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Optimisation of the composition and properties of decorative columns and arches using travertine (shell limestone)

Abstract. The need to enhance the durability and aesthetic stability of decorative architectural elements under the climatic conditions of the Kyrgyz Republic underscores the relevance of researching the properties of natural building materials such as travertine. The aim of this study was to analyse the physical and mechanical characteristics of travertine and optimise its properties for effective use in the design of decorative columns and arches. The research involved comprehensive laboratory methods, including tests for compressive strength, water absorption, abrasion resistance, frost resistance, and ultraviolet (UV) radiation resistance. The experiments examined the behaviour of travertine under variable humidity and temperature fluctuations. It was established that the material has a compressive strength of 45-55 MPa but shows water absorption of up to 10-15%, indicating its porous structure and the need for additional

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protection. The abrasion coefficient ranged from 0.8 to 1.2 mm, while compressive strength decreased by 15-20% after 50 freeze-thaw cycles. The study of hydrophobic and polymeric impregnations revealed a twofold reduction in water absorption and an increase in frost resistance. The paper also summarises data on the deterioration of travertine's decorative qualities under UV exposure and proposes technological solutions to preserve them. The practical value of this research lies in the development of recommendations for travertine treatment to improve its performance characteristics. These findings can be applied by architects, designers, restorers, and construction professionals when designing buildings and structures in the sharply continental climate of Kyrgyzstan

Keywords: decorative architectural elements; physical and mechanical properties; material durability improvement; construction materials and climate

INTRODUCTION

Improving the performance characteristics of decorative architectural elements is a key task in modern construction, especially in the harsh climate of the Kyrgyz Republic. Natural stone materials such as travertine, with their high aesthetic and physico-chemical properties, are widely used for facade cladding and the creation of columns, arches, and other architectural forms. However, travertine's porous structure, high water absorption, and susceptibility to abrasion limit the durability of such elements in conditions of cyclical temperature changes and high humidity. Therefore, optimising the composition and properties of travertine is of particular relevance.

The processing and use of natural stone in construction have been addressed in several studies. Zh. Usubaliev & K.T. Elikbaev (2024) analysed modern technologies for extracting and processing natural stone in Kyrgyzstan, emphasising the need to improve cutting, grinding, and polishing methods to enhance the quality and durability of building products. They noted that the introduction of modern processing lines contributes not only to increased strength but also to greater resistance to climatic influences. B.T. Assakunova *et al.* (2018) explored the use of travertine sawing waste to produce gypsum composites, demonstrating that secondary mineral raw materials can significantly improve mechanical strength, reduce water absorption, and optimise the cost of final products – an important factor for Kyrgyzstan's construction sector. A.N. Zhakanov (2023) showed the potential of using travertine waste in the production of lightweight concrete, stating that the addition of porous mineral fillers improves thermal insulation properties while maintaining sufficient strength, thus expanding travertine's application in small architectural forms and facade systems.

G.A. Issabayev (2022) focused on architectural solutions involving cantilever structures made of natural materials, highlighting the importance of stone's resistance to deformation and external loads. The author emphasised that using natural stone in load-bearing and decorative elements requires careful consideration of its strength characteristics and proper preparation at the design stage. S. Rescic *et al.* (2024) investigated the historical use of travertine in Tuscan architecture and confirmed that, when properly processed, the stone exhibits high resistance to weathering and retains its decorative properties for centuries. S.Y. Erdinç (2023) explored the potential of natural stone in contemporary architecture and identified key technological factors influencing product longevity, including pre-treatment hydrophobisation and minimisation of surface microcracks.

M. Casazza & F. Barone (2024) stressed the importance of vibration monitoring systems for the timely detection of internal defects in stone structures, particularly when using travertine in architectural elements exposed to dynamic loads and seasonal temperature changes. C. Conforti *et al.* (2021) analysed the practice of creating full-scale architectural models, highlighting the critical role of proper preparation and processing of building materials, including natural stone, in ensuring operational reliability and aesthetic stability in real-world conditions. M. Grawehr (2022) explored stylistic and structural aspects of travertine in Ancient Roman architecture, with special attention to its durability and cultural and engineering significance in monumental construction. J.L. Sánchez-Cortez *et al.* (2022) investigated methods for assessing the resistance of karst formations to external impacts, directly relevant to evaluating the longevity of porous natural materials like travertine in aggressive climates.

Despite the wealth of research, issues related to improving the moisture resistance, wear resistance, and frost resistance of travertine in the context of the Kyrgyz Republic remain insufficiently explored, necessitating further comprehensive studies. The aim of this research was to comprehensively study the physical and mechanical properties of travertine and to identify ways to optimise its use in the design of decorative architectural elements – particularly columns and arches – taking into account the climatic conditions of Kyrgyzstan.

MATERIALS AND METHODS

The study was conducted at the Building Materials Laboratory of the Kyrgyz State Technical University named after I. Razzakov from January to October 2024. The laboratory experiments were based on travertine samples extracted from the Kyzyl-Tuu and Sulyikta deposits in the Kyrgyz Republic. These sites were selected due to their industrial significance, stable physico-mechanical properties of raw material, and the need to develop effective technologies to enhance the durability of decorative architectural

elements under the region's continental climate conditions. Sample selection was carried out directly at the Kyzyl-Tuu and Sulyikta quarries. To ensure representativeness, six samples were collected (three from each site). Inclusion criteria included structural homogeneity, absence of visible cracks, minimal weathering, and uniform pore distribution. Exclusion criteria were mechanical damage, prominent cracking, foreign mineral inclusions, and non-uniform texture. Selection was conducted visually and using a Schmidt hammer for preliminary field strength assessment. Samples measuring 150×150×150 mm were delivered to the laboratory for testing. Physical and mechanical properties were determined in accordance with international standards. Density was measured using the hydrostatic weighing method as per ASTM C97/C97M-18 (2025) (USA). Water absorption was calculated using the full water saturation method. Porosity was determined by the ratio of pore volume to the total sample volume, using formula (1):

$$P = \frac{Vpore}{Vtotal} \cdot 100\%, \quad (1)$$

where P – porosity in percent; V_{pore} – pore volume; V_{total} – total volume of the sample.

Compressive strength was determined using a Controls Group MCC8 hydraulic press (Italy) according to ASTM C170/C170M-17 (2023) (USA) and EN 1926:2006 (2008). Flexural strength was measured in accordance with EN 12372:2022 (2022). Abrasion resistance was evaluated using an abrasive disc simulating the impact of sand particles on the surface. To simulate operational conditions, samples were subjected to temperature fluctuations from -20°C to +50°C and relative humidity from 30% to 90%. Frost resistance tests followed EN 12371:2010 (2010), including 50 freeze-thaw cycles in a water medium. UV resistance was assessed using an Atlas Suntest CPS+ climate chamber (USA) with 500 hours of irradiation. A comparative analysis of the physical properties of travertine with granite and marble was also conducted, using benchmark data from G. Sarıışık *et al.* (2016), which detailed construction stone properties, including density, porosity, compressive strength, and abrasion resistance. Travertine samples from Kyzyl-Tuu and Sulyikta (10 samples of 100×100×50 mm) were used, conforming to EN 1926:2006 (2008). Inclusion criteria included natural origin, relevance to decorative architecture in Central Asia, and availability of reliable lab data. Benchmark granite and marble properties were drawn from published results, as those materials were not tested in this study. Samples were irradiated for 500 hours under simulated outdoor Kyrgyz conditions. Brightness and colour saturation changes were recorded every 100 hours via colorimetric analysis. Statistical data were processed using Statistica 13.5 (Dell, USA), with the Student's t-test used to assess differences between independent samples. A paired correlation analysis between travertine characteristics and strength indicators was performed first. In the second stage, regression models were constructed using the least squares method. Model quality was evaluated with multiple determination coefficient (MCD), root mean square error (RMSE), and mean absolute error (MAE). To avoid multicollinearity, a correlation matrix was used.

RESULTS

Experimental data analysis revealed the physical and mechanical characteristics of travertine from the Kyzyl-Tuu and Sulyikta deposits and the effects of surface treatment on material performance. In the first research stage, initial physical properties such as density, porosity, and water absorption were determined. Sample density ranged from 1,850 to 2,450 kg/m^3. Higher density corresponded to lower porosity and, consequently, better mechanical properties. Porosity was calculated using formula (1). Results showed a range of 12% to 22%. Higher porosity increased moisture absorption capacity, confirmed by test data: water absorption was 10% to 15% by sample mass. Density, porosity, and water absorption results are summarised in Table 1.

Table 1. Density and porosity of studied travertine samples

Sample No.	Place of birth	Density (kg/m^3)	Porosity (%)	Water absorption (%)
1	Kyzyl-Tuu	1,850	22	15
2	Kyzyl-Tuu	2,100	18	12
3	Kyzyl-Tuu	2,450	12	10
4	Suliukta	1,880	21	14
5	Suliukta	2,150	17	11
6	Suliukta	2,400	13	10

Source: compiled by the authors

Analysis of the data presented in Table 1 showed that the density of travertine ranged from 1,850 to 2,450 kg/m^3, while porosity varied between 12% and 22%. The water absorption rate of the samples ranged from 10% to 15%, indicating the material's relatively high capacity for moisture retention. Samples from the Kyzyl-Tuu deposit demonstrated slightly higher density and lower porosity compared to those from Sulyikta, suggesting potentially greater resistance to mechanical loads and better suitability for use in structural elements. Nevertheless, all samples exhibited high water absorption rates, highlighting the need for measures to reduce the material's permeability. These results confirm the necessity of applying additional protective treatments – such as hydrophobisation and surface densification – to improve the durability of travertine under conditions of frequent

humidity and temperature fluctuations. The analysis of compressive strength test results before and after 50 freeze-thaw cycles made it possible to assess the frost resistance of travertine from the Kyzyl-Tuu and Sulyikta deposits. The tests were conducted in accordance with EN 12371:2010 (2010), simulating the climatic conditions of the Kyrgyz Republic, where frequent temperature changes and high humidity can significantly affect the durability of construction materials. The changes in compressive strength are summarised in Table 2. Strength values were recorded before the freeze-thaw cycles and again after 50 full cycles.

Table 2. Changes in compressive strength of travertine after freeze-thaw cycles

Sample No.	Place of birth	Strength before cycles (MPa)	Strength after cycles (MPa)	Strength reduction (%)
1	Kyzyl-Tuu	45	36	20
2	Kyzyl-Tuu	50	42	16
3	Kyzyl-Tuu	55	46	16
4	Suliukta	46	37	19
5	Suliukta	51	43	16
6	Suliukta	54	45	17

Source: compiled by the authors

As shown in Table 2, the compressive strength of the travertine samples before the frost tests ranged from 45 to 55 MPa. After 50 freeze-thaw cycles, a consistent decrease in strength by 16-20% was observed, depending on the specific sample and its original properties. The most significant strength loss occurred in samples with higher porosity, confirming the critical role of material structure in frost resistance. On average, travertine from Kyzyl-Tuu showed slightly greater strength reduction compared to samples from Sulyikta, likely due to differences in texture and density. The overall trend indicates high sensitivity of travertine to repeated temperature fluctuations, necessitating protective treatments for use in environments with frequent freeze-thaw cycles.

The analysis confirmed that the highest strength loss occurred in samples with higher initial porosity, indicating a direct correlation between material porosity and frost resistance. The destruction mechanism can be explained by water expansion during freezing within the pores, leading to microcrack formation and a decrease in the load-bearing capacity of the material. Figure 1 illustrates the correlation between the number of freeze-thaw cycles and the decline in strength, visually representing the progressive degradation of the stone structure due to repeated temperature changes.

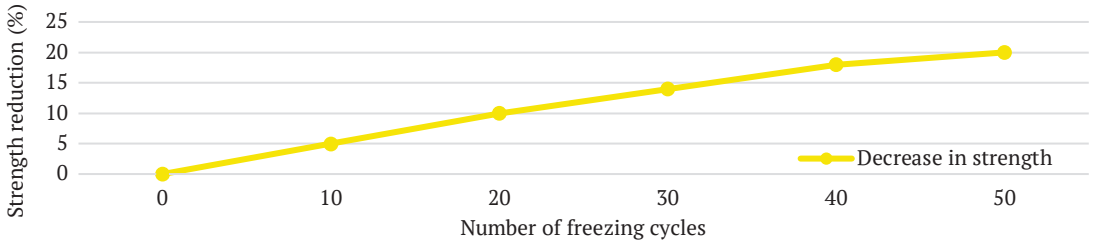

Figure 1. Correlation between number of freeze-thaw cycles and compressive strength reduction
Source: compiled by the authors

As shown in Figure 1, the decrease in travertine strength after freeze-thaw cycling was distinctly progressive. Samples with higher initial porosity showed a significantly greater percentage loss in mechanical strength compared to less porous counterparts. A clear trend is observed: as the number of freeze-thaw cycles increases, the deterioration of mechanical properties becomes more pronounced (Ermolaev *et al.*, 2017). This confirms that travertine's internal structure is prone to damage due to water expansion when freezing, leading to the accumulation of microcracks and a loss of structural integrity. These dependencies underscore the importance of assessing the physical structure of travertine in advance before using it in constructions exposed to temperature variations, as well as the need to apply protective measures to improve the stone's frost resistance.

The analysis of experimental data also allowed for the assessment of travertine's water absorption capacity and its impact on material durability in comparison with other natural stones – namely granite and marble. The goal of this research stage was to determine the relationship between porosity, moisture absorption capacity, and resistance to environmental influences characteristic of the Kyrgyz Republic's climate. Water absorption data are summarised in Table 3, which presents average values for travertine, granite, and marble.

Table 3. Water absorption of travertine compared to granite and marble

Material	Water absorption (%)	Compressive strength (MPa)
Travertine	10-15	45-55
Granite	0.05-0.4	120-250
Marble	0.1-0.5	70-150

Source: compiled by the authors based on G. Sarıışık *et al*. (2016)

As shown in Table 3, travertine significantly exceeds granite and marble in water absorption but falls considerably short in terms of strength. Travertine's porous structure accounts for its high moisture retention, leading to strength reduction, crack formation from water freezing within the pores, and a heightened risk of chemical degradation due to salt crystallisation (Adjamskiy *et al*., 2022). It was demonstrated that granite has a compressive strength of 120-250 MPa with water absorption of 0.05-0.4%, and marble – 70-150 MPa with water absorption of 0.1-0.5%. By comparison, travertine demonstrated a compressive strength of 45-55 MPa and water absorption of 10-15%. These findings confirm the need for additional processing of travertine to reduce its water absorption and improve resistance to environmental exposure. Statistical analysis confirmed a high degree of positive correlation between porosity and water absorption of travertine (correlation coefficient $r = 0.91$). This indicates that the higher the porosity, the greater the material's moisture retention capacity, which negatively affects its durability. Figure 2 illustrates the relationship between water absorption level and expected material durability.

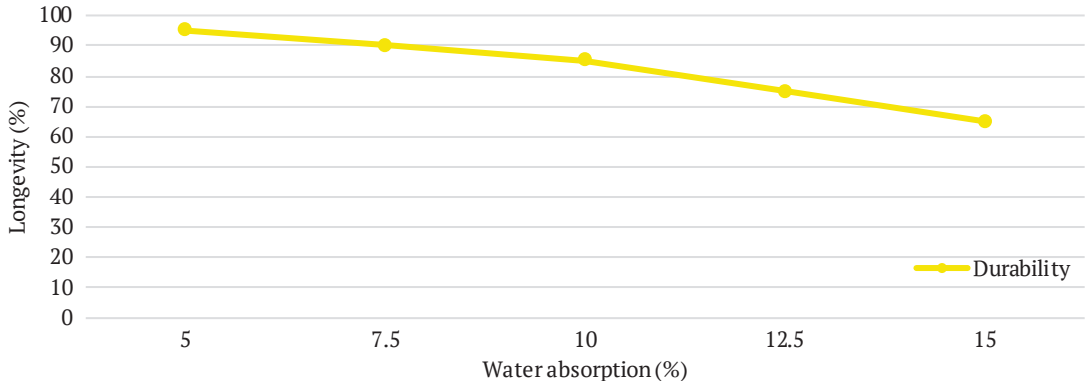

Figure 2. Influence of water absorption level on durability

Source: compiled by the authors

Figure 2 clearly illustrates that as the level of water absorption increases, there is a distinct trend toward a reduction in the durability of travertine. Based on the experimental data, it is evident that samples with water absorption above 12% exhibit accelerated loss of strength and decreased resistance to external climatic influences. This confirms the necessity of pre-treating the travertine surface with hydrophobic agents or by polishing, which significantly reduces moisture penetration into the material's structure, lowers the risk of microcrack formation, and increases the overall service life of the stone when used for façade cladding, interior finishing, and other architectural applications under variable temperature and humidity conditions. Abrasion tests revealed that untreated travertine samples had higher wear coefficients, ranging on average from 1.0 to 1.2 mm, while treated surfaces (polished and ground) showed significantly better results, with abrasion coefficients within the range of 0.5-0.7 mm. These findings confirm that surface pre-treatment can significantly improve the material's resistance to abrasive stresses. The study established that the difference between average abrasion coefficients was statistically significant at the $p < 0.05$ level, confirming the effectiveness of surface treatment of travertine. The results are summarised in Table 4.

Table 4. Abrasion coefficients of the tested samples

Sample No.	Place of birth	Surface treatment	Abrasion coefficient (mm)
1	Kyzyl-Tuu	Untreated	1.2
2	Kyzyl-Tuu	Polished	0.7
3	Kyzyl-Tuu	Ground	0.6
4	Suliukta	Untreated	1
5	Suliukta	Polished	0.5
6	Suliukta	Ground	0.6

Source: compiled by the authors

As shown in Table 4, untreated travertine samples from both Kyzyl-Tuu and Suliukta exhibited the highest abrasion coefficients – 1.2 mm and 1.0 mm, respectively. In contrast, the samples that underwent polishing and grinding showed much better performance, with abrasion coefficients reduced to 0.5-0.7 mm. This indicates that surface treatment significantly increases the wear resistance of travertine by reducing the rate of material degradation under abrasive stress. The differences between treated and untreated samples were statistically significant, confirming the advisability of polishing or grinding to improve the operational durability of architectural elements made from travertine. Figure 3 presents the dynamics of mass loss during abrasive testing, visually confirming the benefits of surface pre-treatment.

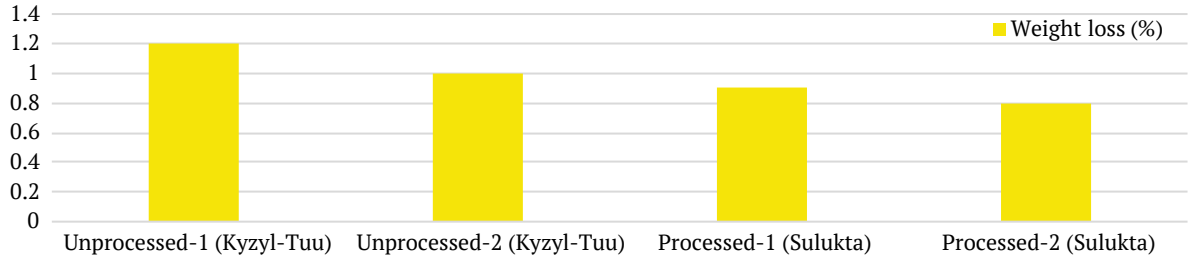

Figure 3. Dynamics of mass loss in travertine

Source: compiled by the authors

As can be seen from Figure 3, untreated travertine samples lost an average of 1.2 mm of mass during abrasion testing, whereas samples treated with hydrophobic agents showed a reduced abrasion loss of 0.8 mm. This means that the treatment reduced the mass loss by 33%. Thus, surface pre-treatment significantly enhances the wear resistance of travertine, slowing mechanical degradation and extending the material's service life under intensive use. Tests also assessed changes in the colour characteristics of travertine under ultraviolet (UV) radiation in the Atlas Suntest CPS+ (USA) climatic chamber. The data processing showed that the average decrease in colour brightness was 8.3%, with a variance between samples not exceeding 1.2%, indicating a high level of repeatability. The greatest colour change was observed in untreated samples, while those treated with hydrophobic and protective coatings showed a much lower degree of fading. The results of UV exposure tests are summarised in Table 5.

Table 5. Colour change of samples after ultraviolet (UV) radiation tests

Sample No.	Place of birth	Treatment type	Colour change (%)
1	Kyzyl-Tuu	Untreated	12
2	Kyzyl-Tuu	Hydrophobised	8
3	Kyzyl-Tuu	Polished	5
4	Suliukta	Untreated	11
5	Suliukta	Hydrophobised	7
6	Suliukta	Polished	5

Source: compiled by the authors

As shown in Table 5, the most significant decrease in colour brightness was observed in untreated samples from the Kyzyl-Tuu and Suliukta deposits, with losses of 12% and 11%, respectively. These findings highlight the high sensitivity of exposed travertine surfaces to photochemical processes caused by UV radiation. In contrast, the hydrophobised samples showed much lower colour change – 8% for Kyzyl-Tuu and 7% for Sulyikta – confirming the effectiveness of hydrophobic agents as protective barriers that reduce UV penetration and slow the degradation of the stone's mineral structure. The best results were observed in polished samples, where colour brightness decreased by only 5% for both deposits. This is explained by the lower surface roughness of polished travertine, which results in fewer active sites for UV absorption. Thus, polishing not only enhances the aesthetic qualities of the material but also significantly increases its resistance to photodegradation (Tagybayev *et al.*, 2023). The obtained results demonstrate that applying additional surface treatment methods can substantially delay the degradation of travertine's decorative properties when exposed to intense solar radiation – an essential factor for construction and finishing work in high-insolation regions. Figure 4 shows that the decrease in travertine colour brightness is proportional to the duration of UV exposure.

As shown in Figure 4, travertine colour brightness gradually decreased with increased UV exposure time. The most pronounced fading was observed in untreated samples, clearly confirming their high vulnerability to solar radiation. Samples that were polished or treated with hydrophobic agents showed significantly lower brightness loss: the colour degradation curves were noticeably

flatter compared to those of untreated samples. These data confirm the effectiveness of protective treatments in enhancing travertine's resistance to photodegradation. Thus, applying hydrophobic treatments and polishing can substantially extend the lifespan of the material's decorative properties under solar exposure. The effectiveness of protective treatments was evaluated based on laboratory experiments that analysed changes in water absorption and surface roughness after various technologies were applied. Calculations confirmed that hydrophobic impregnation and grinding-polishing significantly improve the material's operational performance. Table 6 presents comparative water absorption data for untreated, hydrophobised, and polished samples.

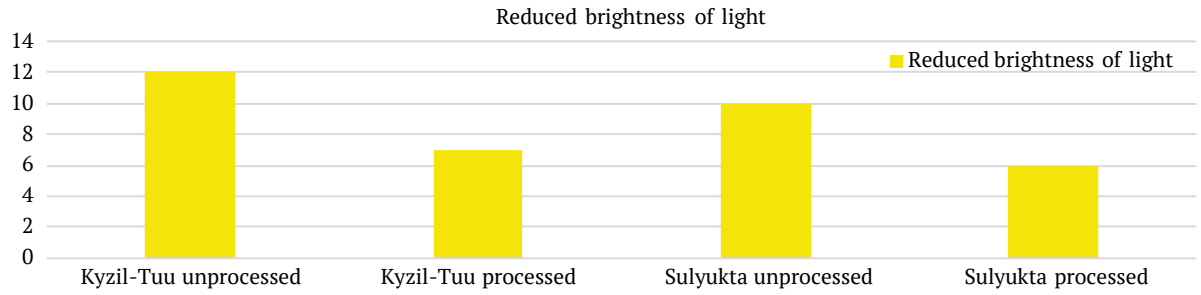

Figure 4. Correlation between colour brightness loss and UV exposure time
Source: compiled by the authors

Table 6. Comparison of water absorption after different treatments

Treatment type	Water absorption (%)	Reduction in water absorption (%)
Untreated	15.0	0
Hydrophobised	7.5	50
Polished	10.0	30

Source: compiled by the authors

As shown in Table 6, different surface treatment methods had a substantial effect on travertine's water absorption. The most effective method was the use of hydrophobic impregnations, which reduced water absorption from the initial 12-15% to an average of 6-7.5%. Polishing also had a positive effect, reducing water absorption to 8-10%, which confirms the effectiveness of this treatment in enhancing the material's performance. Hydrophobic treatment reduced travertine's water absorption by an average of 50%, while polishing reduced it by approximately 30% compared to the baseline. MAE and RMSE values confirmed the stability of the improvements achieved. The MCD for the constructed models was 0.92, indicating a high degree of explained variance and reliability of the conclusions drawn.

