, is crucial for understanding the city’s architectural development. For instance, structures like the late 19th-century Gostiny Dvor exemplify the typical building style of that era, characterised by the use of stone and brick. Public spaces of this period were distinguished by their functional purpose and commercial orientation, aligning with the economic needs of the time.

Astana’s contemporary architecture is focused on innovation and harmonious integration with the natural environment. Projects such as the Baiterek monument, the

Palace of Peace and Reconciliation, and the Elbasy Library showcase pioneering architectural approaches, where technological advancements, modern building materials, and sustainability principles play a pivotal role. These structures symbolise the significant sociocultural and political changes occurring in the country and create new avenues for cultural and public life, transforming them into platforms for events, cultural development, and recreation. For instance, the Palace of Peace and Reconciliation integrates religious and cultural functions, underscoring the society's openness and diversity (Profile of a smart sustainable..., 2020).

A key characteristic of the new architecture is its seamless integration with the natural landscape and the use of environmentally friendly materials such as glass and metal, contributing to a sense of lightness and openness. Structures like Khan Shatyr exemplify the use of modern technologies to maintain a comfortable microclimate within the building, which is particularly important in the continental climate of the capital. Such architectural approaches not only foster the harmonious development of the urban infrastructure but also provide comfortable conditions for residents and visitors alike, taking into account the region's climatic features (Table 6).

Table 6. Comparative analysis of functional changes in public spaces

Aspect	Old architectural solutions	Modern architectural solutions
Functionality of public spaces	Integration into the urban environment	Multifunctionality: commerce, entertainment, leisure, meetings, social events
Materials	Use of traditional materials: stone, brick	Use of modern materials: glass, steel, concrete, environmentally friendly materials
Integration into the urban environment	Spaces that divided different parts of the city or had specific isolation	Complete integration with the urban environment, and creation of accessible public spaces

Source: created by the authors based on Profile of a smart sustainable city Nur-Sultan, Kazakhstan (2020)

Astana's early 20th-century built environment was primarily oriented towards commercial and administrative functions. Structures such as the Gostiny Dvor, Green Rows, and buildings owned by the Kubrin merchants played a pivotal role in the city's economic activity. They served as significant centres of trade and administration, meeting the city's economic and social needs. In contemporary times, the functionality of public spaces has expanded significantly, becoming more multi-faceted. These spaces are now geared not only towards commercial purposes but also towards social, cultural, and recreational aspects of urban life. Examples of such transformations can be seen in buildings like the Palace of Peace and Reconciliation and Khan Shatyr, which combine cultural, entertainment, and community functions. This fosters the creation of new focal points for both locals and tourists, enhancing social engagement and providing venues for interaction and leisure.

Historically, Astana's buildings were primarily constructed using brick and stone, ensuring structural integrity but often overlooking the region's specific climatic conditions, such as extreme temperature fluctuations and strong winds. Contemporary architectural approaches in the city have embraced the use of cutting-edge materials like metal, glass, and innovative composites, enhancing buildings' resilience to harsh weather. In particular, the implementation of energy-efficient technologies, as seen in the Elbasy Library and the glass facades of the Palace of Peace and Reconciliation, contributes to reduced energy consumption, thereby minimising the buildings' environmental impact on the urban setting.

Astana's successful integration of new architectural solutions into its urban fabric is evident in the harmonious blend of modern technology with historical and cultural motifs. For instance, the Khan Shatyr entertainment centre showcases a unique design reminiscent of traditional Kazakh yurts, underscoring the region's cultural identity. Another iconic landmark, the Baiterek monument, presents a symbolic architectural form that combines contemporary technology with elements of Kazakh mythology, creating a striking visual centrepiece in the city's landscape (Profile of a smart sustainable..., 2020). Beyond architectural innovations, significant greening projects have been pivotal in shaping Astana's contemporary development. For instance, Resolution of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan (2021) aims to significantly expand green spaces in Astana. By mid-2024, the "Zhasyl Kazakhstan" initiative led to the planting of around 200,000 trees and shrubs. These changes not only enhance the ecological sustainability of the capital but also ensure a harmonious blend of natural and urban environments, contributing to the city's appeal to both residents and tourists.