The study concluded that travertine demonstrates sufficient strength for use in architectural structures, including façade cladding, decorative elements, and interior finishes. However, despite its good strength characteristics, the material remains prone to mechanical wear, especially under intensive use, which necessitates the application of protective coatings to enhance its durability. The high porosity of travertine leads to significant water absorption, particularly under sharp changes in temperature and humidity, which reduces strength and causes cracking due to water freezing in the pores (Marchuk, 2021). Therefore, hydrophobic agents that create an effective protective layer are recommended to improve water repellency.

Frost resistance tests confirmed a reduction in material strength during repeated freeze-thaw cycles, making it necessary to apply special surface coatings to reduce moisture penetration. The moderate wear resistance of the material requires the use of protective lacquers or impregnations to significantly extend the service life of products subject to heavy mechanical stress, such as flooring and staircases (Lapshyn & Yaroshenko, 2023). UV radiation causes a loss of brightness and colour saturation in travertine; thus, for preserving the aesthetic appearance of exterior elements, UV-resistant coatings are recommended to prevent photochemical damage to the stone's structure (Bilousova, 2023). To improve the performance of travertine under the climatic conditions of the Kyrgyz Republic, a comprehensive approach is recommended, including polishing, grinding, hydrophobisation, and the use of UV-resistant protective compounds, as well as regular maintenance and renewal of protective layers to ensure the longevity and preservation of the material's decorative properties.

DISCUSSION

In the course of this study, a comprehensive analysis was carried out on the physical and mechanical properties of travertine from the Kyzyl-Tuu and Sulyikta deposits in order to assess its suitability for use in decorative architectural elements. The obtained results revealed that travertine possesses high porosity and water absorption capacity, which negatively affect its frost resistance, strength, and overall durability. The observed characteristics of travertine are in good agreement with the findings of M. Özkul *et*

al. (2024), who emphasised the significant variability of travertine properties depending on the conditions of their formation. Similarly, M.Y. Çelik & M. Sert (2020) noted that natural stone materials such as marble and travertine require a comprehensive assessment of their physical and mechanical characteristics prior to architectural use. Following the data by G. Bozkaya *et al.* (2024), who highlighted the importance of the geochemical composition of carbonate rocks, it can be concluded that the mineralogical features of Kyrgyz travertine influence its porosity and water absorption. This fully aligns with the identified need in this study for additional treatment of travertine to enhance its resistance to external impacts.

The analysis of travertine performance under freeze-thaw conditions also support the conclusions of C. Aratman *et al.* (2020), who found that the textural features of travertine significantly affect its strength and durability under changing climatic conditions, especially in regions with extreme temperature fluctuations. Special attention in the current study was given to the influence of surface treatment on the material's wear resistance. The data on water absorption and strength degradation due to moisture exposure are consistent with the research by P. Santi *et al.* (2021), who highlighted the vulnerability of natural stone in high-humidity environments – typical for several regions – thus confirming the need for protective coatings to improve the material's longevity.

The results of abrasion and mechanical behaviour tests also correspond with the observations of A. Maričić *et al.* (2023), who pointed out the importance of preliminary treatment of natural stone for successful use in restoration projects and modern construction. Similarly, the present study confirmed that untreated travertine surfaces are more prone to mechanical damage, which necessitates the use of pre-treatment methods to extend the service life of the material. Furthermore, the influence of ultraviolet radiation on the decorative qualities of travertine is fully consistent with the findings of U.O. Usanmaz (2022), who studied the degradation of ancient Roman surfaces due to photochemical processes leading to mineral structure breakdown and loss of aesthetic properties. The necessity of using hydrophobic and UV-resistant coatings for travertine, as identified in this study, is also confirmed by the work of F. Fratini *et al.* (2022), which demonstrated the effectiveness of specialised protective measures in minimising the destructive effects of aggressive climatic factors on natural stone. In particular, the experiment showed that treated surfaces exhibited significantly less loss in colour brightness and strength compared to untreated samples. The study's recommendations for enhanced comprehensive protective treatment of travertine to improve its longevity are fully supported by the practical conclusions of S. Pescari *et al.* (2023), who emphasised the importance of selecting appropriate conservation technologies in restoring historical buildings and the necessity of considering material specifics to prevent accelerated deterioration in real-world conditions.

In addition, contemporary research underlines the necessity of adapting natural stones to meet new architectural requirements. G. Yıldırım & N. Erdoğan (2024) stressed the growing interest in using natural stone and marble in modern architectural projects, which confirms the relevance of the study's recommendations on using travertine in decorative elements, provided modern treatment methods are applied. Robotic technologies in construction, as shown by M. Alabbasi *et al.* (2023), offer promising opportunities for more precise processing of materials, including stone, thus improving quality and durability in architectural applications. The use of 3D printing technologies for creating architectural elements demonstrates the potential of integrating automated processing methods for travertine to enhance surface quality and optimise production processes, thereby significantly improving the material's performance characteristics (Tasán Cruz *et al.*, 2024; Xue & Bulhakova, 2024). Research by C. Zhang *et al.* (2024) in the field of generative design and structural optimisation shows that the advancement of digital technologies enables more efficient use of natural materials in complex architectural compositions. This aligns with the recommendation to precisely prepare travertine based on its physical and mechanical properties, enhancing its suitability for high-load and aesthetically demanding architectural solutions. The work by H. Wang *et al.* (2021) on generative design methods in construction systems further highlights the importance of new engineering approaches to designing and utilising natural stones in architecture, thereby reinforcing the significance of integrating processing technologies for travertine to improve its performance and resistance to external influences. Such innovative approaches open new possibilities for using travertine in construction and restoration projects, especially under variable climate conditions (Deshko *et al.*, 2024).

E. Yıldırım (2022) demonstrated that topological optimisation of architectural structures can maximise the efficient use of building materials, which is particularly relevant for travertine, given its physical and mechanical limitations. Research by W. Xiaojian & Y. Yuewen (2021) highlights the importance of modernising construction methods in the context of contemporary challenges, which corresponds to the need for enhancing the treatment and protection of travertine to extend its service life under variable climatic loads. The study by M. Attenni *et al.* (2022) on modelling historical structures using Heritage Building Information Modelling (HBIM) emphasises the importance of preserving the properties of natural materials in digital environments. This opens the prospect for digital documentation of travertine structures to enable ongoing condition monitoring. K.G.A.U. Samarakoon *et al.* (2023) provided a review of modern quarrying methods for cladding stone, noting the importance of environmentally sustainable technologies, which is directly related to the need for sustainable use of travertine resources in the Kyrgyz Republic. The study by R. Nadoomi *et al.* (2023) on regional building materials

in hot and humid climates emphasises the importance of local adaptation of technologies, which supports the conclusion on the need for special travertine treatments for use in continental climates with wide temperature and humidity ranges. G. Duarte *et al.* (2021), in their study on 3D printing methods based on historical structures, underline that the use of traditional materials such as stone must be combined with modern design and construction technologies. This once again confirms that adapting travertine treatment methods is strategically important for expanding the scope of its application.

Thus, the study's findings are fully aligned with current global scientific trends, demonstrating the necessity of a comprehensive approach to assessing, processing, and using travertine in contemporary architectural projects. The established relationship between the material's physical and mechanical properties and its operational performance highlights the importance of preliminary raw material diagnostics, optimisation of surface treatment methods, application of protective technologies such as hydrophobisation and polishing, and consideration of the climatic specifics of the region of application. In the context of rapid developments in digital design, additive technologies, and sustainable construction, the role of natural stone, particularly travertine, is increasing significantly. Therefore, integrating modern engineering solutions with traditional materials opens new prospects for improving the durability, aesthetic value, and environmental sustainability of architectural structures.

CONCLUSIONS

The comprehensive study of the physical and mechanical properties of travertine from the Kyzyl-Tuu and Sulyikta deposits in the Kyrgyz Republic has made it possible to establish important patterns in its behaviour under various operational conditions. The analysis of the material's baseline properties showed that the density of travertine ranges from 1,850 to 2,450 kg/m^3, and porosity from 12% to 22%, with water absorption levels between 10-15%. A clear correlation was identified between increased porosity and higher moisture retention, which directly impacts the reduction of strength characteristics. Frost resistance tests revealed that after 50 freeze-thaw cycles, the strength of travertine decreases by 16-20%, especially in samples with high initial porosity. This emphasises the need for preliminary protective measures to ensure the stone's effective use in conditions of temperature fluctuations. Statistical analysis confirmed a strong correlation between porosity and water absorption (r = 0.91), making water absorption a reliable indicator of the material's potential durability. Compared to granite and marble, travertine demonstrated a significantly greater tendency to absorb moisture, necessitating special processing approaches.

Abrasion tests showed that polishing and grinding reduced the abrasion coefficient by an average of 40-50%, significantly improving wear resistance. It was also found that under ultraviolet radiation, untreated travertine samples lost up to 12% of colour brightness, whereas polished and hydrophobised samples showed reduced colour loss (5-8%), confirming the effectiveness of protective treatments. Analysis of water absorption dynamics demonstrated that hydrophobic treatments reduced travertine's moisture absorption by an average of 50%, while polishing reduced it by 30%. High values of the multiple determination coefficient (MCD = 0.92) and low MAE and RMSE values confirm the reliability of the models developed and the stability of the improvements achieved.The data obtained in the study confirm that travertine is a promising material for use in decorative and structural elements such as columns and arches; however, its durability requires the application of additional protective measures. It is important to continue further research in the development of new hydrophobisation compounds and frost resistance enhancers, the optimisation of surface treatment technologies, the assessment of environmental safety in stone extraction and processing methods, and the study of how various climatic conditions affect travertine's durability. Advancing these directions will expand the applications of travertine in construction, increase its resistance to atmospheric influences, and ensure longer service life of architectural structures.

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Оптимізація складу та властивостей декоративних колон та арок з використанням травертину (черепашника)

Анотація. Необхідність підвищення довговічності та естетичної стійкості декоративних архітектурних елементів в умовах кліматичних особливостей Киргизької Республіки обумовлює високу актуальність дослідження властивостей природних будівельних матеріалів, таких як травертин. Метою даної роботи був аналіз фізичних та механічних характеристик травертину та оптимізація його властивостей для ефективного використання у створенні декоративних колон та арок. У процесі дослідження застосовувалися комплексні лабораторні методи, включаючи випробування на міцність при стисканні, водопоглинання, стирання, морозостійкість, а також стійкість до ультрафіолетового випромінювання. В результаті експериментів було досліджено поведінку травертину в умовах змінної вологості та температурних коливань; встановлено, що матеріал має міцність на стиск 45-55 МПа, але при цьому демонструє водопоглинання до 10-15 %, що свідчить про його пористу структуру та необхідність додаткового захисту. Було виявлено, що коефіцієнт стирання варіюється від 0,8 до 1,2 мм, а характеристики міцності знижуються на 15-20 % після 50 циклів заморожування і відтавання. Проведено аналіз впливу гідрофобних та полімерних просочень, який показав дворазове зниження водопоглинання та підвищення морозостійкості матеріалу. Також узагальнено дані про зниження декоративних якостей травертину під дією ультрафіолетового випромінювання та запропоновано технологічні рішення для їх збереження. Практична цінність роботи полягає у розробці рекомендацій щодо обробки травертину для підвищення його експлуатаційних характеристик, що може бути застосовано архітекторами, проектувальниками, реставраторами та спеціалістами будівельної галузі при проектуванні будівель та споруд в умовах різко континентального клімату Киргизстану

Ключові слова: декоративні архітектурні елементи; фізико-механічні властивості; підвищення довговічності матеріалів; будівельні матеріали і клімат

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Use of modular technologies for the construction of low-rise housing in Kazakhstan

Abstract. The study aimed to develop an architectural model of point modular reconstruction focused on sustainable renovation of residential neighbourhoods, incorporating international standards of environmental and social efficiency, as well as the specifics of dense urban development in the southern regions of Kazakhstan. Based on architectural and planning analysis, urban planning expertise, assessment of regulatory applicability, as well as content analysis and SWOT analysis, the article provides a comprehensive assessment of the potential of modular housing and integration of eco-agro-architectural solutions into the living environment of the southern regions of Kazakhstan. An integrative model was developed for the point transformation of outdated neighbourhoods using modular construction, which can be implemented without resettling residents and with minimal time, financial and social costs. The structure of the model includes superstructure blocks erected on solid buildings to expand the housing stock; plug-in modular sections placed in inter-building spaces to compact and diversify the development; and community cores adapted to

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local needs. The decisions are based on the results of a survey of Almaty's districts and accommodate the region's climatic, demographic and regulatory characteristics. The study addressed the integration of eco-agro-architecture elements such as greenhouse modules, agro-platforms, vertical gardening and courtyard composting stations into the structure of residential development. The calculations and analysis demonstrated that the use of these solutions can reduce the heat load on buildings by up to 25%, increase the greening factor by up to 25%, and reduce the conditional carbon footprint by 18% per quarter. In addition, such elements contribute to the development of self-sufficient micro-communities, activating local urban agriculture and involving residents in shaping the environment. This strengthens social cohesion and expands the functional use of intra-quarter spaces. The presented model complies with the norms of the Republic of Kazakhstan and international guidelines for sustainable development, rethinking the local space as a multi-level ecosystem with recreational, social and agricultural functions

Keywords: frame-modular construction; eco-agro-architecture; energy efficiency; sustainable development; spot reconstruction

INTRODUCTION

The research relevance is determined by the growing need of the Republic of Kazakhstan to transform approaches to housing construction, especially in the context of growing urbanisation, seismic activity in the southern regions, climate variability and a shortage of energy-efficient and affordable housing. The modernisation of the urban environment, especially in megacities such as Almaty, is leading to a growing interest in low-rise prefabricated construction technologies based on the principles of modularity, structural flexibility and industrial production. Of particular importance is the integration of environmentally friendly solutions, including eco-agro-architecture and the reconstruction of local spaces, into the structure of existing neighbourhoods.

Recent studies highlight the growing need to rethink approaches to housing construction in Kazakhstan, especially in the context of accelerated urbanisation, high seismic activity in the southern regions and climate challenges associated with temperature changes and wind loads (Urdabayev *et al.*, 2024). In these conditions, traditional forms of mass housing construction are losing their effectiveness and need to be replaced with more adaptive, faster-erecting and energy-efficient solutions. However, there are significant gaps in the existing scientific and design literature due to insufficient study of the use of modular technologies in the southern climatic zones of Kazakhstan, and the possibility of their integration into the renovation of the old housing stock, including the use of ecological and agro-oriented components of the urban environment, is poorly covered. Thus, A.B. Kurmanalina & Z.U. Dzhubalieva (2025) highlighted significant imbalances between supply and demand in the construction industry, emphasising the need to move to industrialised technologies to increase housing commissioning. N.A. Biryukova & G.B. Pestunova (2022) highlighted the problem of systematically unfinished construction projects, highlighting the need for universal and quickly assembled architectural solutions. G. Karabayev & S. Mamedov (2024) highlighted the visual uniformity of residential areas caused by a standardised approach to architecture and emphasised the need for expressive design solutions that can revitalise the urban environment. D.T. Mukaev *et al.* (2023) emphasised institutional barriers to affordable and quality housing. Despite the importance of these aspects, most of these studies are mainly descriptive and do not contain full-fledged architectural models or practice-oriented recommendations adapted to local specifics. Some elaboration of the modular theme in the Kazakh context was presented by D. Tsygulev & R. Sabitov (2020) in an analysis of the use of modular housing in the northern regions of the country. However, the study lacks an analysis of the applicability of these technologies to the southern regions, where the requirements for earthquake resistance, energy efficiency and social and planning flexibility are much higher. In addition, the study by M. Eynullayeva (2023) on the evolution of residential architecture in Baku addressed the issue in a broader post-Soviet context, but it focuses on multi-storey formats and does not cover the specifics of low-rise and transformable housing.

International work has partially filled these gaps and offers both technological and methodological solutions. H. Altan & B. Ozarisoy (2022) highlighted the importance of structural adaptation of modular systems to the climatic conditions of the region, including thermal insulation and resistance to temperature fluctuations. D.F. Parracho *et al.* (2025) substantiated the benefits of digitalisation of modular construction, including BIM technologies, assembly automation and digital life cycle management of buildings, which is especially relevant for the modernisation of infrastructure-stressed areas. C. Tsz Wai *et al.* (2023) identified the difficulties of implementing the Modular Integrated Construction concept in dense urban areas, emphasising the need for interagency coordination and compliance with regulatory constraints. These conclusions directly resonate with the problems of Almaty, where the issue of rational use of limited urban space is acute. D. Aulia *et al.* (2023) examined the management aspects of modular residential complexes, highlighting the key conditions for efficiency: strict quality control of assembly, integration of project participants and construction risk management. These provisions are of particular value for the Kazakhstani context, where the implementation of modular projects is often

complicated by a fragmented regulatory framework and the lack of standardised coordination procedures. Thus, the literature analysis demonstrates both the relevance of the topic under study and the need to develop an applied architectural concept focused on the sustainable development of southern cities in Kazakhstan, incorporating their climatic, technological and social characteristics.

Thus, despite the existence of substantial research, most of it either focuses on general aspects or does not consider the regional specifics of Kazakhstan. The present study fills this gap by proposing an architectural concept that considers local climatic, technological and urban planning parameters, and by substantiating its applicability through a systematic interdisciplinary approach. The study aimed to develop an architectural concept for modular low-rise housing, including three areas: the architecture of prefabricated housing, the principles of introducing eco-agricultural facilities into the urban environment, and modern approaches to the renovation of residential neighbourhoods in Almaty based on sustainable, technological and human-centred design.

MATERIALS AND METHODS

This study was of a review and analytical nature. The main methods used were content analysis of scientific publications on modular and industrial construction covering the period from 2019 to 2025; comparative analysis of implemented architectural solutions in countries with similar natural and climatic conditions; case analysis of projects integrating energy-saving and transformable technologies; and regulatory and legal expertise of building standards and urban planning strategies of the Republic of Kazakhstan. The research was conducted in three areas: (1) architecture of prefabricated housing; (2) eco-agro-architecture and its integration into the urban fabric; (3) opportunities for modernisation and redevelopment of neighbourhoods with outdated housing stock, with the example of Almaty.

A SWOT analysis, which assessed the strengths, weaknesses, opportunities and threats of the three experimental models: block-modular, container and transformable, was conducted. The analysis covered the architectural, planning and technological parameters of the models, the applicability of modular solutions to different settlement scenarios (permanent and temporary housing), as well as compliance with regulatory requirements and infrastructure conditions. The empirical base included thermal modelling using EnergyPlus, wind and seismic load calculations, as well as data on typical low-rise building configurations in the southern regions of the country. This comprehensive approach enabled a comprehensive assessment of the potential of modular construction and the development of a concept suitable for large-scale application in Kazakhstan.

The methodological basis of the work included a comprehensive architectural and technological analysis of modern modular housing construction systems, with an emphasis on frame-modular technologies, including lightweight steel thin-walled structures. The study analysed in detail the key parameters determining the applicability of these technologies in Kazakhstan, namely: thermal insulation characteristics of building envelopes, specific construction cost per 1 m^2, average speed of module assembly on site, energy efficiency indicators under conditions of significant temperature fluctuations, logistical aspects of transporting elements to remote sites, as well as the degree of transformability and adaptability of interior spaces depending on user needs. This approach made it possible to objectively compare the functional and operational properties of various modular systems and determine their potential for use in mass low-rise construction in regions with different climatic and social conditions.

The study used data from standard architectural and construction solutions, technical passports of serial modular structures, as well as current building codes and regulations of the Republic of Kazakhstan. In particular, the regulatory framework was formed by the provisions of the Code of Rules of the Republic of Kazakhstan No. 3.02-101-2012 (2014), Code of Rules of the Republic of Kazakhstan No. 3.01-101-2013 (2014), Code of Rules of the Republic of Kazakhstan No. 1.02-106-2013 (2014), as well as the set of current regulatory documents recorded in the Architectural, Urban Planning and Construction Catalogue-1 (2025). These documents were used to compare the requirements for design, energy efficiency, building density and sustainability of structural systems. The analysis method included a comparison of the technical, economic and operational characteristics of modular and traditional forms of house construction, which made it possible to assess the applicability of frame-modular technologies in the southern and seismically active regions of Kazakhstan. All the above regulatory documents were considered when analysing and assessing the compliance of design solutions with the requirements set out in the construction and urban planning practice of the Republic of Kazakhstan. In the international context, strategic guidelines such as ISO 21931-1:2022 (2022), the New Leipzig Charter (European Parliament, 2020) and the European Green Deal (n.d.) initiative were analysed. Their relevance for Kazakhstan is determined by the need to integrate sustainable, resource-efficient and climate-adapted solutions into national architectural practice.

The empirical basis of the study included an analysis of the architectural and planning structure and urban planning characteristics of residential neighbourhoods in Almaty, mainly in areas with a pronounced level of physical and moral deterioration. The sample included five administrative districts: Auezovskiy, Alatauskiy, Turksybskiy, Bostandykskiy and Zhetysusskiy with different building typologies (from panel five-storey buildings to mixed neighbourhoods), number of storeys (from 2 to 9 floors), population density, state of engineering infrastructure and accessibility of social facilities. The parameters studied included building density, availability of free intra-quarter territories, transport connectivity, and proximity to utility and social hubs. The prospects of integrating modular

blocks for spot reconstruction with minimal interference with the existing structure, without relocating residents and without completely dismantling old buildings, were analysed. Such scenarios were seen as an alternative to major demolition, especially in areas with high levels of social vulnerability and limited budgetary resources.

The sources of data for the empirical base were official statistical materials of the Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2025), including information on population density, the degree of physical deterioration of the housing stock, provision of communal infrastructure and demographic characteristics of districts. Additionally, the study used the provisions of the Almaty City Development Programme until 2025 and Medium-Term Prospects until 2030 (2022), including data on the functional structure of buildings, the condition of the housing stock, and priority areas for modernisation and reconstruction of the urban environment. This approach justified the choice of representative objects for analysis and identify areas where the use of point modular solutions may be most appropriate from an urban planning and social point of view. In this study, two adapted methodologies were used to quantify the environmental impact of eco-agro platforms. The first methodology, proposed by R.S. Mandala & R.R. Nayaka (2025), is based on an integral index of environmental performance of urban micro-interventions and includes indicators of CO_2 emission reduction, increase in green cover ratio and temperature reduction at the level of the pedestrian zone due to local greening. This model was adapted to the conditions of the southern regions of Kazakhstan, considering climatic features, building density and demographic pressure. The second methodology, developed by W. Shahzad *et al*. (2024), can be used to assess the cumulative impact of green platforms on the microclimate of residential neighbourhoods, including the cooling effect of vegetation, reduced dust load and increased carbon sequestration capacity. Both techniques were integrated into a digital spatial analysis model used in the design modelling phase. Thus, the proposed methodology, based on a systematic analysis of architectural, engineering, urban planning and regulatory parameters, ensured the development of an architectural concept for modular low-rise housing focused on three interrelated areas: prefabricated housing, integration of eco-agricultural facilities into the living environment and scenarios for the targeted renovation of outdated neighbourhoods in Almaty.

RESULTS AND DISCUSSION

The development of modular and industrial house building in Kazakhstan is a strategically important vector for modernising the housing environment, especially in the context of a shortage of quality and affordable housing. Based on the analysis of technical and architectural solutions within the framework of frame-modular systems (including lightweight steel thin-walled structures), it was found that these technologies have several significant advantages over traditional capital forms of construction. First, such buildings are characterised by a high degree of prefabrication, which significantly reduces the time required to construct facilities and reduces dependence on seasonal fluctuations. The use of lightweight materials and prefabricated joints makes it possible to reduce the load on the foundation and increase the energy efficiency of the building envelope (Kuznetsov, 2024). Figure 1 shows the key elements of modular lightweight steel thin-walled structures.

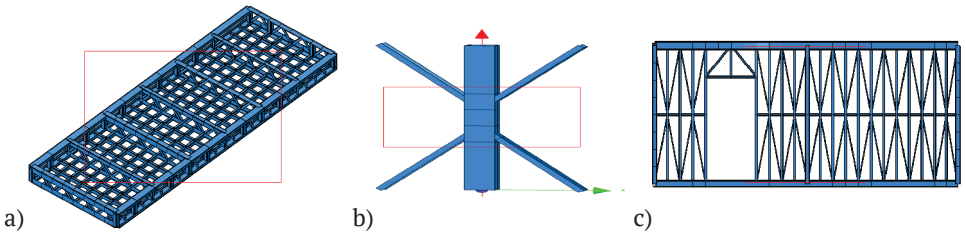

Figure 1. Modular designs
Notes: a) floor and cover panel; b) column (pillar); c) wall panel
Source: compiled by the authors

Following Figure 1, the modular elements of the lightweight steel thin-walled system are structured and highly standardised: the floors and roof panels (a) provide lightness and thermal insulation; the vertical load-bearing posts (b) form a rigid frame that is resistant to seismic loads; and the wall panels (c) enable the rapid formation of building envelopes with specified thermal and physical characteristics. This constructive logic simplifies assembly, accelerates the construction cycle and provides the ability to scale architectural solutions in dense urban areas. Thus, low-rise residential buildings constructed using prefabricated building technologies represent a promising trend in architecture that contributes to the creation of comfortable and affordable housing.

The integration of eco-agro-architectural solutions into the structure of the living environment of the southern regions of Kazakhstan is seen as a promising response to the challenges of urbanisation, the lack of green spaces and the need for sustainable development of high-density neighbourhoods. Modern urban concepts, based on the principles of green architecture, propose to include agricultural platforms, greenhouses, permaculture yards, as

well as local composting and recreation areas in the residential structure (Ismanzhanov *et al.*, 2012; Kolobanova & Tretiak, 2024). Figure 2 shows a scheme for integrating eco-agro-architectural solutions into the structure of a residential neighbourhood, based on the climatic and spatial characteristics of southern cities in Kazakhstan.

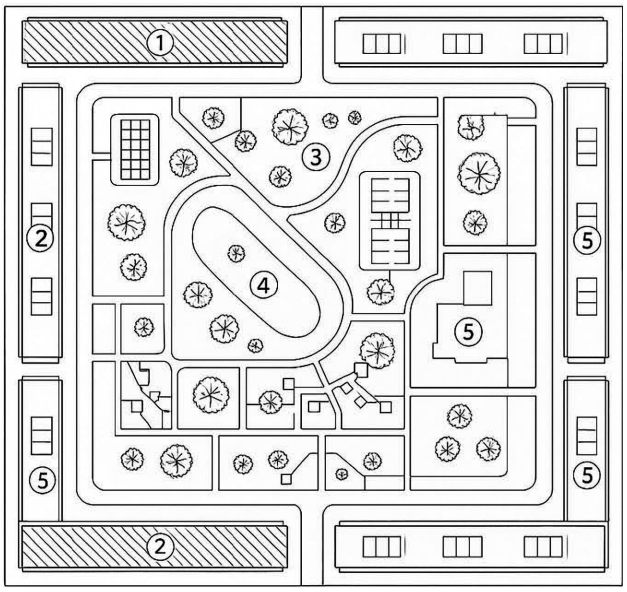

Figure 2. A model for incorporating agricultural platforms into the structure of a residential neighbourhood (based on the example of southern Kazakhstan)
Notes: 1 – greenhouse modules for local cultivation of vegetables and herbs; 2 – peripheral agricultural platforms; 3 – vertical landscaping and buffer green strips along pedestrian routes; 4 – central public green area with recreation, playgrounds and micro-ecosystems; 5 – social and public facilities
Source: compiled by the authors

Following Figure 2, the presented model for integrating agricultural platforms into the structure of a residential neighbourhood is based on the principles of sustainable planning and functional flexibility. Greenhouse modules (designation 1) are placed around the perimeter of the neighbourhood, oriented to maximise natural sunlight, especially in the southern and eastern sectors. These structures are designed for year-round cultivation of vegetables, herbs and seedlings, meeting the local food needs of residents and forming a closed ecosystem within the residential area. Open agricultural platforms (designation 2) are located along the inner boundaries of the neighbourhood, including zoned beds, prefabricated compost plots, vertical farming plots and elements for urban beekeeping. Their proximity to housing and convenient pedestrian accessibility help to engage residents in joint agricultural activities, strengthen the sense of local community and develop sustainable behaviour. The central part of the neighbourhood is dedicated to a green public area (designation 3), designed as a multifunctional space for walking, recreation and cultural and social activities. It includes shade canopies, areas with outdoor furniture, playgrounds, a stage for street events, and open spaces for temporary markets or educational events. A public area with multifunctional infrastructure (designation 4) includes jogging and cycling paths, sports fields, squares with quiet recreation areas and mini-amphitheatres. Zoning distinguishes between active and passive scenarios of territory use and adapts it to the needs of different age and social groups. The perimeter and central façades of the residential buildings (designation 5) are complemented by vertical landscaping using living walls, planters and guides for climbing plants. This solution reduces the level of heat radiation from the walls, helps to retain moisture in the atmosphere of the neighbourhood and creates an expressive architectural appearance.

To assess the environmental effect of the introduction of eco-agro platforms in the living environment, key indicators reflecting the impact of local greening on the microclimate and environmental quality of the urban environment were calculated. The analysis found that the introduction of the platforms resulted in an increase in green surfaces per capita, a decrease in summer air temperature by 1.8-2.4°C, an increase in stormwater retention by 12-18%, and a significant reduction in the concentration of fine particulate matter PM2.5. Taken together, these changes confirm the positive impact of eco-agricultural technologies on the sustainability and environmental adaptability of urban residential development in the southern regions of Kazakhstan. Figure 3 shows a bar chart visualising the key environmental effects of integrating agri-platforms into the structure of residential neighbourhoods in the southern regions of Kazakhstan. All values have been adjusted for building density, insolation regime and climatic parameters of the Almaty districts covered by the study.

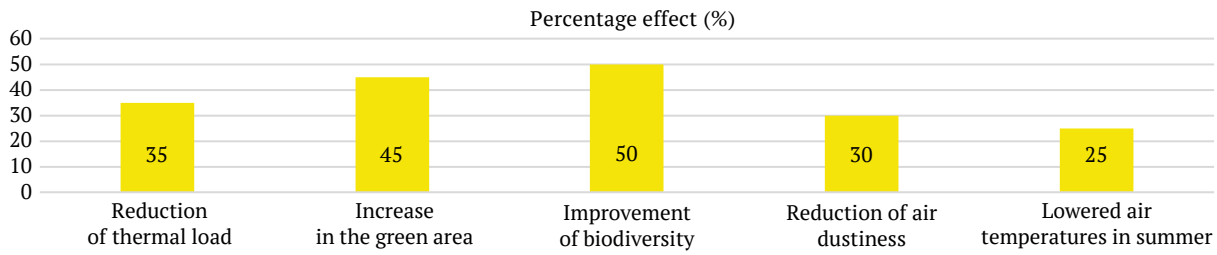

Figure 3. Diagram of the estimated environmental effect of introducing eco-agro platforms into the living environment
Source: calculated and adapted based on materials of R.S. Mandala & R.R. Nayaka (2025) and W. Shahzad *et al.* (2024)

According to the calculations, the introduction of eco-agro-modules can reduce the heat load on buildings by up to 25%, increase the level of local biodiversity by 40%, reduce the carbon footprint by 18% and cover up to 12% of the residents' needs for fresh produce through the greenhouse sector. Such a comprehensive effect demonstrates the significant potential of agro-architectural solutions as a tool for creating a sustainable, environmentally friendly and self-sufficient urban environment. Thus, the introduction of eco-agro-architectural solutions into the residential fabric of southern cities of Kazakhstan can improve the environmental parameters of the environment, strengthen local social ties and form a sustainable, functionally rich and environmentally sensitive urban development model. The current state of the housing stock in several Almaty's neighbourhoods indicates the need for comprehensive reconstruction. The proposed model shown in Figure 2 involves the use of prefabricated modular structures that are assembled on vacant sites between existing buildings or added as superstructures on structurally suitable sites. This approach minimises social risks, does not require major resettlement of residents and provides an opportunity for a phased renewal of the living environment in a functioning neighbourhood. As part of the empirical part of the study, a comprehensive assessment "of the state of the housing stock in five administrative districts of Almaty was conducted, selected based on typical indicators of physical deterioration, building density and availability of free areas for spot reconstruction. The analysis included multi-apartment residential buildings of panel or block construction, built mainly during the period of mass industrialisation of housing (1960-1990). These buildings are characterised by limited load-bearing capacity, outdated layout solutions, low energy efficiency and a high degree of wear and tear on utilities. Typical features of such housing stock include the absence of lifts, similar two- and three-bedroom apartments, low levels of sound and heat insulation, and poor adaptability to the needs of people with reduced mobility. Assessment of the degree of obsolescence (poor functional condition of apartments, lack of modern infrastructure), overloading of engineering systems (deterioration of pipelines, unstable water disposal, power outages), and excessive occupancy density at the neighbourhood level were analysed. These parameters were used to formulate the initial constraints and requirements for modular architectural solutions that can be implemented without the complete dismantling of existing buildings. Table 1 shows the characteristics of the current state (2025) of the housing stock in several microdistricts of Almaty.

Table 1. Condition of housing stock in Almaty's neighbourhoods

Neighbourhood	Auzovskyi	Alatauskyi	Turksybskyi	Bostandykskyi	Zhetysuskyi
Main development period	1965-1985	1970-1990	1960-1980	1980-2000	1975-1990
Physical wear and tear (%)	65	55	70	40	60
Moral depreciation (%)	60	50	65	35	55
Depreciation of utility networks (%)	75	65	80	50	70
Excess density (%)	30	25	35	15	28
Main characteristics of the housing stock	5-storey panel houses of the 1-464 series, poor thermal insulation, lack of parking	Mixed development, partial absence of centralised water supply	Old block stock, dense development, lack of public spaces	Newer housing stock, some late 1990s housing estates, potential for extension	Panel series, problems with insolati on, poor condition of intra-quarterly

Source: compiled by the authors based on the Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2025)

Following Table 1, the condition of the housing stock in Almaty's neighbourhoods demonstrates a high degree of physical and moral deterioration, especially in areas dominated by 1960s-1980s buildings (Mukaev *et al.*, 2023). For example, in the Turksib and Auezovsky districts, physical deterioration rates reach 70% and 65%, respectively, which, combined with the high level of deterioration of utility networks (up to 80%), indicates the need for immediate modernisation measures. There is also a significant excess of the permissible population density of up to 35% above the norm, which provokes overloading of the communal and social infrastructure. Even in relatively newer areas, such as the Bostandyk district, there is up to 50% wear and tear on utilities. Taken together, these data underscore the urgency of moving to a targeted reconstruction using modern construction solutions aimed at extending the life cycle of residential neighbourhoods without the need for large-scale resettlement of residents. Considering the data on physical and moral deterioration of the housing stock in several districts of Almaty, as well as the regulatory possibilities of integrating new structural elements without the need for complete demolition of buildings, an adaptive design model of spot modular reconstruction was proposed. This model emphasised the gradual renewal of the living environment with minimal social risks and without the need to resettle residents.

The design solution is based on three types of modular elements, each of which performs a specific functional task in the structure of the residential neighbourhood. The first type is superstructure blocks, which are installed on solid existing buildings (primarily five-storey panel buildings) and increase living space while improving the energy

efficiency of the facilities through modern materials and technologies. The second type is inter-courtyard inserts. These are prefabricated modular sections placed in free areas between buildings. Their installation is possible without demolishing the existing buildings. Thanks to their connection to existing utility networks, such elements are easily integrated into the urban infrastructure and can serve as additional housing or social services. The third component is public cores. These are modular cultural and service facilities, such as coworking spaces, green rooms, mini-libraries or club spaces. Their implementation can activate courtyard life and the formation of a sustainable community of residents. Table 2 summarises the main characteristics of the model: installation time, number of storeys, energy-efficient technologies and flexible configuration, which enables project implementation without displacing residents and with minimal time and resources. The model is adapted to the conditions of existing neighbourhoods with high building density and physical deterioration of the housing stock.

Table 2. Characteristics of the point modular reconstruction model

Parameter	Characteristic
Types of modules	Superstructure blocks, inter-courtyard inserts, public cores
Installation time	15-20 days per site (based on the analysis of technical data sheets of serial lightweight steel thin-walled structures and completed Modular Integrated Construction cases in SEA and the EU)
Number of storeys	1-3 floors
Energy efficiency	Ventilated facades, solar panels, external insulation with mineral wool (data compared with EnergyPlus modelling and R.S. Mandala & R.R. Nayaka)
Infrastructure integration	Connecting to existing utility networks using modular adapters (based on cases from C. Tsz Wai *et al*.)
Flexible configuration	Adaptation to different densities and neighbourhood morphology; possible transformation of functional purpose depending on needs
Purpose of public modules	Coworking spaces, green rooms, libraries, and club spaces (identified through analysis of foreign examples and consumer surveys)

Source: compiled by the authors based on R.S. Mandala & R.R. Nayaka (2025), W. Shahzad *et al*. (2024), C. Tsz Wai *et al*. (2023)

Following Table 2, the proposed model of point modular reconstruction is focused on the flexible introduction of new architectural solutions into dense urban development without the need for mass resettlement of residents. The superstructure blocks can efficiently utilise the potential of existing five-storey buildings, increasing the usable area and energy efficiency without changing the parameters of the plots. Inter-courtyard inserts are implemented as autonomous prefabricated structures that can be connected to existing utility networks without the need to demolish buildings. This is particularly relevant for areas with worn-out utility infrastructure, where complete replacement of systems is impossible or costly. Public purpose modules (cores), in turn, form socially active spaces in courtyards, such as coworking spaces, libraries, and green rooms, and improve the quality of the urban environment. The key advantages of the model, as shown in Table 2, include a short assembly time (15-20 days), the possibility of individual configuration (1-3 floors), energy-efficient facade and engineering solutions, and adaptability to different types of neighbourhood development. Thus, the model ensures not only technical but also social sustainability of the residential neighbourhood renovation process.

The proposed model has several operational and technical, and economic advantages. Firstly, the installation of the modules takes only 15-20 days per site, which significantly reduces the construction time. Secondly, the configuration can be adapted to the specific conditions of the site from one-storey to three-storey blocks. Thirdly, energy-efficient solutions such as ventilated facades, solar panels, and multi-layer thermal insulation are used. Lastly, the design flexibility enables integration into neighbourhoods of different densities and morphologies, making the model versatile and scalable.

The proposed model of point modular reconstruction was subjected to a comprehensive assessment for compliance with the current urban planning and construction standards of the Republic of Kazakhstan. The main regulatory documents, with which the design solutions were checked were, are used in the framework of urban development regulation in Almaty. The comparative analysis showed that the design parameters of the modular reconstruction meet the main requirements of the regulations in terms of such criteria as building density, permissible height, sanitary and fire protection setbacks, as well as the level of landscaping and engineering integration. The installed modules do not exceed the maximum height of 12 m (up to 3 floors), ensure safe distances to existing buildings, do not violate insolation and sanitary zones, and integrating into existing utilities without causing overloads. Special attention is paid to the criteria of greenery and the creation of social spaces. The standards provide for at least 15-20% of the green area within a quarter. The project proposes a system of vertical and courtyard gardening, as well as the integration of agricultural platforms, which not only meets the requirements but also enhances the environmental effect of the model. Table 3 provides a systematic comparison of key design solutions with the regulatory criteria set out in the Code of Regulations of the Republic of Kazakhstan.

Table 3. Compliance of design solutions with the key provisions of the Code of Regulations of the Republic of Kazakhstan

Criteria	Regulatory requirements (Kazakhstan's JV)	Project model parameters	Compliance	Regulatory document
Maximum module height	Up to 12 m (3 floors)	9-11 m (2-3 floors)	Yes	Code of Rules of the Republic of Kazakhstan No. 3.02-101-2012 (2014)
Minimum distance between buildings	No less than 15 m	15-18 m	Yes	Code of Rules of the Republic of Kazakhstan No. 3.01-101-2013 (2014)
Insolation and sanitary standards	Compliance with SNiP on insolation and sanitary zones	Insolation is preserved; zones are not disturbed	Yes	Code of Rules of the Republic of Kazakhstan No. 3.01-101-2013 (2014)
Percentage of green areas	No less than 15-20%	Up to 25% (including vertical planting)	Yes	Code of Rules of the Republic of Kazakhstan No. 3.01-101-2013 (2014)
Engineering network integration	Does not exceed the permissible loads on the network	Connection to existing networks with redundancy	Yes	Code of Rules of the Republic of Kazakhstan No. 1.02-106-2013 (2014)
Construction and installation time	Not regulated individually	15-20 days	Yes	Code of Rules of the Republic of Kazakhstan No. 1.02-106-2013 (2014)
Fire safety (setbacks, materials)	Compliance with standards for materials and escape routes	Non-combustible materials, fire retreats provided	Yes	Code of Rules of the Republic of Kazakhstan No. 3.02-101-2012 (2014); Architectural, Urban Planning and Construction Catalogue-1 (2025)

Source: compiled by the authors

Following Table 3, the proposed model of point modular reconstruction of residential neighbourhoods fully complies with the main regulatory provisions. In the face of global challenges, sustainable urban development is becoming a priority not only at the level of individual countries but also on the international agenda. The proposed model for the point modular reconstruction of residential neighbourhoods in Almaty was compared with the key international documents in the field of sustainable architecture (European Parliament, 2020; ISO 21931-1:2022, 2022; European Green Deal, n.d.). The ISO 21931-1:2022 (2022) standard regulates methods for assessing the environmental performance of construction projects throughout their entire life cycle. According to this document, energy efficiency, minimal environmental impact, resource recycling and reduction of greenhouse gas emissions are prioritised.

The architectural model developed as part of the study meets these criteria: it involves the use of lightweight prefabricated structures that can be recycled, fast assembly without heavy machinery, and the integration of solar panels and energy-efficient facade solutions. The New Leipzig Charter (European Parliament, 2020) emphasises the importance of inclusive urban development, the creation of shared public spaces and sustainable urban neighbourhoods. The proposed concept includes the placement of modular public cores (coworking spaces, green rooms, cultural venues), which correlate with the "city for all" principle, reduce social isolation and promote local identity in residential areas. The European Green Deal (n.d.) initiative aims to achieve climate neutrality, including through the transformation of the construction sector (Shahini & Shahini, 2025). The concept of point-to-point modular refurbishment supports these goals by offering solutions with reduced energy consumption, reduced construction waste and adaptation to dense urban development without the need to demolish existing buildings. Table 4 shows the key areas of integration of international sustainable architecture standards into urban planning practice in Kazakhstan.

Table 4. Mechanisms for integrating international standards

Direction of integration	International benchmark	Proposed measures for Kazakhstan
Environmentally friendly construction	ISO 21931-1:2022 (2022), European Green Deal (n.d.)	Use of eco-materials, secondary resources, and environmental certification
Energy efficiency	ISO 21931-1:2022 (2022)	Implementation of thermal insulation systems, solar panels and energy audits
Adaptability of design solutions	New Leipzig Charter (European Parliament, 2020), European Green Deal (n.d.)	Flexible modules, possibility of extensions and additions without demolition
Social inclusion and accessibility	New Leipzig Charter (European Parliament, 2020), European Green Deal (n.d.)	Creation of yard service modules, consideration of vulnerable groups
Sustainable urban planning	New Leipzig Charter (European Parliament, 2020), ISO 21931-1:2022 (2022)	Development of green areas, agricultural platforms and compact urban structure

Source: compiled by the authors

Following Table 4, the mechanisms for integrating international standards into architectural practice in Kazakhstan cover both technical and social areas. Mentioned practices can be effectively adapted to the national context, subject to regulatory modernisation and the introduction of innovative design solutions. In particular, the use of

environmentally certified materials and secondary resources, the development of energy efficiency systems (thermal insulation, solar panels, energy audits), and the flexibility of modular construction, which enables the creation of superstructures and extensions without demolition, are priorities (Iskenderov *et al.*, 2024). Another important aspect of social inclusiveness is the creation of courtyard service spaces, incorporating the needs of vulnerable groups. All this creates a sustainable urban environment and is in line with global guidelines for architectural and environmental development.

Based on the results, a comprehensive assessment of the potential of modular and industrial house building in the southern regions of the Republic of Kazakhstan, in the city of Almaty and the Almaty region, was conducted. Given the growing shortage of quality and affordable housing, especially in dense urban areas and deteriorating housing stock, modular technologies are an effective alternative to traditional construction. This form of construction is highly adaptable, technologically advanced and has the potential for rapid scaling, which is especially relevant for regions with high seismic activity and infrastructure overload. The SWOT analysis systematised the main advantages and limitations of modular construction and outlined its strategic prospects and potential risks. The results are summarised in Table 5.

Table 5. SWOT analysis of modular construction

Advantages	Disadvantages	Possibilities	Risks
Fast assembly and installation (15-20 days)	Insufficient regulatory framework	Solving the housing crisis in the regions	Institutional resistance to reform
High energy efficiency	Low level of trust among the population	Development of local production	Lack of funding for pilot projects
Flexibility of modular solutions	Limited number of certified suppliers	Sustainable construction in earthquake-prone areas	Difficulty of inclusion in master plans
Less stress on the infrastructure	Lack of qualified personnel	Integration of green and agricultural platforms	Formal approach to sustainability
Integration into dense development without resettlement	Underdeveloped secondary market for modules	Support through international initiatives	Import dependence of technologies

Source: compiled by the authors

Following Table 5, modular housing construction in the context of the southern regions of Kazakhstan demonstrates significant potential due to the combination of technological flexibility, energy efficiency and speed of implementation. The modular system, due to its high adaptability and energy efficiency, is a universal architectural and technological solution that can effectively respond to a wide range of housing needs (Khomyakov *et al.*, 2017). It ensures not only the efficiency and quality of construction but also enables flexible variation in the format of development from temporary emergency housing to capital apartment buildings with a long service life (Akbarova & Akbarli, 2023). This versatility makes modular construction particularly relevant for Kazakhstan in the context of the need to accelerate the modernisation of the housing stock and improve the sustainability of the urban environment.

At the same time, even with a convincing architectural and technological potential, the practical implementation of modular housing faces several substantial challenges (Cajamarca Dacto *et al.*, 2025). At the same time, there are also serious threats, such as institutional inertia, limited funding for pilot programmes, difficulties in integrating new architectural solutions into existing urban planning regulations, and the risk of superficially copying models without adapting them to the local context (Shvedchykova *et al.*, 2024). Thus, to fully unlock the potential, not only are architectural and engineering improvements needed, but also regulatory and legal modernisation. As shown in the analytical review by R.S. Mandala & R.R. Nayaka (2025), modern building technologies, in particular modular systems, demonstrate tangible advantages in terms of implementation time, cost and environmental sustainability. These characteristics are critically important for Kazakhstan, where the task of large-scale construction of affordable and energy-efficient housing in the context of the transition to a sustainable economy is urgent. The empirical data of W. Shahzad *et al.* (2024), obtained in the analysis of modular construction practices in New Zealand, indicated a comprehensive effect of the introduction of off-site technologies: reduction of construction cycles, minimisation of waste, and increase in productivity. However, at the same time, limitations were also noted that are typical for the Kazakhstani situation: a shortage of qualified contractors, gaps in certification, and regulatory unpreparedness for a new type of design solution. This confirms the need to include institutional reforms in the modular housing implementation model proposed in this study.

S. Khorshid *et al.* (2024) analysed the case of the United States, highlighting modular housing as a strategic response to the housing crisis due to its ability to be replicated, quickly adapted and standardised. The same characteristics reflect the goals of the current model under development, aimed at creating a sustainable architectural infrastructure in the rapidly developing regions of Kazakhstan. The viability of digital architectural solutions is confirmed by the example of 3D modular construction described by P. Jongvisuttisun *et al.* (2024) on the example of Thailand. The use of off-site fabrication and digital

manufacturing solutions ensured high assembly accuracy and structural stability while reducing costs. Given the similarity of climatic conditions and the need for low-cost solutions, these technologies can be adapted in the southern regions of Kazakhstan, especially in post-crisis and low-rise buildings. The innovative LGSF composite house building technology presented by P. Minde & M. Kulkarni (2025) has shown high sustainability and adaptability in climatically stressful regions of India. This technological flexibility is one of the basic architectural strategies for the eastern and mountainous regions of Kazakhstan, where strength, thermal stability and quick assembly are important. At the same time, as emphasised by A. Bello *et al*. (2024) emphasised that even the most advanced architectural solutions cannot be implemented effectively without institutional support. Their study, based on the example of developing countries, identified systemic barriers ranging from market unreadiness to the lack of regulatory frameworks and poor training. These challenges are fully consistent with the current study, which confirms the need for accompanying reform of the legal framework, development of professional education and stimulation of private demand for modular construction.

W. Ferdous *et al*. (2022) emphasised that the transformation of the construction industry is impossible without the introduction of modular technologies, as they provide for shorter construction times, reduced dependence on manual labour and increased flexibility of architectural solutions. These provisions are directly related to the tasks of accelerating the deployment of high-quality housing in Kazakhstan, where the issue of renovating the housing stock with limited resources is acute. The model of automated module placement proposed by Z. Fan *et al*. (2023) is based on the use of genetic algorithms and can significantly improve the accuracy of planning decisions. This technology can be implemented in the Kazakhstani context, especially in conditions of high building density and limited available land plots in large cities. The review by J. Jayawardana *et al*. (2025) of the social and economic aspects of modular construction sustainability emphasised its advantages at all stages of the building life cycle. This statement fully correlates with the presented concept of integrated sustainability, which is embedded in the architectural and planning model adapted to the conditions of Kazakhstan. M. Tenório *et al*. (2024) revealed the design features of multi-storey wooden modular buildings. This approach, which considers climatic and seismic characteristics, can be adapted to the conditions of the northern and mountainous regions of Kazakhstan, where the use of wood and lightweight eco-friendly structures will achieve a balance between strength and energy efficiency. The three-level modular grid developed by C. Liu *et al*. (2023) for industrial housing provides flexibility in the design of facilities in heterogeneous environments from megacities to peripheral areas. This approach echoes the concept of a transformable structure proposed in the study, which can adapt to different development scenarios. Y.W. Lim *et al*. (2022) highlighted the key role of logistical synchronisation in the implementation of modular projects. This observation is particularly relevant for Kazakhstani practice, where infrastructure constraints and supply volatility require clear planning of assembly processes and coordination of construction participants.