Figure 2, created using Quantum GIS (QGIS), aims to characterise the landscape organisation of Astana, with a particular focus on green spaces and the improvement of public areas. The map divides the city into various administrative districts, displaying their boundaries, which allows for a visual representation of the distribution of green spaces and greening efforts in each district. This mapping approach aids in urban planning and the development of environmental strategies by providing data on the spatial distribution of green zones to enhance public spaces.

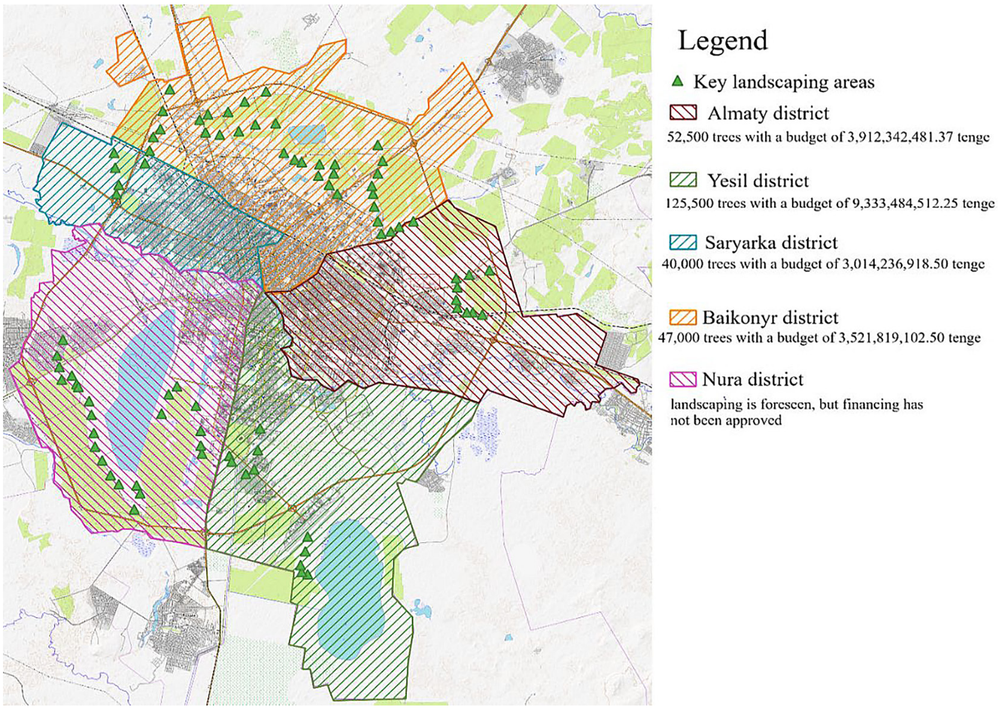

Figure 2. Zoning of Astana and the landscape organisation of green spaces
Source: created by the authors

The development of Astana's built environment requires consideration of the region's climatic and social characteristics. In a harsh continental climate with extreme temperature fluctuations and strong winds, the creation of covered pedestrian zones and windbreak green barriers is recommended. Public spaces must serve not only recreational but also cultural functions, fostering social integration. Contemporary projects should utilise environmentally friendly materials such as self-healing concrete and glass, and incorporate energy-saving technologies including solar panels and rainwater harvesting systems. A harmonious integration with the landscape involves creating green boulevards and providing easy access to public spaces, which may include developing cycling paths and eco-friendly transportation. These measures will enable Astana to combine comfort, innovation, and environmental sustainability within the context of its regional specificities. Therefore, developing a model for improving public spaces is crucial for the development of cities in harsh climates and with evolving social needs (Fig. 3).