In the architectural concept of modular house building in Kazakhstan, technological aspects of installation and stability of structures in dense urban development are noteworthy. A. Zhu & W. Pan (2022) proposed an innovative system for planning crane equipment trajectories during the assembly of high-rise modular buildings, which can significantly improve the accuracy, safety and speed of installation work. Given the growing density of buildings in Kazakhstan's megacities, this experience can be adapted to improve the efficiency of construction logistics in limited areas. The problem of energy efficiency and sustainability of building materials is becoming particularly relevant in the context of the state's decarbonisation strategy. The study by W. Pan & Z. Zhang (2023) demonstrated the advantages of steel modular systems compared to concrete, including a smaller carbon footprint and better adaptability to urban environments. These findings support the focus of this project on the use of lightweight and sustainable materials in mass housing construction. E. Iacovidou *et al*. (2021) highlighted the importance of digital labelling of modular elements, which creates the basis for their reuse and the formation of a circular economy. Such a system can be integrated into the presented model of industrial modular construction, which will significantly reduce construction waste and increase production profitability.

The modelling results of B. Castillo Torres *et al*. (2025) demonstrated the effectiveness of structures with thin reinforced concrete walls and elastomeric insulation in seismic conditions. These data have practical implications for the southern regions of Kazakhstan, such as Almaty and Turkestan oblasts, where seismic resistance is a mandatory design element. H. Ma *et al*. (2025) proposed an innovative cross connection for modular steel buildings that increases resistance to dynamic and wind loads. Incorporating the continental climate of Kazakhstan with sharp temperature fluctuations and strong winds, this development can be implemented in projects in the steppe and mountainous regions of the country. G. Marrone *et al*. (2025), concerning the quick installation of plug-and-play façade systems, are particularly relevant for the renovation of the post-Soviet housing stock. The possibility of renovation without resettling residents makes such technologies an effective tool for modernising the urban environment in Almaty, Shymkent and other large cities. The system framework developed by A.H. Ali *et al*. (2024) covers all stages of the modular building life cycle from design to operation. Its application in the architectural practice of Kazakhstan will increase the transparency, manageability and technological reproducibility of the entire construction process. The study by K. Jaisankar & S. Gupta (2025) demonstrated

that the parameters of building shape, orientation and insolation level have a significant impact on the energy balance of buildings. These findings formed the basis for the development of the design criteria for this study, adapted to the climatic conditions of the southern regions of Kazakhstan, where passive architectural solutions with high levels of thermal insulation are becoming increasingly important. The facade strategies proposed by H. Kalwry & C. Atakara (2025) include the use of modern sunscreens and innovative materials that reduce energy consumption. Given the high solar activity in the south and west of Kazakhstan, such technologies can significantly improve the energy efficiency of modular housing and reduce the cost of cooling the premises in the summer.

Thus, the synthesis of modern scientific approaches and foreign practices in the field of modular house building demonstrates the high applicability of these solutions to the conditions of Kazakhstan, especially in the field of low-rise construction. Studies in the field of digital labelling, energy-efficient facade systems, earthquake-resistant connection units and architectural form optimisation confirm the feasibility of transitioning to industrialised, environmentally sustainable and adaptive structures. These conclusions are consistent with the objectives of accelerating the construction of high-quality and affordable housing in small towns, rural and suburban areas of Kazakhstan, where rapid assembly, energy efficiency and resistance to climatic stress are particularly important.

CONCLUSIONS

The study successfully developed the architectural concept of a modular low-rise housing model adapted to the conditions of the southern regions of Kazakhstan. The regulatory, architectural, planning and urban planning analysis made it possible to justify the choice of frame-modular technologies and adapt the design solutions to the specifics of the existing residential development in Almaty. The study confirmed that the development of modular and industrial house building in the southern regions of Kazakhstan, particularly the city of Almaty, is a priority area for modernising the living environment in the face of a shortage of affordable and high-quality housing.

Frame-modular construction technologies, including lightweight steel thin-walled structures, provide a high degree of prefabrication, energy efficiency, reduced installation time (15-20 days), reduced foundation load and the ability to integrate into dense urban development without resettling residents. This is particularly relevant in conditions of high seismic hazard, worn-out utility networks and overloaded urban infrastructure. The integration of eco-agro-architectural solutions such as greenhouse modules, agro-platforms, and vertical gardening provides a favourable microclimate, reduced heat load, increased biodiversity and strengthened local social ties. This model renders the living environment not only more environmentally friendly but also socially sustainable, correlating with the principles of green architecture.

The proposed model of point modular reconstruction, including superstructure blocks, inter-courtyard inserts and community cores, has proven to be compliant with regulations and feasible in the existing urban structure. Its advantages are flexibility, energy efficiency, the ability to connect to existing networks and minimisation of social risks. The SWOT analysis had a direct impact on the formation of the architectural model, which can be used to adapt the design solutions to the identified conditions. Based on the strengths, the design and technological parameters of the modules were refined: prefabricated frame solutions, energy-efficient envelopes and configurations that enable integration into existing buildings without resettlement were envisaged. In response to the identified weaknesses and threats, the model includes mechanisms for flexible phased implementation, the use of standardised elements that minimise design and installation risks, and a scenario for testing in a limited area. Incorporating institutional barriers and limited funding, the model provides for reduced construction costs through standardisation, modular logistics and phased implementation with the possibility of scaling.

Thus, unlocking the full potential of modular construction requires a systematic update of the regulatory framework, the introduction of educational programmes to train specialists, the development of domestic production of building modules and targeted government support. Only with an integrated approach can the architectural, technological and social benefits of modular solutions be fully realised, ensuring the transition to a sustainable, functional and inclusive urban environment in Kazakhstan. The limitation of this study is the lack of pilot testing of the proposed model in real conditions, as well as the limited empirical data on the performance of modular structures in the southern seismically active regions. Promising areas for further research include the development of scenarios for digital life cycle management of modular housing, modelling the behavioural and economic effects of spot renovation, and testing energy-efficient solutions at experimental sites.

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Використання модульних технологій для будівництва малоповерхового житла в Казахстані

Анотація. Мета цього дослідження – розробка архітектурної моделі точкової модульної реконструкції, орієнтованої на стійке оновлення житлових кварталів з урахуванням міжнародних стандартів екологічної та соціальної ефективності, а також специфіки щільної міської забудови південних регіонів Казахстану. На основі архітектурно-планувального аналізу, містобудівної експертизи, оцінювання нормативної застосовності, а також контент-аналізу і SWOT-аналізу в статті було здійснено комплексне оцінювання потенціалу модульного домобудівництва та інтеграції екоагроархітектурних рішень у житлове середовище південних регіонів Казахстану. Було сформовано інтегративну модель точкової трансформації застарілих мікрорайонів з використанням модульного будівництва, реалізація якої можлива без відселення мешканців і з мінімальними часовими, фінансовими та соціальними витратами. Структура моделі включає надбудовні блоки, що зводяться на міцних будівлях для розширення житлового фонду; вставні модульні секції, що розміщуються в міжкорпусних просторах для ущільнення та функціонального урізноманітнення забудови; а також громадські ядра, адаптовані до локальних потреб. Рішення базуються на результатах обстеження районів Алмати і враховують кліматичні, демографічні та нормативні особливості регіону. У дослідженні особливу увагу було приділено інтеграції елементів екоагроархітектури – тепличних модулів, агроплатформ, вертикального озеленення і дворикових компостних станцій – у структуру житлової забудови. Проведені розрахунки та аналіз показали, що застосування цих рішень дає змогу знизити теплове навантаження на будівлі до 25 %, збільшити коефіцієнт озеленення території до 25 %, а також скоротити умовний вуглецевий слід на 18 % у розрахунку на один квартал. Крім того, такі елементи сприяють розвитку мікроспільнот, що самозабезпечуються, активізуючи локальне міське землеробство і залучаючи мешканців до формування середовища. Це зміцнює соціальну згуртованість і розширює функціональне використання внутрішньоквартальних просторів. Представлена модель відповідає нормативам Республіки Казахстан і міжнародним орієнтирам сталого розвитку, переосмислюючи прибудинковий простір як багаторівневу екосистему з рекреаційними, громадськими та аграрними функціями

Ключові слова: каркасно-модульне будівництво; екоагроархітектура; енергоефективність; сталий розвиток; точкова реконструкція

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Architectural and artistic solution of the town hall in Buchach

Abstract. The town hall was not only the building of the city self-government body, which housed the city government but also a very important public architectural structure of the city, which performed an administrative function. Square in plan, but diverse in the form of completion and dimensions, building material, compositional, constructive, and plastic solutions, town halls were the main architectural and artistic accents of the market squares of Ukrainian cities. The article was devoted to the study of the construction history and artistic and compositional features of the unique town hall in Buchach, dated 1750-1751, which had survived to 2025 in its authentic form. The study of the architectural and artistic solution of the town hall in Buchach was a source of the aesthetic perception of the society of artistic values of a specific historical era. The history of the construction of the baroque town hall built according to the project of the outstanding architect Bernard Meretyn and the sculptor Johann Georg Pinzel, with the funds of the patron Mykolai Pototsky, was revealed. This highly artistic architectural building reflects the high level of skill and talent of the architect and sculptor of the Baroque era. The peculiarities of the use of decorative stone carvings and sculptural compositions on mythological subjects in the decoration of buildings in the late Baroque period were considered. The plastic treatment of mythological sculptural compositions on the parapet and on the pediment of the main facade of the town hall was analysed. As a result of atmospheric effects, the decor, and individual sculptures had suffered significant losses and require restoration work. Due to a lack of funds, restoration work had been stopped. The researched unique architectural object had a high artistic and artistic value and belongs not only to the artistic heritage of Ukraine but also to the world's cultural heritage

Keywords: architect B. Meretyn; sculptor I. Pinzel; planning; composition; decor

INTRODUCTION

The rich historical, architectural and artistic heritage of the city of Buchach (Ternopil region) was a significant part of the cultural heritage of Ukraine. Among the numerous architectural monuments of the small town of Buchach, which were organically inscribed in a unique landscape environment, the town hall stands out for its architectural

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and artistic solution, artistic qualities, which made a great aesthetic impression on the viewer. A town hall was a public building that was used in the Middle Ages to administer a city or municipality. It was a meeting place for local government representatives and community members. The town hall not only functioned as a centre of administration, but also played an important role in the social and public life of the community, reflecting the architectural style and civic pride of the Middle Ages. The study of the public administrative building in Buchach, which did not function according to its purpose, but was in the final stage of restoration, was relevant.

The unique monument, dated 1751 and preserved in an authentic state, was a true witness of the historical past, had a high historical and cultural value and was of scientific interest to researchers, art historians and scientists. The basis for the theoretical study of the town hall in Buchach was the analysis of research and scientific works of Ukrainian and worldwide architects, art critics, and scientists. Particular attention should be paid to the work of O. Popova (2021), who considered the history of the emergence and development of town hall architecture. L. Chen (2022), researching the stylistic features of Pinzel's sacred stone sculptures in Buchach, found common features with the plastic sculpture on the parapet of the town hall. The development of 20th-century town halls in Denmark, Sweden, the Netherlands, Great Britain, Norway, Italy, Finland, Japan, Canada, the United States, Iceland, Spain, and Switzerland was explored in book by J. Stewart (2019). Basic research of the town hall was carried out by P. Arkarapotiwong (2021). The adaptive reuse of city halls in Australia was explored in a dissertation by S. Yazdani Mehr & S. Wilkinson (2018). M. Folin & E. Svalduz (2024), studying the architecture of Italian town halls of the 14th-17th centuries, noted that town halls were considered an expression of local civic identity and had great cultural and original significance.

The purpose of the article was to reveal the history of the construction of a unique town hall in the city of Buchach, Ternopil region, to analyse the peculiarities of its compositional, artistic and plastic solution and to determine its place in the cultural heritage of Ukraine.

MATERIALS AND METHODS

The town hall in the city of Buchach, Ternopil region, was the best example of civil late baroque architecture not only in the Western region but in the whole of Ukraine. Its unique architectural and artistic solution aroused the interest of architects-researchers, art critics and scientists. In the process of scientific research of the architectural and artistic solution of the town hall in Buchach, general scientific (empirical – observation, description, theoretical – analysis, systematisation, comparison, generalisation) and special professional research methods (morphological (stylistic) analysis, field survey method, photo fixation method) were used). The visual inspection of the unique architectural monument carried out at the first stage of the study made it possible to determine the range of current problems of the phased study. The analysis of literary sources made it possible to determine the level of study of the object. The analysis of iconographic images from the Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.) made it possible to trace the general appearance and sculptural decor of the town hall as of 1927-1954, which changed, in particular, the form of the completion of the town hall altered after the restorations in 1988 and 2000. The artistic features of the architecture and decorative decoration of the investigated town hall were revealed by the method of art analysis. Based on the analysis of the artistic and plastic solutions of the town hall, it can be stated that its architecture was characteristic of the late Baroque style. The compositional analysis made it possible to reveal the three-dimensional architectural and structural structure of the town hall and reveal the regularities of its compositional solution. The stylistic analysis made it possible to study the individual features of the artistic solution of sculptural mythological scenes, the visual language of the facial expressions and body postures of the characters on the parapet and pediment of the building, and to establish the architectural and artistic value of the architectural work. On the basis of the conducted stylistic and compositional analysis, the theoretical part of the study of the sculptural compositions of the town hall was formed, which can become the basis for further practical restoration.

RESULTS AND DISCUSSION

The town hall was an important city administrative building designed to house the body of local self-government (local government) in the European countries of the Middle Ages (Tymofiienko, 2003). Usually, the town hall was built in the form of a compact square multi-story structure with a meeting hall, a balcony from which to address the people, and a high-tiered tower. It was located separately on the market square of the city. In Ukrainian cities, the town hall appeared in the 14th century mainly in Western Ukraine (Smoliy, 2012), while in Europe, town halls began to be built in the 12th century (the city of Rome in Italy (1144), the city of Cologne (1135) in Germany (1135)) (Popova, 2021).

Among the numerous architectural monuments of Ukraine, it was worth highlighting the building of the town hall in the city of Buchach, Ternopil region, which was unique in terms of its architectural, artistic and constructive solution. The city was located in a picturesque area above the banks of the Strypa River canyon. It was famous for a large number of architectural monuments, among which the filigree town hall stands out with its silhouette, dimensions and perfect proportions. Buchach Town Hall was located in the lower central part of the city on a small market square. It stands out among low-rise buildings with its dimensions, clear delineation of volumes, and plastic late-baroque expressiveness (Fig. 1). The town hall symbolises civic identity, acting as the third element of the triad that characterises the urban landscape. Town halls often became centres of urban sociability, reflecting the customs,

inclinations, and characteristics of the local ruling authorities, and therefore the prestigious decoration of the building was important (Folin & Svalduz, 2024).

Figure 1. Town hall in the urban planning environment of Buchach
Source: authors' photo (2019)

The town hall was built at the expense of the funder M. Pototsky in 1750-1751 (Voznytskyi, 2005) with a height of 53 metres, designed by the Lviv architect Bernard Meretin in the late baroque style (Syrotiuk, 2014). The height of the town hall without the baroque dome was 35 metres. The structure, built from local sandstone, had a pronounced vertical-centric composition, ending with a tower. A two-story tower rests on a powerful two-story cubic volume, which originally ended with an eighteen-metre-high spire, and now with a baroque dome. The square plan of the town hall was divided into 12 halls covered by cross vaults (Fig. 2). In the middle room there was a spiral stairwell, which led to the flat roof of the 2nd floor, which served as a viewing platform, from where incredible views of the city opened. The central room, in which the stairs were arranged, carried a tall two-story tower. In order for the tower to be proportional to the main volume, the architect made it more massive, expanding under the roof in the attic with the help of huge stone consoles. The corners of the tower were rounded, and the walls between them were concave inward and pierced with large arched windows to lighten the massif. The third tier of the clock tower, compared to the second, narrows to the size of a stairwell. In this way, the architect managed to create a tower-like volume of the town hall and harmoniously combine all three tiers into a single whole. The building had deep branched basements, which housed trade and warehouse premises. The city administration (magistrate) was located on the 2nd floor of the town hall, and shops and warehouses were located on the 1st floor. On the south side, the self-government rooms were located on the 1st floor, which was 2 m lower due to the sloping relief (Logvin, 1959). The building had deep ramified basements. The entrances to the basement rooms were decorated modestly and simply without decorative elements.

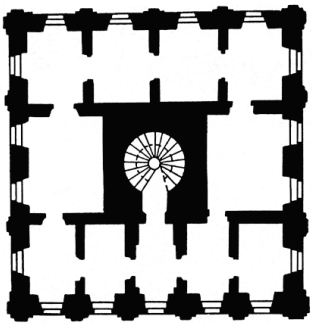

Figure 2. Plan of the 1st floor of the town hall in Buchach
Source: V. Vecherskyi (2021)

The desire of the city elite to lavishly decorate architectural buildings in the Baroque era led to the flourishing of monumental sculpture. Stone sculpture and ornamental decorative carvings in architectural details were the most common in the decoration of buildings in Ukrainian lands. Ornamental carvings were especially widely used in the decoration of window and door openings. (Yablonsky, 1995). Windows and doors were decorated with carved stone frames similar in composition, which were impressive with the richness of plastic ornamentation.

The town hall in Buchach was decorated with exquisite late-baroque plastic that enriches the main western facade (Figs. 3-4). The architect Meretyn, educated on the best European models, created an original compositionally perfect solution of the main facade, using an arsenal of artistic tools to create a unique work that had no analogues in the architecture of Ukraine. The decoration uses a synthesis of arts, where architecture and sculptural decor in the form of high-relief and round sculpture were organically combined (Tymofiienko, 2003). The facade was energetically divided in height by pilasters, ten caryatids in pairs support five balconies. Windows and doors were decorated with baroque stone frames. On its pediment there was a cartouche with the family coat of arms of the founder "Pylyava". Allegorical sculptures were placed on the parapet and pediment along the axis of the pilasters of the main facade: David kills Goliath, nearby – Themis, the goddess of justice, further – a Zaporozhian sitting and smoking a pipe, further – a peasant in chains and on the outermost pillar of the parapet – Hercules teared the lion's mouth open (Logvin, 1959). On the opposite side, Hercules slaying the Lernaean hydra and Neptune calming the raging sea were placed (Fig. 5).

Figure 3. General view of the town hall in Buchach from the west (1954)
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

Figure 4. The modern view of the town hall in Buchach from the southeast
Source: authors' photo (2019)

Figure 5. Pediment of the main western facade of the town hall in Buchach (archive photo)
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

The decorative and sculptural decoration of the town hall in Rococo style was performed by the brilliant sculptor Johann Georg Pinzel, who lived in Buchach at that time. Initially, the town hall was decorated with 14 narrative sculptural compositions on biblical and ancient mythological themes. In 1859, during a fire in the city, the town hall was also damaged (Sulimierski & Walewski, 1880), in particular, the eighteen-metre spire of the tower burned down. During the fire on July 29, 1865, part of the sculptures were destroyed by fire, and only 9 sculptural compositions survived. In 1870, the town hall was rebuilt (Voznytskyi, 2005).

Analysing the allegorical sculptural compositions with which J. Pinzel decorated the Buchach town hall, it can be stated that the figures of ancient heroes emphasise strength, courage and faith in the victory of good over dark forces. In an extremely dynamic pose, the sculptor depicted the young shepherd David killing the mighty Goliath for his people (Figs. 6-7). The sculptor depicted the body of David in a strong movement, swinging with both hands, which were clutching a staff. The folds of David's clothes that fit the body were treated in a general way. David's head was especially clearly carved. In his expressive face with an open mouth and clearly defined nose and chin, an expression of energy and strength was reflected. The hair of the head was modelled with large strands. The fallen giant Goliath, lying prostrate, his arms and head thrown back and hanging over the parapet. Thrown hands, open mouth, expressive face, depressions in the eyes testify to Goliath's powerlessness (Logvin, 1959). The plastic of this composition vividly conveys the triumphant victory of David over the fallen giant.

Figure 6. Allegorical sculptures on the pediment of the town hall in Buchach
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

Figure 7. David kills Goliath
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

In contrast to David's dynamic composition, the figure of Themis standing next to him was depicted in a calm pose. Folds of draperies picturesquely hug the body of a slender goddess. The bent left arm in a graceful gesture emphasises the easy movement and slenderness of the character, while the slight bend of the left leg and the turn of the shoulders demonstrate the calm, easy movement of Themis (Fig. 6). On the volute of the parapet, a naked figure of a Zaporozhian was seated in majestic repose (Logvin, 1959). In the sitting figure, the sculptor embodied peace and rest. The correct anatomical proportions were given in the torso, muscles of the shoulder girdle and biceps of the Zaporizhia. His left-hand rests on his side, and his right hand, holding a cradle, rests on his knee. The head calmly confidently looks ahead towards the castle.

On the opposite side, an allegorical sculptural composition of Hercules tearing the lion's mouth was symmetrically placed (Fig. 8). In the sculpture of Hercules, J. Pinzel energetically conveyed the strength in the tense muscles of the character and extraordinary dynamics, depicting him naked with a bandage on his hips, firmly holding the lion's mouth. The figure of Hercules was depicted in an inclined movement towards the pediment. With the knee of his right leg, he rests on the lion's back and tears his mouth open with his hands. Beautiful anatomical structure of a slender body of a young man, clearly carved legs and thigh muscles, powerful biceps, shoulder girdle and neck. The head was energetically turned, and the eyes looked forward. The sculpture was full of energetic movement. In terms of emotional expression and plasticity, the sculpture can be compared to the sculpture of St. Onuphrius in Rukomysh (Chen, 2022).

Figure 8. Hercules tears the lion's mouth open
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

The figure of the captive was depicted on the volute in a bent position (Fig. 9). The prisoner's hands tied behind his back were trying to break the shackles, and his face, swollen from muscle tension and grimacing, was full of anger and hatred, emphasising the difficulty of the struggle and the bitter defeat. His face was turned downward and he looked at the city and the market with hatred. The sculptor conveyed his insubordination, although he was defeated but not broken.

On the eastern corner of the town hall was an allegorical figure of Hercules killing the Lernaean hydra, in the form of a snake with 9 heads (Fig. 10). In the sculptural composition Hercules killing the Lernaean hydra, Pinzel depicted the tense muscular physique of the hero, who kills the nine-headed monster (hydra) with a massive stick in his right hand, and strangles it with his left hand. The jagged tail of the hydra coiling around Heracles' legs, the drapery of the cloak fluttering in the wind, enhance the dynamics of the sculpture and give it grandeur and solemnity. A head

with a mane of curly hair rests on powerful shoulders. The sculptural composition was emphasised by the dynamism of movements, energy, and expression.

Figure 9. The figure of a captive
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

Figure 10. Hercules kills the Lernaean hydra
Source: Archive of V.G. Zabolotnyi State Scientific Library of Architecture and Construction (n.d.)

On the north-eastern corner, there was a figure of Neptune in unrestrained motion. A vivid allegorical sculpture of Neptune taming the raging waves of the sea with a wave of his rod. His left leg, which was sharply brought forward, and his right hand, holding a trident, which was brought back, emphasised the movement of the allegorical sculpture. The folds of Neptune's muscles and his menacing face were anatomically correctly treated. Expressive plasticity of figures, realistic interpretation, facial gestures, tense muscles of arms and legs of allegorical sculptures impress with extraordinary dynamic movements and high artistic qualities. The sculptures of J. Pinzel at the town hall were close in terms of emotional resolution to Michelangelo's "Battle of the Centaurs". All sculptural compositions on the parapet and pediment of the facade of the town hall were so arranged that they organically merged with the rocaille decoration of the building.

The clear architectural forms of the Buchach Town Hall were organically connected by sculptural works of monumental and decorative art, giving it lightness and elegance. In the architecture of the facades of the town hall, the desire for aesthetic, artistic, unique monumental and decorative decoration inherent in the Ukrainian national character of the time was conveyed. The high skill of execution, the expressive plasticity of the building, the richness of the decor and dynamic allegorical sculptures with penetrating emotional gestures were a means of expressing the worldview of the society at that time. Ukrainian architectural thinking of the Baroque era was manifested by a fascination with luxurious decor, a desire for multi-meaning mythological decorations and high poetics. The expressiveness and integrity of the composition of the Buchach building were achieved not only by artistic means, but also by the balance, and proportionality of all its elements and the proportionality of the ratios of its parameters. The vertical lines of numerous elegant pilasters with Corinthian capitals, shaped window frames, and niches enhance the slenderness and dynamism of the building. The complex contours of the pediment with a rocaille asymmetric cartouche, decorated with the family coat of arms of the founder M. Pototsky, which was the main accent of the central part of the main western facade of the town hall, reinforced the aesthetics of the architecture of the late Baroque building. A feature of B. Meretin's creativity was the impeccable choice of location for the town hall, organic combination with the urban planning environment and landscape environment. This gave the architect the opportunity to create a unique, integral, highly artistic, aesthetically expressive building.

The study of the late Baroque municipal monument in Buchach, Ternopil region, dated 1751 with exquisite proportions and an original artistic solution, which was the architectural and artistic accent of the market square of Buchach, was a source of knowledge of cultural values and scientific knowledge of the Baroque era. The well-known Ukrainian architect H. Logvin, thoroughly researching the town hall in Buchach, measured the monument and concluded that the town hall was built before 1751. Also, in his research, he highlighted the historical facts of the construction of the town hall and the stylistic features of the decor and sculptural plot compositions, emphasising the inseparable unity of sculptural decor with architecture. However, he questioned I. Pinzel's authorship of the sculptural compositions (Logvin, 1959). This statement can only be partially agreed upon. Analysing Pinzel's Buchach works (roadside sculptures of the Mother of God and Jan Nepomuk) with exquisite late-baroque plastic, it can be asserted that the sculptural works of the town hall in Buchach were made by I. Pinzel and partly by his students. The dynamic poses of the allegorical sculptural compositions of the Buchach Town Hall with the vividly conveyed emotional nature of the faces, and the energetic movement of the characters' bodies, testify to the masterful manner of performing works by I Pinzel. In his writings, G. Logvin (2002) compared Ukrainian baroque sculpture, including Pinzel's

works, with world examples of this style, emphasising the variety of artistic means and aesthetic expressiveness in Pinzel's sculptural works.

Pinzel's work was thoroughly studied by B. Voznytskyi (2005), collecting his works during the creation of the museum of the same name in Lviv. Exploring the town hall in Buchach, he noted the original design, bold solution, and elegance of the building's proportions. J.K. Ostrowski (1996), studying and analysing the works of Pinzel in the European context, expressed their hypotheses regarding the origin of the artist, his education, and creativity. T. Mankowski (1937), a Polish researcher of J. Pinzel's work, emphasised that Pinzel was an exponent of a peculiar direction of expressive dynamics, which was achieved by bold processing of material and interpretation of clothing draperies. The Polish art critic A. Bochnak (1931), studying the plasticity of Pinzel's late baroque sculptures, compared them with South German sculptural works. Unlike previous researchers, Z. Hornung (1976) sees in Pinzel's sculptures the influence of the Prague Baroque. This testifies to the sculptor's unique talent and high familiarity with the art of European countries.

In the process of researching the unique building of local self-government bodies – the town hall in Buchach, Ternopil region, dated 1750-1751, it was found that the architectural and spatial arrangement of the monument combines the constructive logic of the architect B. Meretin and the rich decorative sculptural decoration of the sculptor IG Pinzel. Refined proportions and high architectural and artistic qualities of the town hall demonstrated the high professionalism of the architects. The architectural design of the building embodies the synthesis of arts, where architecture, decor, and sculpture were organically combined, which was the ideal of beauty and emotional delight (Denysenko *et al.*, 2022). Based on the analysis of allegorical sculptures of the late baroque works of the town hall in Buchach, the individual manner of I. Pinzel's performance of high-art works had been proven. The high architectural and artistic value of the town hall with its unique decoration, which reflects the outlook and cultural values of the society of the late Baroque era, was revealed.

CONCLUSIONS

Thus, the outstanding architect B. Meretyn and the talented sculptor J. Pinzel enriched Ukrainian architecture with their real masterpiece – the town hall in Buchach, which was distinguished by its originality, exquisite proportions, and high architectural and artistic qualities. Behind the magnificent decorative and sculptural baroque decoration of the town hall, the strict constructive logic of the building can be felt. A high two-story tower rests on the base of the square two-story volume of the building. The building, which was square in plan, had a centrally symmetrical composition, to which all the elements of the building were subordinated.

The artistic principles of the late baroque in the town hall were carried out consistently and highly talented. Wall masses were energetically dissected both vertically and horizontally. The game of numerous vertical lines of pilasters with capitals of the Corinthian order, cornices, and belts, a tall two-story tower with finely decorated pilasters, balustrades, sculptures on the parapet, caryatids supporting the balconies, a cartouche with the family coat of arms of the founder on the pediment create a cartouche with the founder's family coat of arms on the pediment created a unique highly artistic image of the building, designed to be viewed from all sides. The sculptural decoration not only organically enriched the architecture of the facades of the town hall, but also emphasised the professionalism of the architects, who managed to convey the worldview of the ruling city elite and the founder.

Expressive plasticity, dynamism of movements, internal tension, drama, exquisite poses, and silhouettes of the monumental sculptures of the Buchach Town Hall emphasised the struggle against the dark forces of evil, the victory of reason, and the light nature. The architectural solution of the town hall was an example of the synthesis of arts, where architecture and sculpture were so organically merged that the building was perceived as one large sculptural work, designed to be viewed both from a close distance and when viewing it from elevated areas adjacent to the city. The Town Hall was a vivid work of architecture and art of the late Baroque era, when noble elegance, grandeur and artistic sophistication were intertwined, demonstrating the ideal of unique beauty that evokes emotional admiration in the viewer.

The article analysed the architectural and artistic solution of the town hall in Buchach, Ternopil region, determining its main architectural, planning, compositional, and plastic features. It demonstrated the Ukrainian identity of the mythological sculptural works used in the decoration of the town hall and determined their prominent place in Ukraine's cultural heritage. The results of the research add knowledge of the history of architecture and art and can be used for further research on the town hall.

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CONFLICT OF INTEREST

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Архітектурно-художнє вирішення ратуші в м. Бучачі

Анотація. Ратуша була не лише будівлею органу міського самоврядування, в якій розміщувався міський уряд, але й дуже важливою громадською архітектурною спорудою міста, що виконувала адміністративну функцію. Квадратні в плані, але різноманітні за формою завершення та розмірами, будівельним матеріалом, композиційним, конструктивним і пластичним вирішенням, ратуші були головними архітектурно-художніми акцентами ринкових площ українських міст. Стаття присвячена дослідженню історії будівництва та художньо-композиційних особливостей унікальної ратуші в м. Бучачі 1750-1751 рр., яка збереглася до 2025 р. в автентичному вигляді. Дослідження архітектурно-художнього вирішення ратуші в м. Бучачі стало джерелом естетичного сприйняття суспільством мистецьких цінностей конкретної історичної епохи. Розкрито історію будівництва барокової ратуші, зведеної за проектом видатного архітектора Бернарда Меретина та скульптора Йогана Георга Пінзеля на кошти мецената Миколи Потоцького. Ця високохудожня архітектурна споруда відображає високий рівень майстерності і таланту архітектора і скульптора епохи бароко. Розглянуто особливості використання декоративного різьблення по каменю та скульптурних композицій на міфологічні сюжети в оздобленні будівель доби пізнього бароко. Проаналізовано пластичне вирішення міфологічних скульптурних композицій на парапеті та фронтоні головного фасаду ратуші. Внаслідок атмосферних впливів декор та окремі скульптури зазнали значних втрат і потребують реставраційних робіт. Через брак коштів реставраційні роботи були зупинені. Досліджуваний унікальний архітектурний об'єкт має високу художню та мистецьку цінність і належить не лише до мистецького надбання України, а й до світової культурної спадщини

Ключові слова: архітектор Б. Меретин; скульптор І. Пінзель; планування; композиція; декор

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Origins and development of Moorish architecture in Europe from the Middle Ages to the early 20th century

Abstract. The purpose of this study was to explore the functional, artistic, and compositional characteristics of Moorish architecture in Europe, tracing its origins in Byzantine masonry drawings from medieval Bulgaria. The study examined how the style spread across synagogues, mosques, Catholic churches, and public institutions in countries like Hungary, Romania, Ukraine, Bosnia, and others. The research methodology included a combination of the chronological principle, art historical and design approaches, ontological, axiological, hermeneutical, historical-genetic, comparative, socio-cultural, cross-cultural, formal-stylistic, typological, and art historical analysis methods. Findings of the study were as follows. The few monuments with elements of "embroidered" masonry preserved in the Balkans, particularly in the old part of the Bulgarian Nessebar, have become a valuable source of the formation of Moorish (Spanish-Moorish, Andalusian)

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style. This tradition, which originated in the Byzantine-Mediterranean context, later transformed into a recognisable architectural trend. In the 19th and early 20th centuries, the fashion for oriental forms spread across Europe, from the Caucasus to Italy. In different countries, it manifested itself in the architecture of palaces, synagogues, kenesas, theatres, administrative buildings, and sacred buildings. The study proved that the formation of the Moorish (Andalusian) style in European architecture has deeper than previously thought Byzantine-Antique roots, with further flourishing in the 19th and early 20th centuries under the influence of Oriental and Western European styles. The practical significance of these findings lies in providing architects, conservators, and urban planners with an evidence-based framework for the restoration, adaptive reuse, and sensitive integration of Moorish-style elements in European heritage and contemporary architectural projects

Keywords: monumental and decorative art; "embroidered" masonry; Orientalism; composition; environmental design

INTRODUCTION

Moorish architecture has attracted attention, as well as the question of the origins of its origin, sources of style inspiration, its spread within European countries, the specifics of building orders, and their typological (functional) characteristics. However, despite numerous publications on this topic, the essence of the components of the Moorish architecture style in Europe has not been comprehensively understood. The terminology of the Moorish style, as well as the issue of its precise definition in architectural discourse, has been actively discussed in contemporary scholarship. In a series of studies, this style was defined as "neo-Moorish" or as a phenomenon of "Islamised Orientalism", which showed a complex typology of cultural interpretations depending on geography, chronology, and aesthetics (Al-Fahad, 2023). Particularly noteworthy in this context was the concept of "hybrid identity", which, as A.O. Ibrahim (2022) showed, was central to shaping the architectural landscape in Sudan, where Moorish forms served as a cultural bridge between Arab and African traditions.

N. Ait-Aoudia Meriem (2025) presented a comprehensive study of the neo-Moorish façades of residential buildings of the 19th-20th centuries, where the author conducted an in-depth architectural and stylistic analysis of the buildings in the Algerian city of Blida. The researcher classified the façade solutions by morphological features, identifying a combination of arcades, colonnades, friezes, and traditional ornamentation. The conclusions emphasised that the style was not a replica of historical forms, but served to preserve cultural identity in the context of colonial modernisation. N. Saldja & Y.S. Youcef (2024), analysing the architecture of the City Hall in Philippeville, emphasised that the neo-Moorish style served an ideological function as an instrument of "architectural diplomacy" of the French colonial authorities. The building's décor, including domes, panels, and paintings, became an element of "visual politics" that appealed to traditions while asserting the power of the colonisers.

R. Blanco-Guzmán (2023) considered the European interpretations of the style, exploring the decorative paintings of Al-Andalus through the metaphor of "epidermal architecture", where the façade was interpreted as a "skin" that both protected and visualised the privacy of the space. This concept echoed the research by F. Zahra & S.B. Shahir (2024), who interpreted Islamic ornamentation as a visualisation of sacred order, infinity, and harmony that formed a space for spiritual attunement. From a geocultural perspective, M.J. Schreffler (2022) analysed the spread of the Mudehar style in Latin America as a result of the colonial rivalry between Spain and Portugal. The researcher emphasised the universality of Moorish forms capable of adaptation in new contexts. A. González & I. Llano (2024) traced the influence of Maghreb music on southern Spain, particularly in the genres of flamenco and ethnomusic, emphasising the interaction of music and architecture as elements of a common cultural space. A.B. Follana (2023) focused on the penetration of Andalusian motifs into the works of composers Debussy, de Falla, and Ravel, emphasising the role of Moorish aesthetics as a source of inspiration in European art. M.W. Dariyadi *et al*. (2022) analysed the modern urban planning of Islamic cities, focusing on the preservation of the sacred and symbolic content of classical elements (domes, arcades, lattices) in new urban realities. A.H. Radwan (2021) demonstrated an analogous approach, considering the mosque not only a sacred but also a social and organisational centre of the Islamic city. In the Ukrainian academic context, O. Shkolna & O. Kovalchuk (2023) studied the influence of Moorish aesthetics on jewellery art, and the previous study by O. Shkolna (2019) considered the architectural elements of the East (mashrabiya, shabbak), which became part of Moorish ornamentation.

Thus, the available research testifies to the multidimensionality of Moorish stylistics, which was manifested in architecture, music, decorative arts, and urbanism, serving as a carrier of cultural memory and postcolonial dialogue in a global context. However, all the studies cited above did not cover the issue of the spread of the Maritime (Spanish-Moorish, Andalusian) style in Eastern, Central, Northern, and Western Europe from the Middle Ages to the early 20th century. The purpose of this study was to identify the locations of the spread of Moorish-style buildings in Europe from the Middle Ages to the early 20th century, as well as to reveal their functional, artistic, figurative, and compositional features.

MATERIALS AND METHODS

The methodology of this study was based on an integrated approach that included historical-genetic, comparative, formal-stylistic, typological, art historical, and hermeneutical methods. The application of the chronological principle helped to determine the key stages of the development of the Moorish style from its origin in the decorative masonry of the Byzantine period in the Balkans (Bulgaria, Croatia) to the spread of this style in the forms of churches, mosques, synagogues, kenesas, palaces, and educational institutions in different European countries. Particular attention was paid to architectural monuments in Bulgaria (Nessebar, Belovsk Basilica), Turkey (Mevlana Mausoleum in Konya, Topkapi Palace), Hungary (Pasha Gazi-Kasim Mosque), Ukraine (Karaite kenesas in Kyiv and Vilnius), Croatia (Capuchin Church of Our Lady of Lourdes), Bosnia and Herzegovina (Sarajevo City Hall), Lithuania (Vilnius Choral Synagogue), and others. The art historical approach was to identify the key features of architectural solutions characteristic of the Moorish style. The use of elements of "embroidered" masonry, pinnacles, muqarnas, openwork perforations, horseshoe and spade arches, as well as the influence of the Manuelino, Plateresco, Mudejar, and Alhambra styles on the decorative decoration were explored. The study analysed how these elements have been preserved and adapted to various architectural structures, including sacred buildings (mosques, synagogues, kenesas, churches) and public complexes (palaces, administrative buildings, educational institutions, theatres). The comparative method was employed to compare architectural solutions in different countries. This helped to identify local peculiarities of the Moorish style adaptation and its interpretation in the context of different cultural environments. The hermeneutic approach helped to reveal the significance of architectural forms in the context of social, religious, and cultural aspects of different regions of Europe. Attention was paid to the issues of religious pluralism and the influence of Jewish, Arab, Turkish, Portuguese, Spanish, Georgian, Ottoman, and other traditions on the development of style.

The study was based on numerous scientific publications, architectural reports by A. Chalabi & Y. Lazri (2021), Q.H. Hamamurad & N.M. Jusoh (2023), photographic materials and direct visits to the research sites. The current state of Moorish-style buildings in Europe was also analysed. Particular attention was paid to the issues of their restoration, preservation and adaptation to modern conditions. To assess the current state of the objects, the method of visual architectural monitoring was employed, which included the analysis of photographic records, digital architectural passports, as well as a comparison of historical and modern façade plans. Open access sources were used, including official reports on the condition of cultural heritage sites, materials from architectural conferences, monument catalogues, and online registers such as the European Heritage Label and the architectural archives of the cities of Barcelona, Paris, Granada, and Lisbon. Wherever possible, the method of typological analysis was used to compare structural elements (arcades, mashrabiyas, ornaments, mosaics) according to the criteria of preservation, interpretive transformation, and restoration intervention.

The question of whether the construction of new Moorish-style buildings continues in Europe and how this style is used in modern interior decoration was also considered. The study paid special attention to examples of architectural solutions in European countries, particularly Spain, Portugal, France, Turkey, Ukraine, Lithuania, Bosnia and Herzegovina. The choice of these countries was conditioned by the historical and cultural significance of the Moorish tradition in each of the regions, as well as the presence of characteristic examples of architecture that demonstrate stylistic imitation or reinterpretation of Moorish motifs in different historical periods. The analysis involved the study of new projects, including public and cultural centres, private houses, and religious buildings (mosques, synagogues, kenesas) that reproduce or interpret elements of the Moorish style. The application of an integrated approach helped to cover the functional, compositional, artistic, and figurative features of Moorish architecture in Europe, to determine its historical development and to identify modern trends in the use of this style.

RESULTS

The "Moorish (from the outdated name of Morocco "Mauritania") style" spread in the traditions of masonry of sacred buildings in the lands of ethnic Bulgaria (the Byzantine Empire) from the 11th to the 13th centuries. For example, in the area of Sveti Spas in Bulgaria, there are ruins of the Belov Basilica of the 4th-5th centuries with decorative coloured masonry in some parts of the building, which do not yet have such a rhythmic composition as would be common in Bulgaria in the period of late Byzantium from the time of the Comnenians (Fig. 1). A series of monuments have also been preserved in the Old Town of Nessebar. This feature in decorative techniques indicates possible shared sources of influence and confirms the hypothesis of the circulation of stylistic forms in the Mediterranean region, which was the subject of analytical consideration by R. Blanco-Guzmán (2023), where patterned masonry was presented as the basis for interpreting the façade as a "blanket of space". In Figure 1, the coloured masonry of the façade of the 4th-5th century Belovski Basilica in Bulgaria shows a combination of ochre brick and light stone in horizontal stripes, creating a decorative effect close to ornamental decoration. Nearby is the entrance to a Roman tomb in Anhialo with an arched portal typical of underground structures of the 2nd-4th centuries. These examples demonstrate the continuity of architectural techniques and decorative forms from antiquity to the early Middle Ages in the region. Other examples include the ruins of ancient baths (6th century), St. Sophia Church (5th-6th centuries), the Basilica of the Virgin Eleusis (Delight) (6th century), St. Stephen's Church (10th century), the churches of St. John the Baptist (10th-11th centuries), St. Demetrius (10th-11th centuries), St. Stephen

(11th century), St. Paraskeva (13th century), St. Paraskeva (13th century), St. Todor (13th century), St. Archangels Michael and Gabriel (13th century), St. John Alitourgethos (Unsanctified) (14th century), Christ the Pantocrator (Almighty) (14th century), St. Saviour (Ascension of Christ) (17th century) (Ivashko *et al.*, 2021).

Figure 1. Coloured masonry elements of the Belov Basilica of the 4th-5th centuries AD in Nessebar and the entrance to the ancient Roman tomb nearby in Anhialo of the 2nd-4th centuries AD Bulgaria
Source: Sboryanovo Archaeological Reserve (n.d.)

Using the example of early Byzantine terms of the 6th century, laid down at the beginning of the development of the "city of forty churches in Bulgaria" under Justinian the Great, it is noticeable that the masonry of the walls is already acquiring the nature of "embroidered", creating a clear rhyme of repetition of ochre stripes in the composition, which gives the image of the building a sense of solemnity of ablutions, which were part of the way of life of the nobility. Therewith, from the 5th to the 6th century (when the fortress walls with "embroidered" masonry were built) and the 6th century (when the public buildings were constructed) in the Old Town of Nessebar, the culture of masonry with coloured "interruptions" became a virtuoso part of the work of masons who alternated tuff masonry with thin reddish plinth of apses, naves, semi-arched spaces, window frames and friezes that emphasised the architectonics. This technique resonates deeply with the "architecture as a bedspread" concept proposed by R. Blanco-Guzmán (2023), where the façade is viewed as a visual text that interprets space through layers of form, texture, and colour. All this testifies to the wide circulation of aesthetic principles within the Byzantine-Moorish cultural area.

From the Romanesque and Gothic periods to the Renaissance, local craftsmen not only performed the typical Moorish style "metopic-triglyph" decorative types of masonry, but even experimented with a "cross" swastika-meander pattern made of ochre bricks, they added rows of glass elements between the bricks (as in the Spanish Mudejar style of the 11th and 16th centuries), and created relief ornamental patterns on the façades with coloured bricks (Fig. 2). This applied not only to buildings for liturgical purposes, but also to private houses of local residents, which are still a decoration of the ancient part of the city, which is now under the protection of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

Figure 2. Ruins of the early Byzantine terms of the 6th century, founded under Justinian the Great, and the temple of Christ Pantocrator (2 projections) in Nessebar in the 14th century (Bulgaria)
Source: Sboryanovo Archaeological Reserve (n.d.)

In Figure 2, the architectural heritage of Nessebar is striking in its multilayered stylistic influences, which can be traced back to the 6th and 14th centuries. The left part of the image shows the ruins of the early Byzantine termini, built during the reign of Emperor Justinian I, where the characteristic massive masonry with preserved fragments

of arched passages and the remains of brick friezes, which served as both structural and decorative elements, is visible. On the right side of the composition, the Church of Christ the Pantocrator is presented in two projections – the front and the side. Particular attention is drawn to the "embroidered" masonry of the façade, where the alternation of red plinth and light stone forms a complex geometric system of rhythms. This not only creates an expressive plastic image of the building but also testifies to the continuity of decorative techniques from early Christian monuments to late medieval examples. Figure 2 illustrates the cross-cutting nature of the ornamental code that was inherent in Byzantine-Balkan architecture and later became part of the formative arsenal of Moorish style.

That is, from the Early Middle Ages of Justinian the Great to the Baroque period, the phenomenon of "embroidered" masonry walls, which had rows of coloured terracotta plinths and appealed to the architectonics and rhythm of the patterns of the walls of buildings made in the Spanish-Moorish style in the Maghreb countries (Algeria, Morocco and Tunisia), was recorded in this region. The local fashion in these lands gave impetus to the development of such traditions of building in the Mediterranean (North Africa). Furthermore, from the Middle Ages and the Early Modern period, elements of such "embroidered" masonry became part of the development of the lands of modern Croatia, which is recorded in the patterns of the walls of churches on the island of Ston (the Church of St. Vlach, 14th century, St. Liberan, 17th century with later interventions, etc.) (Fig. 3).

Figure 3. Church of St Vlach, 14th century, Ston, Croatia
Source: My Croatia (2012)

The Church of St Vlach on the island of Ston (Croatia, 14th century) demonstrates a pronounced use of coloured masonry, typical of late medieval Byzantine and post-Byzantine architecture. The façade of the church features an alternation of light stone blocks with horizontal rows of red plinths, forming a kind of decorative ornament in the style of "stone embroidery". This not only gives the building visual plasticity but also demonstrates the influence of techniques inherent in Balkan and Asia Minor sacred architecture on the formation of the local Croatian architectural landscape. The use of this technique demonstrates the profound transregional connections between the Byzantine heritage, Slavic building traditions, and the decorative canon, which later transformed into one of the key aspects of Moorish style. The décor of the ochre brick "partitions" had more ascetic forms, which only emphasised the architecturally significant details of the exteriors and interiors: semicircular elements of framing doorways (portals), wind roses in the Gothic fashion, which served as desjudeports (decorative ornaments above the front door) and light wells, lunettes above pilasters and arcades, columns topped with spires.

The introduction of rhombic masonry, borrowed from the Mudejar style, which was widespread in Spain in the 11th and 16th centuries under the influence of the mixing of Jewish, Christian, and Moorish cultures, was a local know-how, compared to the buildings in Bulgaria, where it was fashionable to decorate the façade with coloured plinths with rows of ceramic (terracotta) bands, Christian and Moorish cultures (a typical example is the tower of the Cathedral of Santa Maria de Mediavilla, a UNESCO World Heritage Site), under the slopes of the ochre tiled roof. At the same time, somewhere in the 16th century, a fashion for decorating arched spaces and windowsills with coloured "interruptions" appeared in the former lands of Byzantium itself. Specifically, on the territory of modern Turkey, in the city of Konya, near the complex of the mausoleum of Celeidin Rumi (Mevlana), the Konya Selimiye Mosque, built by Sultan Selim II between 1558 and 1567 by the architect Mimar Sinan with coloured masonry elements above the arches, has been preserved (Fig. 4).