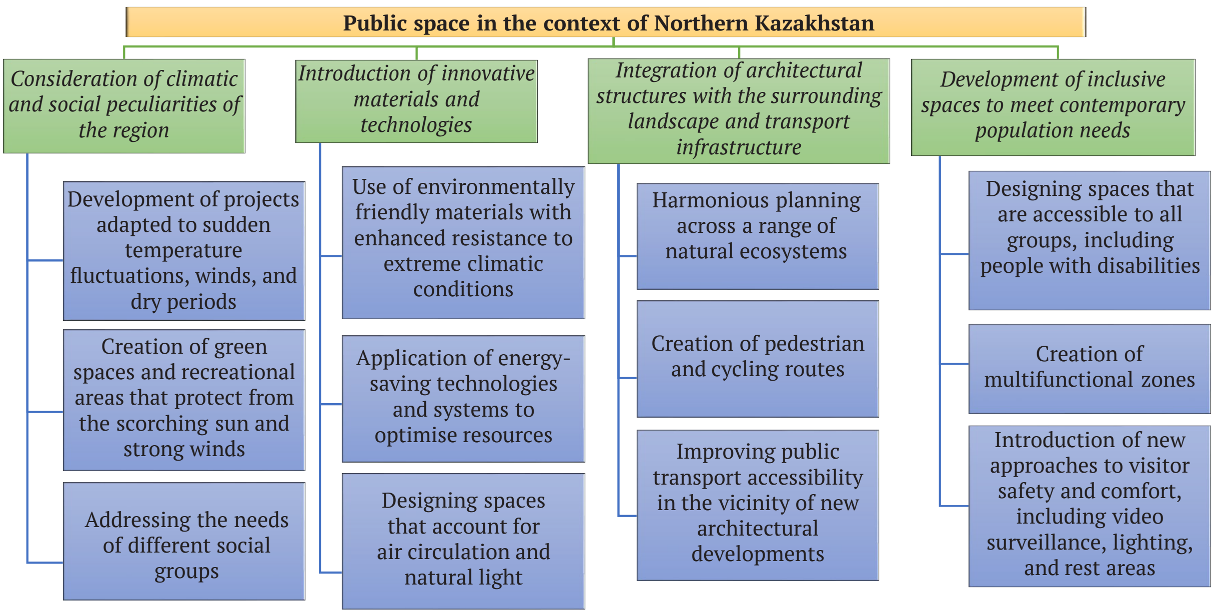

Figure 3. Structure of the model for improving public spaces in Northern Kazakhstan
Source: created by the authors

Adapting projects to extreme temperature fluctuations and climatic challenges can enhance the quality of life for residents and increase the resilience of urban areas to adverse natural conditions. The implementation of innovative materials and energy-efficient technologies helps reduce operational costs and minimise the environmental footprint, aligning with contemporary sustainable development goals. The harmonious integration of architectural structures with the natural landscape and transportation infrastructure improves accessibility and connectivity within the urban environment, creating comfortable conditions for citizens to move around and relax. A particular focus on the inclusivity of public spaces ensures that the needs of all population groups are considered, fostering social integration and enhancing the quality of urban interactions. Thus, this model represents a comprehensive approach aimed at creating a more sustainable and comfortable urban environment capable of addressing the challenges of climate change and the growing demands of society.

DISCUSSION

The contemporary context of rapid urbanisation, increasing urban populations, and climate change demands a comprehensive approach to planning urban areas in Northern Kazakhstan. It is crucial to consider not only socioeconomic but also environmental aspects, particularly in the region's harsh climate characterised by extreme temperature fluctuations, strong winds, and prolonged winters, which present significant challenges to the design and operation of public spaces. The integration of green infrastructure and the application of energy-efficient technologies can not only improve the microclimate but also enhance the overall resilience of the urban environment, making it more comfortable for living and development (Askaraliev *et al.*, 2024). This is particularly significant in regions with extreme climatic conditions, such as Northern Kazakhstan, where winters last for more than half a year and summer temperatures can exceed 30°C. Studies conducted in Lahore, Pakistan, by R. Khalid & M. Sunikka-Blank (2020) and D.H.I.L. Mohamed (2021) highlight the importance of efficient energy use in the residential sector. However, this research focuses on adapting these approaches to public spaces, which is particularly relevant for cities with cold and variable climates.

S.O.S.E. Ermgassen *et al.* (2022) proposed solutions to meet housing needs with minimal impact on ecosystems in England. These approaches can be adapted to Kazakhstan, where infrastructure development must balance economic growth with environmental conservation. In Northern Kazakhstan, where preserving unique natural landscapes and biodiversity is of strategic importance, it is essential to develop measures aimed at creating green corridors and urban green spaces, which can improve the microclimate and provide comfortable living conditions for residents. The specific local climatic conditions, including strong winds and significant temperature fluctuations, necessitate adaptive solutions to create sustainable green areas. E. Manahasa & O. Manahasa (2020) analysed the impact of socioeconomic changes on the built environment in Tirana, highlighting the role of societal changes in shaping the urban environment. In Northern Kazakhstan, similar processes related to migration, changes in employment structure, and adaptation to new economic conditions also influence the development of public spaces. However, there is a greater need to focus on environmental aspects here, as the transition to a market economy and urbanisation have increased the burden on natural resources and ecosystems. Adapting green spaces to harsh climatic conditions requires the use of specific plant species resistant to cold and wind, allowing for the creation of harmonious public spaces with minimal environmental impact (Kucherenko *et al.*, 2024).