Figure 4. Mevlana Museum and Mausoleum in Konya (Turkey), 13th-16th centuries
Notes: coloured masonry elements only on semicircular or rounded elements
Source: photo by the authors of this study

The Mevlana Mausoleum complex (13th-16th centuries) in Konya, Turkey, demonstrates the decorative elements of coloured masonry typical of late Ottoman architecture, concentrated mainly in arched spaces and rounded architectural elements, as exemplified by the Selimiye Mosque, built between 1558 and 1567 by the famous architect Mimar Sinan on the orders of Sultan Selim II. The colourful

accentuation of the arches with alternating red and white stone blocks performs both a decorative and a structural function, emphasising the rhythm of the façade plastic and the arrhythm of the stained-glass lighting. This use of masonry is an aesthetic echo of Byzantine, Seljuk, and Persian influences, which in Ottoman art were synthesised into a new artistic language that later became a source of inspiration for neo-Moorish architects in Europe. Mimar Sinan also designed the Mihrimah Sultan Mosque in Edirne Kapı (western Istanbul) (Fig. 5). Between 1562 and 1565, he built a whole complex of a mosque, madrassa, hammam, turbeh (tomb), fountain, and shopping arcades. The mosque used striped decoration of the vaulted arches with greenish paint according to Moorish traditions in the interior, coloured white and brown "interruptions" of the keeled arched vaults above the fountain, etc.

Figure 5. Architect Mimar Sinan. Interior of the mosque of Mihrimah Sultan (daughter of Suleiman the Great and Roksolana) in Edirne Kapı (Istanbul), 1562-1565
Source: photo by the authors of this study

Designed by Mimar Sinan in 1562-1565, the interior of the Mihrimah Sultan Mosque in the Edirne Kapı district of Istanbul embodies a sophisticated style of decorative decoration that combines Ottoman architectural traditions with Moorish motifs. Attention is drawn to the striped elements of the vaults, painted in greenish-ochre shades, which form a clear rhythm around the sub-dome arches. The white and brown keel-shaped arches surrounding the fountain in the courtyard also acquire a special decorative significance. The colour scheme emphasises the vertical and horizontal plasticity of the interior space, referring to the principles of visual "interruption" of the plane inherent in Moorish and Andalusian architecture. The Mihrimah Sultan complex not only illustrates the high level of architectural synthesis of the Ottoman Empire, but also demonstrates how oriental ornament motifs are integrated into sacred architecture in its post-Byzantine interpretation, where, similar to the architecture of the Buddhist dwellings, each element of space acquires a symbolic meaning, representing religious ethics, ideas of prayer and harmony (Alifuddin *et al.*, 2021; Chung, 2025).

Some parts of the Topkapı Palace in Istanbul, the main residence of the Turkish padishahs after the conquest of Constantinople by the Ottomans, date back to the 15th and 17th centuries. Among others, the decoration of the arched structures with coloured striped masonry of the Sofa-i Humayun terrace stands out, where ochre elements bend in an S-shaped manner, creating the effect of "dancing" wavy lines (built in 1638). Such a compositional solution not only emphasises the architectonic lines of the building but also conveys its playful character in its artistic and figurative sound (Fig. 6). The ensemble of the building includes a gilded gazebo with a dome called Iftar (Iftariye Kosku), intended for fasting in the holy month of Ramadan and contemplation of the Golden Horn Bay.

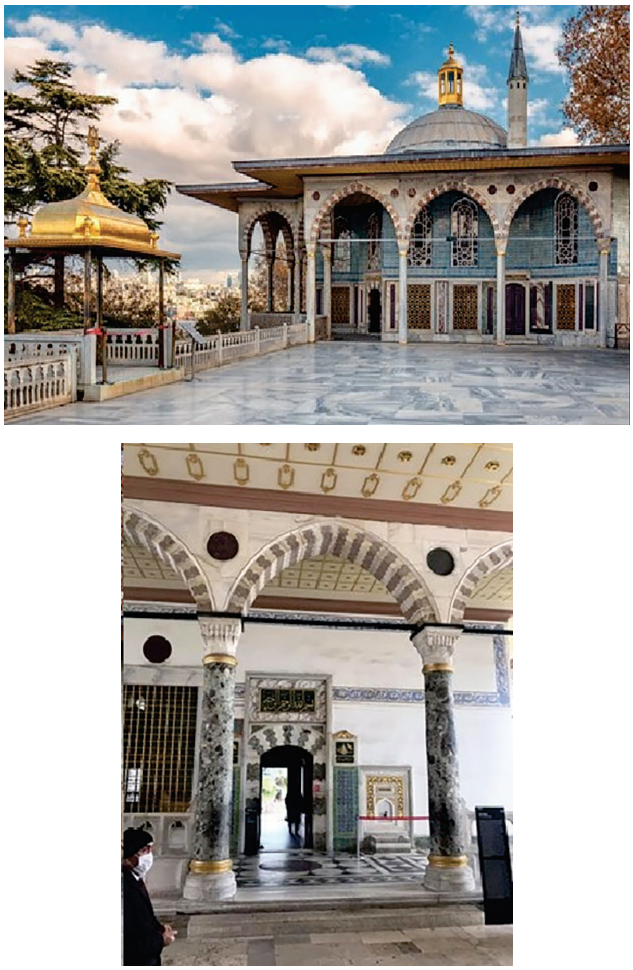

Figure 6. Sopha-i Humayun Terrace and examples of coloured masonry arches in the Topkapı interior ensemble (Istanbul), late 16th – early 17th century
Source: Topkapı Palace in Istanbul is most actively visited by Ukrainian tourists (2021)

The Sopha-i Humayun Terrace in the Topkapı Palace Complex in Istanbul, dating back to 1638, represents the sophisticated technique of coloured striped masonry, typical of late Ottoman architecture. The S-shaped geometry of the ochre and whitish arched segments is noteworthy, creating the effect of "dancing" lines, giving the architectural space visual dynamics and playful expression. The plastic

solution not only enhances the depth of the interior but also integrates visual ornamentation motifs inherent in the Moorish architectural tradition. The composition is complemented by the gilded dome of the Iftariye Kosku gazebo, which accentuates the sacred and domestic function of the ensemble, symbolising the combination of visual luxury and spiritual purpose in the structure of the palace environment.

In the Reception Hall gallery of the complex, an analogous motif is repeated, but with alternating segments with and without the "waving" lines of dark masonry. After being built in the time of Mehmed II, most of the complex was renovated during the reign of Suleiman the Great and later. The wavy lines of alternating masonry, which depart from the traditional methods of figurative imitation of harpsichord and piano keys, are also found in the interiors of individual rooms of the Topkapı, particularly the Hall of Receptions (Audience), built during the reign of Mehmed III in 1595-1603 in the Third Court of the complex (Blanco-Guzmán, 2023).

In the Muslim traditions of the Ottomans, the Parsan Mosque in Konya was built in 1676, where the tradition of introducing the above elements of façade decoration through coloured masonry has been preserved. Mosques in the territories conquered by the Ottomans were built in the same tradition. Specifically, in the city of Pécs in Hungary, there is a typical example of a building of the 16th and 17th centuries with mashrabiyas – the Pasha Gazi-Kasim Mosque, later converted into a Christian church, the façade decor of which also includes "striped" completions of keel arches with perforated masonry walls above the windows (Fig. 7).

Figure 7. Architect Kermendi. The Pasha Gazi-Kasim (Jami) Mosque in Pécs, Hungary, later converted into a Christian church, 17th century
Source: photo by the authors of this study

Figure 7 presents one of the most prominent Ottoman buildings in Central Europe, the Pasha Gazi-Kasim (Jami) Mosque in Pécs, Hungary, which was converted into a Christian church after the fall of the Ottoman Empire. This architectural object, built in the 17th century by the architect Körmendi, shows close ties to Moorish and Ottoman styles. The façade design features perforated mashrabiyas above the windows, typical of Muslim architecture, and alternating ochre and light elements in the ends of the keeled arches. During the 17th century, there was a pause in Europe's fashion for Moorish architecture. This can be explained by the fact that after the triumphant conquest of Palestine, Iranian Azerbaijan, Caucasian Armenia, the Balkans, Algeria, and Tunisia in the 16th century, the Turks for a while united large areas of the Islamic world under their protectorate, and then Moorish (associated with the Maghreb countries) became part of their empire (Auanasova *et al.*, 2025). However, the Turkish-Persian wars continued, draining the country's economy from 1514-1515 to 1821-1823, which led to the collapse of the Ottoman Empire. These trends became especially evident after the victories of Ukrainian-Polish King Jan III Sobieski over them near Vienna in the late 17th century and the exhausting Russian-Turkish war of 1768-1774, when the Derebeys' rule began, characterised by the weakening of central authority in the Port and the spread of robbery in the interior of the country (Shkolna & Kovalchuk, 2023; Shtohryn & Tretiak, 2024).

Pan-Ottoman conquest narratives ceased to be dominant within the country from that time on, and many European states outside the country, which were experiencing reformist transformations in their religious, socio-political, and economic systems (after the era of the East India campaigns, the era of bourgeois revolutions began), were not particularly fascinated by this exoticism, as Indo-Saracenic and Chinoiserie motifs became fashionable at that time. After the end of the Mannerist, Baroque, and Rococo eras, Moorish art, which in Portugal and Spain was extremely acute in the architecture of Manuelino and Plateresco in the 16th century, was recalled in Europe during the Historicist era, which focused on its elements in the updated elements of the 19th-century synthetic Alhambra style. At this time, the Moorish style became part of traditional oriental themes in the art of academicism, decorative arts and sculpture (Shkolna, 2019). In the late 19th century, the Turkish House and the Italian Secondary School in Rijeka, Croatia, and the Vijecnica City Hall in Sarajevo (Bosnia and Herzegovina) were built (Fig. 8). The public buildings of this Mediterranean region were characterised by the use of not only striped masonry variants, but also elegant oriental mouldings with muqarnas, typically Moorish, borrowed from Manuelino and Plateresco, pinnacles at the end of the roof, the use of openwork mashrabi perforations in the lunettes of the descudeports and horseshoe-shaped rows of arches (Shkolna, 2019).

Figure 8 shows a fragment of the plastic decoration of the Vijecnica City Hall in Sarajevo, a landmark of neo-Moorish architecture in the Balkans designed by Czech architect Karel Parzik in the late 19th century. This object is a vivid example of the adaptation of Moorish decorative forms in the European environment. A typical set of oriental elements was used: pinnacles with a neo-Gothic interpretation, lunettes with openwork ornamentation, perforated inserts in arched passages, and complex mouldings with muqarnas,

which originate from the Muslim traditions of Andalusian and Moroccan architecture. Transitional arches framed by striped masonry, combined with perforations in the form of mashrabiyas, create a multi-layered perception of space and an expressive play of light and shadow, typical of the Moorish style. It is these decorative components, which have shared origins with the forms of Manuelino and Plateresco, that demonstrate the profound syncretism of cultural heritage within the neo-Moorish architectural canon (Shkolna, 2019).

Figure 8. Architect Karel Parzik. Elements of the plastic decor of the Sarajevo City Hall (Bosnia and Herzegovina), made in the Moorish style

Source: Sarajevo City Hall (2008)

At the turn of the 19th and 20th centuries, this style was also used to build the Beit Israel synagogue complex (with a community centre and kosher restaurant) in Brasov (Romania), the choral synagogue in Vilnius, Karaite kenesas in Kyiv and Vilnius, the Goldenberg Hospital in Kropyvnytskyi (Fig. 9), the horseshoe-shaped Moorish Arch on the French Boulevard in Odesa, the Capuchin Church in Rijeka (Croatia), the St Nicholas Cemetery Church in Belgrade (Serbia). Elements of the style are present in the main staircase and some rooms of the Central Building of the Kyiv Polytechnic Institute (Ukraine).

Figure 9. The Goldenberg Hospital in Kropyvnytskyi, Ukraine

Source: R. Malenkov (n.d.)

Figure 10 presents the façade of the Capuchin Church of Our Lady of Lourdes in Rijeka, Croatia, built between 1904 and 1929 by architect Giovanni Mario Curetta. The sculptural design was created by Urbano Botasso, and the decorative carvings were created by Antonio Marietti. The building combines neo-Gothic features with expressive oriental elements, particularly in the form of arches, pinnacles, columns with decorative finials typical of Moorish style. The striped masonry design of the façade, contrasting zoning of materials, and elements of mashrabiya stylisation on the window openings indicate a close relationship with the Moorish architectural canon, which was widespread in religious construction in Central and South-Eastern Europe at the turn of the 19th and 20th centuries. This object represents the specifics of the adaptation of Moorish decorative models to Catholic sacred architecture, while preserving the profound semantic and aesthetic features of the oriental architectural heritage (González & Llano, 2024). For instance, the façade of the early 20th-century Capuchin Church (Basilica) of Our Lady of Lourdes in Rijeka features three-lobed arches, more typical of Algerian architecture, and fashionable in the 19th century (they were used in interior designs, specifically, in the Mikhail Vorontsov Palace in Tiflis in the third quarter of the 19th century), as well as pinnacles, repeated "blind" arches, lunettes, portal niches with openwork plastic modelling and sculpture, and even mosaics, which gave the whole eclectic composition a special artistic and figurative sound.

Figure 10. Architect Giovanni Mario Curett, sculptor Urbano Botasso, and carver Antonio Marietti. The Capuchin Church of Our Lady of Lourdes in Rijeka, Croatia. 1904-1929
Source: photo by the authors of this study

As of 2025, a considerable number of Moorish-style buildings still exist in Europe, although their condition varies considerably depending on the country, local traditions of cultural heritage protection and the current functional use of the buildings. Many historic Moorish buildings are under the protection of UNESCO and national heritage protection programmes. For instance, the Old Town of Nessebar in Bulgaria, which has preserved numerous examples of ochre plinth masonry and decorative bands, is a UNESCO World Heritage Site. This helps to ensure stable funding for restoration work and measures to protect the architectural heritage. At the same time, not all Moorish-style buildings are properly maintained. Some synagogues, kenesas, and mosques, especially in Central and Eastern Europe, are in need of immediate restoration work or have already been destroyed during the 20th century due to wars, repression, or economic hardship. Specifically, many Karaite kenesas that functioned in Kyiv and Vilnius have been rebuilt or lost their original functional purpose (Ivashko *et al.*, 2021). At the same time, the modern practice of preserving and restoring Moorish-style buildings includes not only restoration work but also adaptation to new functional needs. For example, in Barcelona, new architectural projects interpret the Moorish style using modern building materials and technologies, creating interesting examples of an eclectic mix of historical motifs and modern design concepts (Fig. 11).

Figure 11. Casa Batlló in Barcelona, reconstructed from 1904 to 1906
Source: photo by the authors of this study

Figure 11 shows one of the most striking examples of an eclectic approach to the interpretation of the Moorish style in architecture – the famous Casa Batlló in Barcelona, reconstructed in 1904-1906 by Antoni Gaudí. Although this object is mainly associated with Catalan modernism, its façade displays numerous decorative elements that share similarities with the Moorish style, primarily in the rhythm of arcades, wavy lines, mosaic decoration, and colour schemes. The analogies are particularly noticeable in the use of coloured ceramics, the outlines of window openings and the distribution of spatial accents on the façade. This combination allows discussing the conscious aesthetic borrowing of Moorish ornamentation motifs within the modernist discourse, which creates a new level of perception of oriental heritage in the urban space of the early 20th century. The Arab World Institute (Institut du Monde Arabe) is a

prominent architectural project in Paris, located on the left bank of the Seine in the Latin Quarter. The building was constructed in 1987 by the famous French architect Jean Nouvel, who sought to combine elements of Arabic architecture with modern construction technologies (Fig. 12).

Figure 12. Institut du Monde Arabe, Paris, 1987
Source: Arab World Institute (n.d.)

The key feature of the Arab World Institute is the façade, made in the form of a complex metal mesh of 240 photovoltaic apertures that imitate traditional Arabian window grilles – mashrabiyas. These diaphragms automatically open and close depending on the intensity of sunlight, creating a dynamic effect of light and shadow inside the building, as well as providing natural ventilation and lighting. This technological approach, based on the principles of ecological design, emphasises the integration of architecture with the environment. The building is shaped like a "U" and includes a library, exhibition halls, museum, conference rooms, restaurant, bookstore, and administrative offices. The architectural style of the Institute combines modernism with Moorish motifs, which is expressed in the use of geometric patterns, symmetrical structures, and ornamental elements. The purpose of such an approach is to create a cultural bridge between the West and the Arab world, preserving traditions and demonstrating their adaptation to modernity. Notably, the Arab World Institute has become not only an architectural landmark in Paris, but also a symbol of cultural dialogue between European and Arab cultures. Its façade has become a famous example of how traditional architectural motifs can be adapted to modern technology and design, leaving them recognisable but giving them new life in a modern city (Burke, 2022).

Another prominent aspect is the preservation of building interiors. For example, the decoration of horseshoe arches, openwork perforations, muqarnas, and mosaic inserts typical of Moorish architecture is actively used in the interior design of cultural and public buildings (Chernyshev *et al*., 2020). For instance, in the restored interiors of the central building of the Kyiv Polytechnic Institute, as well as in some modern hotels and restaurants in Europe. In 2025, the Moorish style is finding new life in private and public construction. Some architectural firms are actively using elements of the Moorish style in their projects, including in the design of cultural centres, art galleries, and tourist complexes. Although it is still largely decorative, this style continues to attract the attention of designers due to its expressive aesthetics and symbolic meaning. In contemporary interior design, Moorish ornamental motifs are often used to create ethnic or exotic spaces, especially in hotels, restaurants, tourist centres, and private homes. Furthermore, elements of Moorish architecture are used in ecological design, which seeks to integrate traditional decorative techniques with modern energy-saving technologies (Ivashko *et al*., 2020).

Thus, the Moorish style in European architecture, which emerged based on the traditions of the Byzantine Empire and spread from Bulgaria through the Balkans, the Black Sea region to Spain, Portugal, Italy, France, Hungary, Ukraine, and other regions, continues to be a significant cultural phenomenon in European heritage. Its emergence and popularisation are associated with the use of decorative coloured plinths, pinnacles, openwork perforations, decorative arches, and other artistic and figurative elements that reflect the influences of the Spanish-Moorish Mudejar style, Portuguese Manuelino, Gothic-Saracenic, and Indo-Saracenic styles. Despite considerable losses and destruction during the 20th century, many Moorish-style buildings still exist and are protected by national programmes and UNESCO. The current state of these objects ranges from well-preserved to endangered. At the same time, the Moorish style continues to be relevant in modern architecture and design, especially in the decorative design of public and private buildings, hotels, restaurants, and cultural centres. The use of Moorish motifs in interiors and the adaptation of this style to modern architectural needs demonstrates its attractiveness and potential for further development. The preservation and restoration of historical objects created in the Moorish style continue to be crucial tasks for modern architects, restorers, and scholars studying the architectural heritage of Europe.

DISCUSSION

The conducted study demonstrated that the Moorish style in European architecture has a long history, beginning with the Byzantine masonry tradition and developing under the influence of Islamic architecture, particularly during the expansion of the Ottoman Empire. The analysis of modern sources helped to better understand the processes of preservation and transformation of the Moorish style in different regions of Europe, as well as its influence on contemporary architectural projects. N. Ait-Aoudia Meriem (2025) showed that Blida (Algeria) has preserved numerous examples of neo-Moorish buildings of the 19th-20th centuries, which served as a source of inspiration for architects. The researcher pointed out the stylistic features of the façades of such buildings, which combine traditional elements with new materials and decorative motifs. Analogous trends can be found in modern buildings in Paris and Barcelona, where the Moorish style is interpreted through the lens of

modern technology and design. P. Burke (2022) addressed the fact that Islamic art, including architecture, actively influenced European culture through contact zones between Christian and Muslim states. These conclusions were confirmed by the results of the present study, which showed how the Spanish-Moorish Mudejar style and Gothic-Saracenic motifs became popular in regions that had close cultural and political ties with the Muslim world. A. Zerrouki (2021) noted that in Algeria, the development of the Moorish style was inextricably linked to the colonial period. The researcher emphasised the transformation of the Moorish style into the neo-Moorish style, which is marked by elements of continuity and a break with the past. These conclusions are a prominent aspect for the present study, as comparable processes can be observed in European architecture, where the Moorish style is gaining a new sound in the context of modernism and postmodernism.

F. Mazouz & M. Triqui (2024) focused on the fact that Algeria is experiencing a revival of Moorish architectural identity in new projects that combine traditional decorative elements with modern materials. These findings are in line with the presented results, which showed that in contemporary architectural projects in Paris and Barcelona, architects are actively using Moorish motifs to create modern buildings adapted to modern requirements. J. Taheri (2021) emphasised the significance of decorative arts and architecture for human psychological comfort, especially within Muslim communities. This idea is of great significance for the present study, as the contemporary use of the Moorish style often focuses on creating harmonious spaces that combine aesthetic and functional requirements. Y. Ivashko *et al*. (2021) emphasised the need to preserve and restore architectural objects in the neo-Moorish style. Their study focused on the monumental works and façades of architectural monuments of the late 19th – early 20th centuries, which often need to be preserved due to the influence of climatic factors and negligent use.

Analogous challenges are relevant for many of the European monuments considered in the study. S. Harrington *et al*. (2022) explored modernisation trends in the architecture of Bosnia and Herzegovina in the early 20th century. The study enabled a better understanding of how the Moorish style interacted with other styles, particularly during the period of national revival and cultural renewal. R.Y. Kassab (2024), in the study on the development of the Habus district in Casablanca, discussed the processes of interpreting the Moorish style in urban spaces. Comparable processes are observed in the contemporary architecture of Paris and Barcelona, where architects use Moorish motifs to create culturally significant objects. N. Lopez-Jantzen (2021) analysed the periodisation and historiography of interaction between Europe and Africa, particularly Italy and the Islamic world. The study focused on the cultural exchange and adaptation of Islamic architectural elements in medieval European art. These findings were in line with the presented results of this study, which demonstrated the influence of the Moorish style on architectural structures in Europe, especially within the former Byzantine domains and territories under Ottoman control.

C. Mileto & F.V. López-Manzanares (2023) considered the protection of historic cities and the conservation of architectural monuments belonging to the UNESCO heritage. The analysis of the case of the Lonja de la Ceda in Valencia illustrates the significance of restoration and conservation of buildings of historical significance, which confirmed the observations on the need to restore many European Moorish-style buildings that are endangered or need to be adapted to modern requirements. G. Murray-Miller (2023) examined Orientalism in Europe in the long 19th century, analysing its epistemological and practical manifestations. The researcher pointed out that interest in Islamic architecture was part of a broader cultural phenomenon, which was expressed through attempts to combine European traditions with exotic motifs brought from the Middle East and North Africa. The findings obtained, which demonstrated the active use of the Moorish style in European buildings from the 19th to the early 20th century, are in full agreement with Murray-Miller's conclusions.

A.W. Sukkar *et al*. (2024) presented an interesting view on the use of artificial intelligence in the creation of Islamic architecture, particularly in the design of modern buildings based on traditional architectural principles. This opens new opportunities for the development of the Moorish style in modern architecture. The findings of the study also confirmed that new projects in Paris and Barcelona are partly inspired by the Moorish style but are actively adapting it to modern functional requirements through innovative technologies. A.E. Arsuaga (2021) studied the development of urban spaces in the Middle Ages, specifically, how Muslim minorities tried to adapt to the new conditions of existence in Christian states. This issue is vital for understanding how elements of Islamic architecture penetrated European cities, became part of local architectural styles, and even formed separate districts. The study showed that Moorish motifs were actively used in both sacred and secular architecture. R. Tottoli (2023) examined the cultural influence of Islamic texts in Europe, which was also reflected in architectural styles. Although the study focused more on textual studies and cultural exchange, the influence of Islamic aesthetics on European architecture is evident and continues to be a prominent aspect of the present study.

A.V. Braga (2022) explored the role of colour, geometry, and patterns in Islamic art, emphasising their decorative and symbolic function. This study is crucial for the current analysis, as such decorative elements form the basis of the Moorish style, which is actively used in modern buildings in France and Spain. S. Karray *et al*. (2023) presented a modern interpretation of the Moorish style in Testur (Tunisia), which showed that Moorish architecture is not an outdated phenomenon, but a living tradition that continues to evolve in the context of new technologies and urban concepts, which is confirmed by the results obtained, showing that Moorish elements are actively used in modern architectural design in Europe, in particular in Paris and Barcelona.

Thus, a comparison of the results obtained with the existing thematic publications showed that the Moorish style was not only a prominent part of European architecture in the past but also continues to be a significant source of inspiration for contemporary architects and designers. The Moorish style is not only a historical phenomenon, but also a living architectural tradition that is constantly evolving and changing in modern conditions. Considering the identified trends, this style can arguably develop further and find use in modern design, making it a unique example of cultural and architectural dialogue between different civilisations. All the studies reviewed confirmed the relevance of this subject, emphasising the value of preserving historical heritage and integrating traditional motifs into modern architecture.

CONCLUSIONS

Thus, a careful study of the formation and development of the Moorish (Andalusian) style in European architecture demonstrated the emergence of the tradition of "embroidered" wall masonry with rows of coloured ochre flat bricks (plinths) in masonry within the provinces of the Byzantine Empire, also in the Black Sea region, dating from the 4th to 5th centuries. Thus, from the 4th to 6th centuries, a series of monuments were built in the Balkans, within the borders of modern Bulgaria, which later became part of the architectural and construction fashion of the Adriatic during the Middle Ages. Later, the ideas of religious architecture were introduced into the sacred buildings of Muslims in Hungary, and neo-Moorish ideas were spread in Bulgaria, Croatia, Turkey, Ukraine, Croatia, Bosnia and Herzegovina, Romania, Italy, Serbia, Lithuania.

The general features of architecture referring to the Moorish style include, firstly, buildings made with elements of "embroidered", striped masonry of façades and interior decoration. Orthodox churches in Byzantium, the Balkans, and the Slavic countries of Europe; mosques, synagogues, Karaite kenesas, Catholic churches, cemetery churches, and secular buildings such as theatres, city administrations, cultural centres, hospitals, schools, and restaurants were traditionally built in this style. Secondly, the defining influences include the style of the Spanish Mudejar (11th-16th centuries), Portuguese Manuelino and Spanish Plateresco (both 16th century), as well as the late synthetic styles of the 19th century – Gothic-Saracenic, Indo-Saracenic, Alhambra style. All of them were reflected in plastic plaster decoration, carved alabaster, and stucco, which should be associated primarily with solemn, "remodelled" elements of the interior design of European buildings of the second half of the 19th and early 20th centuries.

The limitation of this study was the focus on the surviving architectural monuments, as well as the limited access to archival materials on lost or rebuilt Moorish-style objects. Prospects for further research should be associated with an in-depth study of architectural structures built on the territory of ethnic Ukraine in the Moorish (Spanish-Moorish, Andalusian) style during the 19th and early 20th centuries. Specifically, this applies to lost synagogues, Karaite kenesas, hotels, tenement houses, mansions, palaces of the period.

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Витоки і розвиток споруд у мавританському стилі в Європі часів від Середньовіччя до початку XX століття

Анотація. Метою цього дослідження було вивчення функціональних, художніх і композиційних характеристик мавританської архітектури в Європі, простежуючи її витоки у візантійських мурованих кресленнях із середньовічної Болгарії. У дослідженні розглядалося, як цей стиль поширився на синагоги, мечеті, католицькі церкви та громадські установи в таких країнах, як Угорщина, Румунія, Україна, Боснія та інші. Методологія дослідження включала поєднання хронологічного принципу, мистецтвознавчого та дизайн-підходів, онтологічного, аксіологічного, герменевтичного, історико-генетичного, порівняльного, соціокультурного, крос-культурного, формально-стилістичного, типологічного та мистецтвознавчого методів аналізу. Результати дослідження виявилися наступними. Нечисленні пам'ятки з елементами «вишитої» кладки, що збереглися на Балканах, зокрема в старій частині болгарського Несебра, стали цінним джерелом формування мавританського (іспано-мавританського, андалузького) стилю. Ця традиція, що зародилася у візантійсько-середземноморському контексті, згодом трансформувалася у впізнаваний архітектурний напрям. У XIX та на початку XX ст. мода на східні форми поширилася по всій Європі, від Кавказу до Італії. У різних країнах вона проявилася в архітектурі палаців, синагог, кенас, театрів, адміністративних будівель, сакральних споруд. Дослідження довело, що формування мавританського (андалузького) стилю в європейській архітектурі має глибші, ніж вважалося раніше, візантійсько-античні корені, з подальшим розквітом у XIX – на початку XX ст. під впливом східних і західноєвропейських стилів. Практичне значення цих висновків полягає у наданні архітекторам, реставраторам і містобудівникам науково обґрунтованої бази для реставрації, адаптивного повторного використання та делікатної інтеграції елементів мавританського стилю в європейську спадщину і сучасні архітектурні проекти

Ключові слова: монументально-декоративне мистецтво; "вишивана" кладка; орієнталізм; композиція; дизайн середовища

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Development of railway connections in Zakarpattia

Abstract. The issues of supply and evacuation became acute with the outbreak of the active phase of Moscovits war against Ukraine in 2022. In this context, rail transport has demonstrated its stability and reliability throughout the country, making this study is relevant. The purpose of this study was to investigate the railway line of the Zakarpattia (Transcarpathia) region of Ukraine as a major economic, social, and cultural factor and its potential in the national and international context. The results highlighted the need for reliable transport links with the most remote western edge of the state's territory, which, among other things, has been politically isolated from the rest of Ukraine for centuries due to the lack of proper connections through the Carpathian Mountains. The study identified the possibilities and future development of the resource of railway connections between Zakarpattia and the countries of the European Union. For this, historical and geographical analyses and the method of comparing railway connections using field, published cartographic and satellite materials were used. The entire territory of Zakarpattia and neighbouring areas was analysed; the commonalities and specific features of the region's development were noted; all railway lines and the main mountain road lines were considered. The future development of railway communication was proposed, based on the principles of restoration, supplementation, extension, unification, duplication, dispersion, and variability of communication lines. Based on various aspects of the study, conclusions were drawn on the possibility of such development, which constituted the practical value of the present study. The necessity of involving research from other areas for future searches in line with the military and economic feasibility of developing railway connections in Zakarpattia was emphasised

Keywords: railway station; track; narrow-gauge railway; war; mountainous terrain

INTRODUCTION

Rail services all over the world are proving to be a reliable element of transport, economy, culture, and national strategy. In European countries, railways have a long tradition that continues to provide and influence transportation and, more generally, communication in society. At the same time, railways have become a military and political tool in international relations. The realities associated with the war in Ukraine prompt taking a closer look at the existing resource of railways in the defence and development of the region. The territory of Ukrainian Zakarpattia is the

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westernmost part of the country outside the Carpathian range, with significant transport links, including direct rail links to Slovakia, Hungary, Romania, and other European countries. This poses a particular interest and challenge that must be addressed for further development. Railways form an integral part of the country's overall transport system, which includes air and water transport in addition to another land mode, the road, and not to mention cable cars, power grids, and pipelines. Railways should be connected to these modes of transport, having their unique advantages and efficiency. All railways form the contact of this mode of transport with cities and settlements through stations, railway stations, and railway terminals. They connect the community in the urbanised space through architecture. These positions are also significant considering Ukraine's integration into the European Union, which makes the study relevant.

A series of scientific studies investigated the design, urban planning, and architectural properties of railway stations and railway terminals. I. Dreval (2019) addressed the urgent problem of the functioning of railway station complexes in Ukraine as significant structural and functional elements of a modern city. The researcher identified the essential features of the architectural and urban planning organisation of modern railway station complexes based on the analysis of experience in functional, transport, compositional, economic, and ergonomic aspects. The study by V. Timokhin *et al*. (2023) is analogous in terms of the problematic of the study, noting that the efficient use of land resources to free up pedestrian areas, separate traffic and pedestrian flows, organise shortest routes to different types of transport and evacuation when used as shelters, etc., is achieved by arranging underground spaces of transport and interchange hubs. Some studies address the development of railway station architecture.

The doctoral thesis of Y. Rotchniak (2021), apart from general development trends, also focused on regional, artistic, compositional, and other features of railway station buildings depending on the territorial distribution of these objects. The researcher considered the design, urban planning, and transport context. M. Nazaruk (2021) explored the architecture of the railway stations of Holoby and Kovel in Volyn region. The most successful and famous railway stations are presented as professional achievements. J. Gympel (2020) demonstrated and commented on the most beautiful railway stations in Germany as a reflection of the architecture of different eras.

F. Jeschke (2021) studied the formation of a 'national space' in the Czechoslovakian railways in the interwar period. It is of interest to explore the ways of building a national railway network in the physical landscape on the remnants of connections from the Austro-Hungarian monarchy. At the same time, there is a desire to create a modern international transport network of the state of that time. Zakarpattia was part of this state at that time. The monograph by R. Kellermann (2021) has philosophical and cultorological foundations, covering the phenomenon of 'waiting' on the railway stations. The historical development of railway station premises reflects the dynamics of this category in 1830-1935. The acceleration of movement processes opens a new field for research in this aspect.

Y. Rotchniak (2024), based on the historical experience of countries with mountain railway connections, explored the possibility of restoring some of the narrow-gauge railways in the Carpathian region of Ukraine. Their extensions and mergers in remote mountainous areas are intended to create a complementary and alternative connection to existing railways and roads. The creation of a narrow-gauge network with connections to broad and normal gauges will contribute to the economic, social, and tourist development of the region, and in times of war will improve and change the routes of movement for the security and defence of the state.

The purpose of the present study was to identify the potential of existing railway connections in Zakarpattia (2025), determine the lines of restoration of the former tracks, propose ways to extend them, and build new ones with connections to existing railways to increase the transport resource of the state.

MATERIALS AND METHODS

The material base of the study was primarily cartographic material from published sources in print and electronic form. Considering the limited access to more detailed information during the war, the focus was on the main lines of railway connections based on topographic maps and railway track diagrams. As of 2025, the restrictions on movement within the Zakarpattia region, security requirements in border areas, and the very nature of the railway as a state strategic facility do not allow for a more detailed study of the research topic in the field. However, official public electronic resources provide an opportunity to obtain the background data and conduct a search with sufficient accuracy.

The research methods were based on historical, geographical, and comparative analyses of railway connections using field and cartographic materials, published sources, and satellite image data. Observations of spatial patterns during travel and comparison with satellite imagery data allowed designing future railway lines. The established principles for the development of these railway lines become the basis for future implementation. This research topic was considered in the historical, territorial, technical, political, and partially in the socio-cultural aspects of the development of railway connections in Zakarpattia. It formed the basis for the implementation of the idea of creating an integral and uniform railway network of the region in the context of Ukraine and communication with foreign countries.

Thanks to the materials used and the research methodology applied, the historical context of railway connections in Zakarpattia in terms of internal coherence and external contacts was comprehensively established. Therewith, the historical background of the construction of the main motorways of the territory as primary lines and networks of movement was considered. Roads were a prerequisite and

at the same time an indirect determinant of railway connections. The focus on the military expediency of the lines of movement provided an explanation for their position and the current state of these roads. In connection with the railway lines, the architecture of the region's railway stations was an expression of the past and present capabilities and preferences of society in different time periods and political epochs. At the same time, it was an active 'fixed' component of transport in the urban environment.

RESULTS AND DISCUSSION

To overcome natural obstacles in mountainous areas, 'transverse' and 'through-mountain' railways were built along the general directions of movement, and 'longitudinal' lines were built to the main ridges through side valleys connecting these transverse railways. These are, relatively speaking, the two principal ways of traversing the mountains.

Mountain railway connections in Europe. The railway network of the Republic of Austria is a network of three track corridors across the Alps with a general north-south direction: 1) Vienna – Graz – Celovec/Klagenfurt. As part of this line, the world's first mountain railway, the Semmeringbahn, is included; 2) Salzburg – Schwarzach – St.Veit – Villach (Tauernbahn); 3) Scharnitz – Innsbruck – Brenner (Brennerbahn). In the mountainous part of the state, these transit lines intersect with the west-east main line (Bregenz – Innsbruck – Kufstein – Schwarzach – St.Veit – Bruck an der Mur). Together with the denser northern 'Danube' railways, a fairly uniform network of tracks covers the entire state. These lines originated during the monarchy and are part of a larger network that is also located in neighbouring countries.

The construction of the Galician Transversal Railway was clearly military in nature. It was completed in 1885 by connecting the existing lines and extending to the Zbruch river to the south and parallel to the older foothill private Galician railway named after Karl Ludwig. The main connections of the Karl Ludwig company: Kraków – Peremyshl (Przemyśl) – Lviv – Krasne – Brody/Ternopil – Pidvolochysk(-a). In the west, the Galician Transversal Railway ran mainly along mountain ranges. The transverse track was laid farther north from the then state border with the Moscovits Empire. Its total length was 768 km from Zwardoń, Oświęcim (Auschwitz), Kraków, via Nowy Sącz, Hrybiv (Grzybów), Jasło, Korosno (Krosno), Sianik (Sanok), Zahiria (Zagórz), Khyriv, Sambir, Stryi, Stanislawiw, Buchach, to Husiatyn on Zbruch river. A significant part of the railway passed through the mountains, connecting to the Trans-Carpathian railways: 1) Oświęcim – Zwardoń – Čadca – Žilina; 2) Tarniv (Tarnów) – Hrybiv – Nowy Sącz – Lelukhiv (Leluchów) – Orliv (Orłów) – Priashiv (Prešov) – Koshytsi (Košice) – Myshkovets (Miskolc); 3) Peremyshl – Khyriv – Zahiria – Lupkiv (Łupków) – Medzylabirtsi (Medzilaborce) – Humenné – Michalany; 4) Sambir – Sianky – Uzhhorod – Chop; 5) Lviv – Stryi – Batiovo; 6) Stanislawiw – Deliatyn – Voronenka – Dilove – Vyshivska Dolyna (Valea Vișeului) – Syhit Marmaroskyi (Sighetu Marmației). The mountainous part of the Galician Transversal Railway is located in Poland and enters Ukraine through the Korosno (Krościenko) – Stariava border to Khyriv (Hrankin *et al.*, 1996; Bylina, 1999; Tomin *et al.*, 2011).

Narrow-gauge railways are used to overcome the difficulties of the terrain, to pass curved lines of small radius, and to reduce the cost of construction and operation in mountainous conditions. The 'normal' ('normalised', 'standard') gauge is 1,435 mm wide (most railways in the world have it); all wider gauges are "broad" gauges (including 1,520 mm in Ukraine), and all narrower gauges are 'narrow' (750 mm in Ukraine). The use of the term 'euro gauge' to refer to the normal gauge standard is post-Soviet slang that is not used anywhere else.

One of the longest narrow-gauge connections in Europe is in Switzerland, which is located in the general west-east direction (Zermatt – Chur – St. Moritz – Tirano; 1,000 mm gauge), connecting and crossing at junction stations (Brig, Visp, Göschenen) with the transit transalpine railways in the general north-south direction (Gotthardbahn; Bern-Lötschberg-Simplon-Bahn). In the eastern canton of Graubünden, there is a network of narrow-gauge railways that are connected to this narrow-gauge line. The total length of the narrow-gauge railways in the south of the state is many hundreds of kilometres. In the northern foothill cantons, there are separate narrow-gauge lines that are connected to normal gauge tracks at junction stations. Switzerland's railways are integrated into the country's defence sector.

Historical background of the construction of the Transcarpathian railways. The northeastern part of the Middle Danube Lowland, as well as a significant mountainous part of the Eastern Carpathians, was inhabited by Rusyn-Ukrainians since the middle to late first millennium AD. The territory was part of or associated with the state of Rus in its various forms, and as a result of the weakening of the central government, this land came under the influence of Hungary for a long time. To some extent, this was also caused by the natural barrier of the Carpathian Mountains. At the same time, contacts with other peoples and connections with other countries created the specificity of the region. Since 1918, this territory has been known by different names and statuses of administrative units in the vicinity of its current borders: "Ruszka Krajna in Hungary (1918-1919; at the same time, there was an independent Hutsul People's Republic with its capital in Yasynia (Yasinnia) in Rakhiv region, which considerably influenced the formation of the autonomous status of the region and Ukrainian statehood); Pidkarpatska Rus (Podkarpatská Rus, Subcarpathian Rus) in Czechoslovakia (1919-1939), the state of 'Carpathian Ukraine' (1939), and the administrative unit 'Zakarpattia oblast' of the Ukrainian SSR/USSR (since 1945/1946). Since 1991, this region has been part of the state of Ukraine. In a broader sense – historically, linguistically, culturally – Zakarpattia (Transcarpathia) is sometimes referred to as a larger area inhabited, developed, or associated with Ukrainians in Slovakia (Priashiv (Prešov)

region) and Romania (South Marmarosh region), where there are Ukrainian settlements on ethnographic territory, sometimes with the self-designation of 'Rusyns' (Slovakia, Romania) and 'Hutsuls' (Romania). In the modern north-eastern Hungary, there is virtually no autochthonous Ukrainian population (Vehesh, 2009; Zastavny, 2011).

The railway connection in the Carpathians correlates with the roads that were built based on ancient trade routes. The H-13 road through the Uzhok Pass (852 m) is the closest to the Sambir – Uzhok – Uzhhorod – Chop railway. The roads through the Latorytskyi M-06 (770 m) and Serednyo –Veretskyi (Voritskyi) T-1409 (841 m) passes are the closest to the Stryi – Beskyd – Batiovo mainline railway. Analogous is the road H-09 through the Yablunytskyi/Tatarskyi pass (921 m) to the Ivano-Frankivsk – Deliatyn – Voronenka – Dilove railway. The road P-21 Dolyna – Vyshkivskyi Pass (931 m) – Torunsky Pass (941 m) – Mizhhiria – Khust forms an 'independent' mountain crossing (15 mountain passes…, 2021). Thus, three motorways with two tracked mountain crossings between Lviv and the western part of Zakarpattia make up a dense network of roads, while in the east of Zakarpattia, in the neighbouring Ivano-Frankivsk region, there are two motorways, and one tracked road. Other roads through the passes of the Main Watershed Range in Ukraine are not equipped and do not meet the safety requirements for road transport.

The construction of the railways in Zakarpattia took place against the backdrop of industrialisation, after the revolution of 1848-1849 in Europe and the establishment of the dual monarchy of Austria-Hungary in 1867. The region, rich in raw materials (salt, wood, etc.) and agricultural products, needed a reliable means of transportation that would surpass the possibilities of horse-drawn transport and river rafting. To supply and manage the region, railways were built centrally across Hungary with the new capital in Budapest. The star-shaped form of the tracks around the metropolis reflects the shared processes of railway construction as in other capitals such as Berlin, Vienna, London, and Paris. Therewith, a surge in the construction of railway stations took place, which are well preserved, continue to perform their functions, and have become symbols of many cities (Rotchniak, 2021).

The first railway line on the territory of the modern Zakarpattia region appeared in 1872, connecting Dobrochyn (Debrecen) – Kholmiv (Halmeu) – Korolevo – Syhit Marmaroskyi (Sighetu Marmaţiei). In the same year, the railway line Slovenské Nové Mesto (Sátoraljaújhely) – Chorna nad Tysoyu (Čierna nad Tisou) – Chop – Batiovo – Korolevo was put into operation. This line to Syhit Marmaroskyi is a part of the former Hungarian Transversal Railway from the times of the empire. Back then, it connected Chop with Uzhhorod and Batiovo with Mukachevo. In 1873, Chop station was connected to Záhony station. In 1880, a narrow-gauge railway connected Solotvyno via a bridge over the Tysa (Tisza, Tisa, Theiß) river with Cămara Sighet near Syhit Marmaroskyi; later, a normal gauge railway was laid here.

According to the chronology of construction, the railway crossings of the Carpathian Mountains of Ukraine and the adjacent Ukrainian ethnographic territories are as follows: 1) 1872-1874: Peremyshl – Nyzhankovychi – Khyriv – Staryava – Zahiria – Lupkiv – Medzylabirtsi – Michalany, now: Poland – Ukraine – Poland – Slovakia; 2) 1873-1876: Tarniv – Lelukhiv – Orliv – Priashiv, Lemkivshchyna; now: Poland – Slovakia; 3) 1885-1887: Stryi – Lavochne – Volovets – Mukachevo; (in 1872 Mukachevo – Batiovo); 4) 1894-1895: Khryplyn – Deliatyn – Voronenka – Syhit Marmaroskyi; 5) 1904-1905: Sambir – Sianky – Velykyi Bereznyi (1894: Velykyi Bereznyi – Uzhhorod) (Hrankin *et al.*, 1996; Bylina, 1999).

In 1887, the trans-Carpathian branch line Mukachevo – Skotarske – Beskyd – Stryi, built in turns, came into operation, which since the mid-20th century has been double-tracked, electrified, and used as a main line and is part of the Fifth International Transport Corridor. It was the first railway to cross the Carpathians within the modern borders of Ukraine and the third on the Ukrainian ethnographic territory. In 1891, a track was laid from Teresva station along the right bank of the Tysa river to Solotvyno and Velyky Bychkiv. In 1894-1895, from Syhit Marmaroskyi, the track ran along the left bank of the Tysa river to Dilove, and then through Rakhiv, Yasynia through the Watershed Ridge tunnel to Voronenka station in Galicia. In 1913, the station Vyshivska Dolyna was connected to Borsha (Borşa) in South Marmarosh. In 1949, a railway was launched from this branch from the station Vişeu de Jos to Salva in Romania.

In 1905, the trans-Carpathian branch line Uzhhorod – Uzhok – Sianky – Sambir, which was built in turn, came into operation and was electrified. In 1920-1921, the Uzhhorod – Pavlove – Matiovtsi (Mat'ovcé) – Velyki Kapushany (Velke Kapušany) – Trebyshiv (Trebišov) railway was established to avoid the vulnerability of the Chop station on the Hungarian border, which was the only railway connection between Slovakia and Pidkarpatska Rus at that time. In the interwar period, the young multinational state of Czechoslovakia created a modern railway network based on the Austro-Hungarian system. Thus, the railway connections in Zakarpattia (Pidkarpatska Rus, Carpathian Ukraine) became part of the new transport space (Jeschke, 2021).

After the Second World War and with the establishment of new state borders, the tracks of the Zakarpattia region were converted to the standard of the then Soviet width of 1,524 mm. Since then, the main border railway junction of Chop has been providing both wide gauge (now 1,520 mm) and normal gauge (1,435 mm) transport to Slovakia (Chorna nad Tysoyu) and Hungary (Záhony). There is a normal gauge line from Chop through Korolevo to Diakove to Romania (Kholmiv). In 1966, a combined normal and broad-gauge railway was built from Uzhhorod via Pavlove to Matiovtsi and to Haniska near Koshytsi in Slovakia, replacing the previous one from 1920-1921. Since 1984, there has been a connection between Svoboda and Eperjeske to Hungary.

The railway tracks and facilities in the Zakarpattia region of Ukraine are part of the Lviv regional branch of the

Ukrainian Railways. Most of the tracks belong to the Uzhhorod Directorate of Railways, while in the eastern part of the region, the Dilove – Lazeshchyna – Voronenka section belongs to the Ivano-Frankivsk Directorate of Railways (Kartohrafiia, 2008). Three gauges are in use – mostly the national "wide" gauge of 1,520 mm, partly the "normal" gauge of 1,435 mm, which is dominant in Central European countries, and partly the "narrow" gauge of 750 mm on the Borzhava railway and the Uzhhorod Children's railway (Hrankin *et al.*, 1996; Tomin *et al.*, 2011).

The architecture of railway stations in Zakarpattia deserves special attention. It is a spatial and constructional embodiment of the perceptions and capabilities of society in different historical periods and, at the same time, continues to exist and serve the modern community. Railway stations and their buildings form a wide palette of types, sizes, styles, and compositional techniques. They are unique to Ukraine and need to be studied, preserved, and developed (Rotchniak, 2021) (Figs. 1-6).

Figure 1. A typical station building of the Hungarian State Railways (MÁV) from the late 19th and early 20th centuries in Batiovo
Source: photographed by Youri Rotchniak (2015)

Figure 2. The building of the Karpaty railway station (also the eponymous modern sanatorium) of the former palace complex of the Schönborn Counts in the late 19th century near Chynadiievo
Source: photographed by Youri Rotchniak (2010)

Figure 3. Platform of narrow-gauge trains at the Vynohradiv station in the late 19th and early 20th centuries
Source: photographed by Youri Rotchniak (2016)

Figure 4. Khust railway station building
Notes: photograph of 1920-1930 from the exhibition stand of the Lviv Museum of the History of Religion
Source: photographed by the authors of this study (2024)

Figure 5. Building of the Velykyi Bereznyi station in the late 20th century
Source: photographed by Youri Rotchniak (2016)

Figure 6. Complex of the new (left, 2004) and historic buildings (right, 1905) of the Uzhhorod railway station
Source: photographed by Youri Rotchniak (2016)

Geographical and spatial features of railway connections in Zakarpattia. The territory of Zakarpattia occupies the flat steppe part of the Middle Danube Lowland along the Tysa river basin – in fact, 'beyond the Carpathians' ('trans the Carpathians') in relation to Kyiv and most of the country, and in contrast to 'Prykarpattia' (by the Carpathians) – the southwestern foothill part of Galicia and Bukovyna. Zakarpattia is also the mountainous area to the south and southwest of the Main Carpathian watershed of the Tysa river basin. Overall, based on the topography, the main railway lines of Zakarpattia can be divided into plain and mountain lines.