This research highlights the significance of economic zones in driving urban development in Kazakhstan. E. Kumera & B. Woldetensae (2023) examine the impact of economic growth in Ethiopia's special economic zones on urban development. Unlike Ethiopia, Northern Kazakhstan requires stricter controls on preserving natural areas due to its vulnerable ecosystem, imposing additional constraints on economic growth. S. Kumar & H. Banerji (2022) and H. Sami Belmahdi & A. Djemili (2022) employ Bayesian networks to analyse urban resilience, enabling the quantitative assessment of urban areas' adaptive capacity. This study applies similar approaches to evaluate the resilience of public spaces while considering the region's cultural and social characteristics, facilitating the development of more tailored sustainability strategies. A. Senetra & P. SzarekIwaniuk (2020) and M. Wang *et al.* (2022) emphasise the importance of sustainable development in small towns, investigating the Cittaslow network in Poland. These approaches are beneficial for small towns in Northern Kazakhstan, but additional attention is needed to adapt greening methods due to the harsh climate and temperature fluctuations.

This study explores the potential for expanding green spaces in urban areas with limited space, which can improve the microclimate and create more comfortable living conditions for residents. B. Olczak *et al.* (2022) and G.C. de Mendonça *et al.* (2022) also highlight the use of agroforestry systems for landscape restoration, a practice that could be adapted to Kazakhstan's urban environments. C. Basnou *et al.* (2020) and A. Majewska *et al.* (2022) investigate the integration of green infrastructure within the EU, contributing to improved biodiversity in urban settings. This research adapts the principles of creating parks and green corridors to the specific conditions of Northern Kazakhstan, considering the continental climate and the need for green spaces to withstand extreme conditions.

The development of Astana's built environment necessitates a particular focus on adapting urban infrastructure to the harsh climate. This involves creating covered pedestrian areas, windbreak green barriers, and utilising innovative building materials and energy-efficient technologies, thereby enhancing quality of life and reducing heating costs. These findings align with those of K. Xu *et al.* (2020), who studied spatial planning for the restoration of agricultural landscapes, emphasising the importance of integrating green spaces into public areas. However, this research focuses on adapting agroforestry systems to the urban conditions of Northern Kazakhstan, enabling improvements to the microclimate in extreme weather conditions. The creation and development of public spaces in Northern Kazakhstan requires consideration of the region's specific climatic conditions to achieve optimal comfort. In this context, particular attention is given to creating wind-protected zones, using materials resistant to extreme weather, and adapting green spaces to the regional climate. These conclusions resonate with the study of Y. Chi *et al*. (2020), who focused on integrating ecological functions into urban planning. Unlike the aforementioned approach, this study emphasises the importance of creating zones capable of withstanding abrupt temperature changes and strong winds. Additionally, it highlights the significance of a multi-tiered approach to establishing ecological networks, thereby enhancing interactions between various urban ecosystems. These findings align with those of R. Caro & J.J. Sendr (2021) and Y. Yang *et al*. (2022), who proposed similar solutions for creating resilient urban spaces in China. However, this research adapts these methods to the harsh climate of Northern Kazakhstan. Incorporating a multitiered approach enables the creation of a more resilient urban environment that accounts for the region's specific characteristics and promotes sustainable development. Consequently, the study demonstrates that integrating green infrastructure in Astana and other cities in the region is a crucial component of sustainable urban planning. While similar to the conclusions of V. Hermoso *et al*. (2020) and Y. Hu *et al*. (2020) regarding the importance of green infrastructure, this research underscores the need for green spaces adapted to Northern Kazakhstan's extreme climatic conditions. This contributes to the development of cities in the region in line with sustainable development principles and improves the quality of life for local residents.

As of the second half of 2024, there is no consensus among scientists on the optimal approach to optimising public spaces in the extreme climate of Northern Kazakhstan. However, all the studies reviewed emphasise the need for a comprehensive approach that considers ecological, socioeconomic, and cultural factors. The implementation of energy-efficient technologies and the adaptation of green infrastructure to the region's climatic conditions enable the creation of a sustainable urban environment. Although researchers differ in the details of methods and priorities, it is clear that the resilience of urban spaces depends on the ability to integrate environmental, social, and technological approaches. To ensure sustainable development, it is essential to apply multi-level strategies that consider the specific climate and socioeconomic realities, thereby enhancing the adaptability of urban spaces to environmental changes and creating favourable living conditions in the harsh climate of Northern Kazakhstan.

CONCLUSIONS

This study analyses the formation and development of public spaces in the cities of Northern Kazakhstan, considering climatic, social, and architectural factors. It has been established that public spaces, including parks, squares, and promenades, play a significant role in creating a comfortable environment for residents in conditions of a sharply continental climate. Quantitative data, including average temperature and precipitation levels in cities such as Petropavlovsk, indicate the need to account for extreme climatic conditions during the design process. For instance, the average annual temperature ranges from 15°C in January to 20°C in July, influencing the choice of materials and design approaches for buildings and public areas. This also applies to the increased precipitation in summer, which necessitates the use of waterproof materials and drainage systems. Renovations and new projects in cities such as Kokshetau, Pavlodar, and Astana demonstrate a shift towards an integrative approach that combines social, environmental, and cultural aspects.

The findings underscore the significance of employing modern materials such as glass, metal, and eco-friendly components to ensure the durability and energy efficiency of architectural solutions. This not only reduces operational costs but also minimises environmental impact, which is particularly relevant for regions with harsh climates. Additionally, the role of green spaces is crucial in improving air quality and creating comfortable recreational environments.

Limitations of the study are related to the availability of detailed climatic and economic data for individual cities and the ability to accurately model the impact of climate change on architectural planning. This has affected the ability to formulate universal recommendations for all settlements in the region. Future research should expand the database to include more cities and consider the impact of modern technologies on improving the energy efficiency and environmental sustainability of architectural solutions.

Recommendations for further research include developing models for adapting public spaces to climate change using GIS technologies. This will enable the assessment and prediction of the effectiveness of various architectural solutions under changing climatic conditions. Additional focus should be placed on analysing the inclusivity of public spaces to ensure accessibility for diverse populations and improve the quality of social interaction.

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CONFLICT OF INTEREST

None.

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Особливості формування архітектурного середовища на прикладі громадських просторів у регіональних умовах Північного Казахстану

Анотація. Мета дослідження полягала в аналізі змін підходів до проєктування та організації міського середовища, шляхом порівняння архітектурних рішень минулого і сьогодення. У процесі дослідження було вивчено ключові елементи міського середовища, включно з парками, скверами, набережними, площами та бульварами, а також їхню роль у поліпшенні якості життя місцевого населення. Методологія включала аналіз кліматичних умов, таких як температурні коливання, рівень опадів і вітрова активність, а також їхній вплив на вибір будівельних матеріалів та архітектурні рішення. Основні результати показали, що використання сучасних термостійких і вологостійких матеріалів є важливим для забезпечення довговічності об'єктів в умовах суворого клімату регіону. У роботі проведено аналіз формування та розвитку громадських просторів у містах Північного Казахстану з акцентом на архітектурні рішення та просторову організацію міського середовища. Досліджено сучасні підходи до проектування, що включають інтеграцію природних елементів у міське середовище, створення пішохідних зон і поліпшення транспортної доступності. Проведено оцінку ефективності багатофункціональних просторів, а також проаналізовано приклади реконструкції громадських місць у таких містах, як Кокшетау, Павлодар, Петропавловськ, Костанай та Астана. Результати дослідження показали, що впровадження екологічних матеріалів і технологій сприяє створенню стійкого і комфортного міського середовища. У роботі зроблено висновок про важливість створення інклюзивних просторів, що враховують потреби різних груп населення, що дає змогу поліпшити якість життя в умовах суворого клімату регіону. Отримані результати можуть бути використані для розробки рекомендацій щодо вдосконалення громадських просторів в аналогічних кліматичних зонах

Ключові слова: багатофункціональні зони; інтеграція природного ландшафту; сталий розвиток; інклюзивне середовище; міська інфраструктура; кліматична адаптація; культурна спадщина

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