Plain railway lines: 1) Chop – Batiovo – Korolevo – Solotvyno – Velykyi Bychkiv ('Potysnianska' or 'Tysa' railway). As of 2025, the Solotvyno – Velykyi Bychkiv section of the railway is dismantled. The once united village of Velyky Bychkiv has been divided by a border along the Tysa river since 1919/1920; it is now part of Romania's Bocicoiu Mare. Chop station has direct connections to Chorna nad Tysoyu in Slovakia and Záhony in Hungary. This line is connected by a branch line from Esen to station Solovka and then across the border to Eperjeske in Hungary. 2) Korolevo – Diakove; Diakove station connects to Kholmiv station in Romania.

Mountain railway lines (part of the Trans-Carpathian railway): 1) Chop – Uzhhorod – Uzhok – Sianky. From Uzhhorod station there is a broad-gauge branch to Pavlove station and then across the border to Matiovtsi station in Slovakia. 2) Batiovo – Skotarsko – Beskyd; 3) Dilove – Lazeshchyna – Voronenka. From Dilove down the left bank of the Tysa river, a wide railway track enters the territory of Romania, reaching the junction station Vyshivska Dolyna, and then through Velykyi Bychkiv, Syhit Marmaroskyi and Dovhe Pole (Câmpulung la Tisa) via the border bridge "returns" to Ukraine to the Teresva station. Therewith, in Romania, from Vyshivska Dolyna to Syhit Marmaroskyi, there is a parallel or combined track (combined track consists of four rails on one sleeper for bogies of different standards – wide and normal gauge). There were two railway lines between Teresva and Velykyi Bychkiv stations, about 30 km away, on both sides of the Tysa river, connected by three bridges. The only one in operation is the border railway bridge over the Tysa river between Teresva and Dovhe Pole. The bridge in Velykyi Bychkiv – Bocicoiu Mare and the Solotvyno – Cămara Sighet bridge near Syhit Marmaroskyi have been dismantled, although they are still marked on some maps (Kartohrafiia, 2008). On the territory of Romania, the railway line along the Tysa river is fully preserved.

Specific features of narrow-gauge connections in Zakarpattia. In some countries, narrow gauge railways are dominant (New Zealand, South Africa, Japan, etc.), while in others they are used on an equal footing with others (Australia, Argentina, Bolivia, Switzerland, etc.). There are technical, economic, historical, military, and political reasons for the existence of different gauges. In Zakarpattia, narrow-gauge railways of different gauges have been in existence since 1880. At the turn of the century, the 760 mm gauge, the "Bosnian gauge", which existed as a standard in Austria-Hungary and was under special attention of the military, dominated (Wendelin, 2006). The name is associated with the largest narrow-gauge network of the empire in Bosnia, annexed in 1908, which was 665 km long (Kubinszki, 2009).

The narrow-gauge railways in Zakarpattia region were built and used primarily in mountainous conditions for the transport of timber under different economic systems, political regimes, and wars until the 1960s and 1980s. They led to the curtailment of timber rafting along rivers, making the supply and processing of materials year-round and reliable. The lines continued to be built after the Second World War, starting at railway stations or timber processing farms on normal/wide gauge tracks and running along rivers and streams high into the mountains. Along the way, places were arranged for travel and loading of materials. Narrow-gauge railways played an important economic and social role in the orderly development of mountainous areas. Other raw materials and supplies were also transported by narrow-gauge; by the mid-20th century, some tourist trains were launched, and later regular passenger trains were launched in the valleys of settlements. The total length of the narrow-gauge tracks in Zakarpattia at that time was about 990 km, and in the Ukrainian Carpathians as a whole – about 1,410 km (Klapchuk, 2009; 2016) (Fig. 7).

In the mid-20th century, all narrow-gauge railways in Zakarpattia were converted to the all-Union 750 mm narrow-gauge standard, which is still in use in Ukraine. Starting in the 1980s and into the early 2000s, many narrow-gauge railways in the region were degraded and dismantled due to low efficiency, poor management, lack of awareness of their value, and theft by some owners and local residents. The only operating railway with restrictions is the Borzhava narrow-gauge railway, which connects the stations of Berehove, Khmilnyk, Irshava, and Vynohradiv in the Borzhava river basin. It is a part of a large network that once reached the slopes of the Polonyna Borzhava.

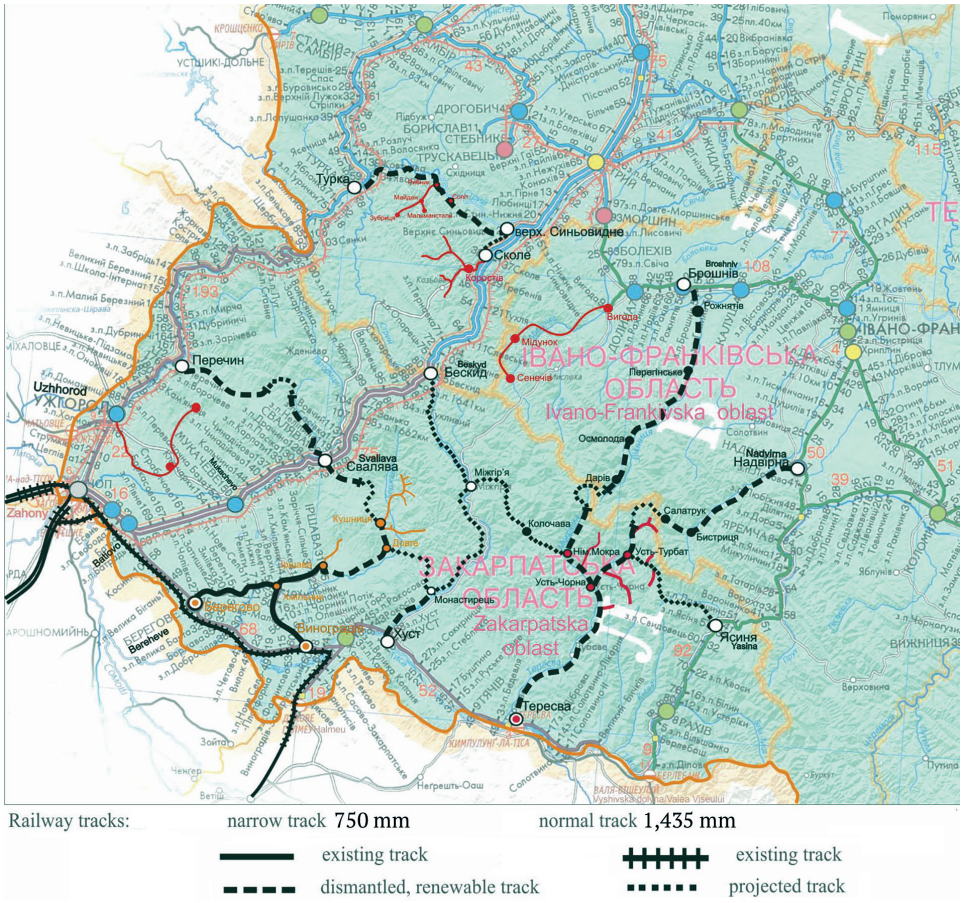

Figure 7. Scheme of narrow-gauge railway lines in the Carpathian region of Ukraine based on the map of the Lviv railway
Source: created by the authors of this study based on data from Kartohrafiia (2008) and Y. Rotchniak (2024)

The children's railway (750 mm) in Uzhhorod starts at the Molodizhna station near the Philharmonic (former synagogue) in the city centre and runs for 1.1 km to the Parkova Station along the right bank of the Uzh river to the eastern part of the Uzhhorod Botanical Garden. It was opened in August 1947 in the wake of the construction of analogous Children's Railways as a centre for teaching children railway skills and as an attraction for recreation in city parks. In total, 9 Children's Railways are recognised as operating in Ukraine, 11 are closed, and 2 are not implemented. Due to the martial law and uncertainty, some of them are not operating.

The role of the railways in the history of Ukraine, and particularly in its wars, is discussed in a series of studies and theses, which demonstrate the significance of this mode of transport in the political and military aspect. I. Agiyenko (2011) focused on the early period of the emergence and development of railways in Ukraine as part of two empires and specifically emphasised the military and political component of this process. S. Bohatchuk (2000) investigated the socio-economic aspect of the railway transport of Ukraine in the second half of the 19th century and the early 20th century. O. Kryvopishyn (2011) covered the construction and role of the Bender-Galatian (between cities Bender, now in Republic of Moldova, and Galaţi in Romania) railway in the military operations of 1877-1878 and in the economic context. The location of this line and its connection to the tracks of the territory of modern Ukraine are vital for understanding the role of military and political visions. Historical aspects of the formation and development of railway transport in the east and south of Ukraine in the second half of the 19th century and the early 20th century were covered in the theses of R. Ponomarenko (2007) and S. Pryimuk (2010). In his thesis, I. Tolokniov (2001) studied the railway transport of Ukraine during the First World War. V. Klapchuk (2009; 2016) explored the railway connections and transport of Galicia and the Carpathians in their economic and political contexts. These academic sources comprehensively covered the historical basis for the development and role of railway connections in different regions of Ukraine and, to varying degrees, addressed the military context. However, in this vein, there are no separate studies on the railways of Zakarpattia.

Since 2014, Ukraine has been waging a defensive war against imperial aggression, which is based on the principles and methods of the 19th and early 20th centuries. As in the past, the tools of warfare stay the same, despite the seemingly more effective means of attack and destruction. The needs and advantages of railway communication are used for both offensive and defensive purposes. This means

that the historical experience of using railways must be studied and applied regardless of time, territorial distance, or seemingly peaceful conditions. Based on the presented results, a series of positions were outlined, according to which the future development of railway connections in Zakarpattia is seen. By analogy with F. Jeschke (2021), the territory of Pidkarpatska Rus – Carpathian Ukraine, which in 1919-1939 belonged to Czechoslovakia, was considered in this study as the Zakarpattia region of Ukraine and, accordingly, from the perspective of Kyiv's political, economic, and military interests.

Based on the experience of laying railway lines in the military-political context, it was concluded that multi-line communication is necessary for the security of the state's territories (Bylina, 1999). Specifically, it is known from history that in the absence of an alternative railway connection of Bukovyna (Bukowina, Bucovina – the easternmost crown land of the monarchy) through the Carpathians to Semyhoroddia (Transilvania) before the First World War, the region twice fell victim to occupation and devastation from the Eastern invasion (Hrankin *et al.*, 1996). At that time, the crown land of Galicia and Volodymyriia (Volyn) had 6 railway crossings of the Carpathian Watershed Ridge with connections to the sub-Hungarian territories of the empire (Kubinszki, 2009). In-depth studies of different ways of communication and connections in Zakarpattia are needed, following the example of V. Klapchuk (2009; 2016), which concern Galicia and the Ukrainian Carpathians. Apart from economic reasons, it is advisable to focus on the political and military component of railway communication, as some railways were built for war and during the war.

The railway lines in Zakarpattia mentioned above in this study form a developed network mainly in the plains and along the state border. There are two equidistant branches crossing the Carpathians to Galicia in the western part of the region: 1) Chop – Uzhhorod – Sianky – Sambir and 2) Batiovo – Mukachevo – Beskyd – Stryi. The tracks along the western and southern border and the incomplete branch crossing the mountains through Ukrainian territory to Galicia in the eastern part of the region are distinguished. There is a noticeable convergence of lines and interstate railway crossings with Slovakia and Hungary in the west of the region in the Chop – Batiovo area; and in the east – with Romania in the Teresva – Dilove area. Thus, there are two railway crossings with Slovakia, two railway crossings with Hungary and three with Romania. The preserved Borzhava narrow-gauge railway on the Berehove – Irshava – (Dovhe) section runs roughly parallel to the Batiovo – Svaliava main line (Fig. 8).

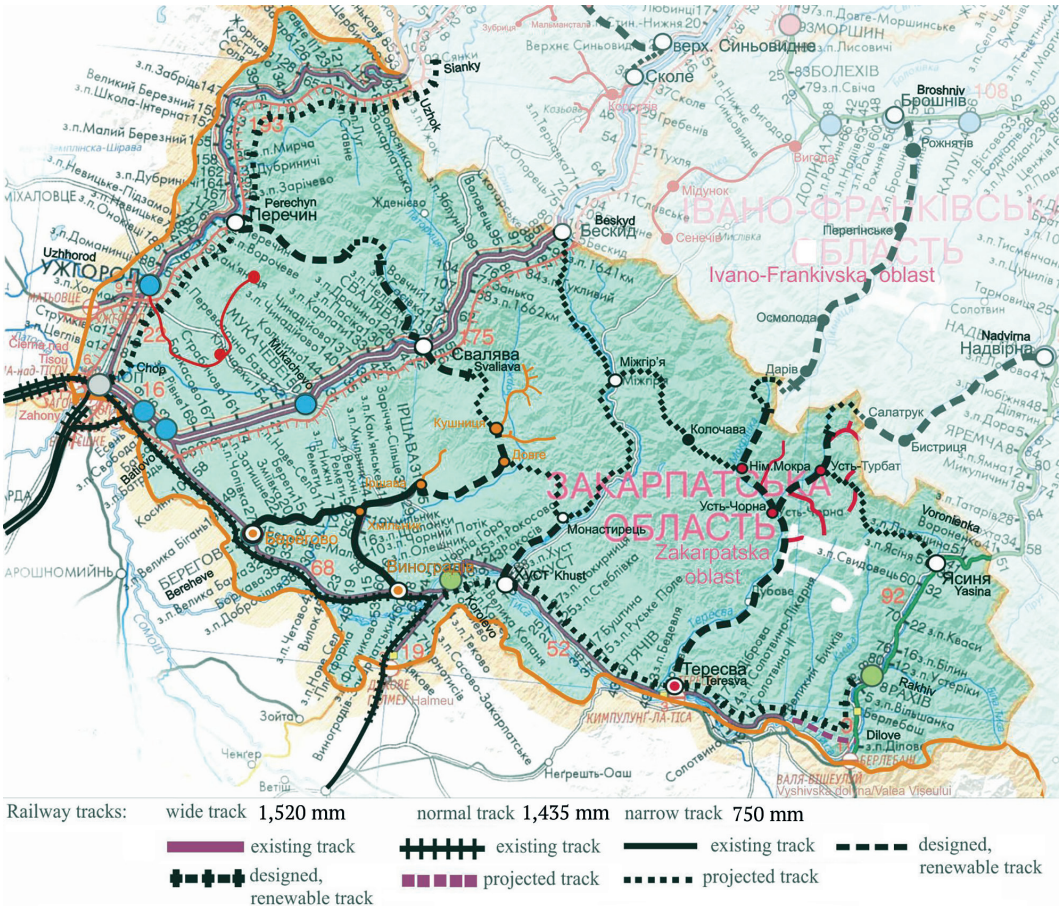

Figure 8. Scheme of railway lines of the Zakarpattia region of Ukraine based on the map of the Lviv railway
Source: created by the authors of this study based on data from Kartohrafiia (2008) and Y. Rotchniak (2024)

Ways to develop railway connections in Zakarpattia. The future development of railway communication is based on the following principles: restoration, addition, extension, merger, duplication, dispersion, and variation of lines. The principles are implemented by the following means: renewal of existing tracks, rebuilding of former tracks, extension and merging with other railways, connection to stations and railway stations, construction of new railway lines. It is necessary to restore the Solotvyno – Velykyi Bychkiv railway line and rebuild two railway bridges in the Upper Potyssia between Ukraine and Romania – 1) Velykyi Bychkiv – Bocicoiu Mare in the first place and 2) Solotvyno – Syhit Marmaroskyi (Cămara Sighet), if possible. The duplication of different gauges of combined track along the border on each side of the Tysa river can considerably increase and diversify passenger and freight traffic. The construction of a new railway line of normal and wide standards from Velyky Bychkiv station on the right bank of the Tysa river, on Ukrainian territory, to Dilove station, will completely independent the railway connection in Zakarpattia. Thus, trains from Uzhhorod would use the Potysnianska railway to reach Rakhiv without two border crossings. From there, they would continue through the Lazeshchyna – Voronenka passage to the east to Galicia and then to the rest of Ukraine's railways.

A new railway line of normal and wide gauge from Velykyi Bereznyi to the border and on to Stashtchyn (Stakčín) in Slovakia would ensure reliable transport in agreement with that country. This third railway crossing to a neighbouring country would further diversify interstate transport. The political will of the government of Carpathian Ukraine to build this railway was reported in the study by M. Vehesh (2009) in the context of changes in Zakarpattia in 1938-1939. The construction of the Perechyn – Svaliava – Khust narrow-gauge line using former dead-end sections (Perechyn – Turya river valley, Svaliava – Polyana, Svaliava – Rososh, Khust – Monastyrets) made it possible to connect settlements along the rivers to these broad-gauge stations. Connecting these towns by rail would have been an implementation of this idea since the autumn of 1938, when, along with the Potysnianska railway, the southern regions of Pidkarpatska Rus (Zakarpattia), as well as the southern regions of Slovakia, were occupied by Horticist Hungary. The connection of Velykyi Bereznyi with Stashtchyn on a wide and normal gauge is part of this older idea (Vehesh, 2009).

At Dovhe station, the line would connect to the Borzhava narrow-gauge railway. The Khust – Monastyrets – Mizhhirya – Beskyd narrow gauge along the valleys of the Rika, Rypynka, and Studenyi rivers would connect to the Beskyd broad gauge station before the tunnel on the Galician side of the double-track international highway. The former narrow-gauge railway Teresva – Dubove – Ust-Chorna – Ruska Mokra – Ust-Turbat – Brustury and its branch Ust-Chorna – Nimetska Mokra are viewed as crucial for development. This network should be extended through the Carpathian passes and connected to analogously non-existent narrow-gauge railways in Galicia along the Broshniv – Rozhnyativ – Perehinske – Osmoloda – Dariv line (to the line at Nimetska Mokra) and the Nadvirna – Rafailova (Bystrytsia) – Salatruk line (to the line at Brustury). These two lines would have enabled the fourth crossing of the Watershed near the Nimetskyi (German) Pass (1,177 m) and the fifth near the Legion Pass (before 1914 – Velyki Rogodze; 1,110 m) to cross the Carpathians, connecting stations on different branches of the broad gauge lines – Teresva, Broshniv, and Nadvirna. A possible name for these two lines is "Trans-Gorganian Railways". A connection between Mizhhiria – Kolochava – Ust-Chorna – Yasynia would complete this proposed network of narrow-gauge railways in Zakarpattia. This line runs roughly parallel to the Watershed Ridge and, together with the revitalisation of a series of abandoned forest roads, would create another transport reserve in the north-eastern parts of the Zakarpattia region. These considerations are based on the findings of Y. Rotchniak (2024) on the development of narrow-gauge railways in the Carpathian region of Ukraine in the context of the war.

Strategic resource in the development of railway connections in Zakarpattia. Thus, the three existing branches of the Trans-Carpathian broad-gauge railways would be complemented by a fourth, and with a branch and a fifth branch, by the Trans-Carpathian narrow-gauge railways. They would all have been connected by transverse narrow-gauge lines much further from the state borders in the mountains of Mizhhirya, Tyachiv, and Rakhiv districts within Ukrainian Zakarpattia. Overall, there would be junction stations with interchange/reloading of wide and narrow-gauge trains – Perechyn, Svalyava, Teresva, Khust, Yasynia, together with the existing Berehove, Vynohradiv in Zakarpattia region, and Beskyd and the former narrow-gauge interchange Broshniv, Nadvirna in Galicia. The existing part of the Borzhava narrow-gauge railway needs to be restored to the platform of the Berehove railway station. From a strategic perspective, this is a key to increasing mobility, diversifying supply lines, and enhancing safety in rail transport. The use of narrow-gauge platform bogies allows partially transporting "large" wide gauge and normal gauge wagons on narrow gauge tracks. This further contributes to the manoeuvrability of rail transport. These positions will help to increase the mobility of residents, develop tourism, and manage forest lands (Kovalyshyn *et al.*, 2023). The restoration of former dead-end narrow-gauge railways, such as Antalovetska near Uzhhorod; Dubrynychi – Liuta; Bilo-Tysnianska (Vydrychka – Shchaul river) near Rakhiv; near Lazeshchyna, and others would be fragmentary and would facilitate local track connections for local passenger transport, tourism, and partly economic purposes.

The children's narrow-gauge railway in Uzhhorod is a separate educational and cultural segment of the railway connections and can be connected by extending this narrow gauge through the preserved former railway bridge near the power plant to the passenger stop at the Domanyntsi station on the Uzhhorod – Perechyn section. Boarding passengers at this stop in the suburbs of Uzhhorod would

provide an alternative access to the city centre, bypassing existing rail and road routes, and would be worthwhile for sightseeing and recreational trips along the picturesque Uzh.

The introduction of narrow-gauge railways in the Zakarpattia region will markedly improve access and connectivity between various recreational and sporting areas. A series of settlements along the Polonyna Borzhava (Volovets, Podobovets, Pylypets, Mizhhiria), Polonyna Krasna (Kolochava, Ust-Chorna), Polonyna Svydovets, Drahobrat (Chorna Tysa, Yasynia), etc., will improve contact with the existing railways of the Uzh, Latorytsia, Borzhava, Chorna Tysa, and Tysa river valleys. The approach and two crossings of the Gorgan massifs will help regulate the use of natural areas and make these ranges easier to access for tourism. In addition, as a result of the narrow-gauge railways crossing the Carpathian Watershed, there will be contact with the railways of Galicia in the areas of the Prut river (stations and settlements: Vorokhta, Tatariv, Bukovel, Yaremche), Limnytsia river (Osmoloda), and Opir river (Slavske, Skole, Tysovets, Plavie-Plai) basins, etc.

Thus, the giant railway arc along the state border in Zakarpattia should be supplemented by a wide and normal gauge track on the Solotvyno – Velykyi Bychkiv – Dilove section. This arc should be joined by internal and international tracks. The existing two-track Batiovo – Mukachevo – Stryi railway, which is far from the borders, should stay a wide two-track line, while the two trans-Carpathian single-track lines 1) Chop – Uzhhorod – Uzhok – Sianky – Sambir and 2) Vyshivska Dolyna – Dilove – Lazeshchyna – Voronenka – Deliatyn – Kolomyia should become combined – with one wide and one normal gauge. Narrow-gauge lines and a network of narrow-gauge railways will be an alternative and complement to the main railway connections.

The construction of normal and broad-gauge railways in Zakarpattia in parallel or combined will provide for more options for travel. Connecting narrow-gauge railways to junction stations requires the same approach – the restoration and development of narrow-gauge railways is viewed as a promising way to create a narrow-gauge railway network in Zakarpattia region in areas that are remote from existing broad and normal gauges and from state borders. The basis is the remnants of some narrow-gauge lines and the traced lines with the lower track structure. The use of the three-gauge standards should turn from a current challenge into an advantage – Ukraine is unique in this regard in the context of rail connections. At the same time, railway stations and interchange facilities should be arranged at railway stations and railway stations, which is the responsibility of planners, engineers, and architects. Accordingly, the connection of road access to stations and railway stations will revitalise the overall transport system of the region.

CONCLUSIONS

Historically, the development of railway connections in Zakarpattia began in the 1870s. At the beginning of the 20th century, a network was established that reflected the economic, administrative, political, and military interests of Budapest and Vienna. Subsequently, the political background led to changes in the directions and volumes of traffic, but there are no noticeable traces of them on the railway lines. The territorial development of railway connections in Zakarpattia initially took place along the Tysa river, and other rivers for connections in the Middle Danube Lowlands. The purpose of the tracks in the valleys was to reach the Watershed Ridge to Galicia. The scattered trans-Carpathian lines were connected to the Potysnianska railway within the region. A network of individual narrow-gauge railways was formed, where the connections were densified. The laying of the railways in the mountains created a grid-like pattern with the main lines crossing the mountains. In the northwestern part of the region, the railway network is denser.

The technical development of railway connections in Zakarpattia was in line with scientific advance: railways were built, main lines were doubled and modified; the latest control and signalling systems were introduced; two trans-Carpathian lines and part of the Potysnianska line were electrified in the west of the region. There are three-gauge standards in place; the dominant one is the national gauge. The strategic development of railway connections in Zakarpattia corresponded to political conditions and military interests: imperial (Austria-Hungary), interwar democratic (Czechoslovakia, Carpathian Ukraine), and authoritarian (Hungary, the USSR). With the restoration of Ukraine's independence, there is a state of inertia in preserving, modernising, and adapting. The railway connections require rethinking and active action in the context of statehood.

The socio-cultural development of railway connections in Zakarpattia is most pronounced in railway stations. Many architecturally distinctive buildings were created before the mid-20th century. Social contacts on the railway reflect industrial, domestic, linguistic, and other relationships; they are a significant layer of culture. The future development of railway connections in Zakarpattia is based on the economic, social, and strategic needs of the state through the restoration, supplementation, extension, unification, duplication, dispersion, and variation of lines. The idea of a continuous railway connection can be implemented by connecting tracks of three standards to hub and border stations. The diversity and multidirectionality of the lines adds to the reliability and controllability of railway traffic.

The potential of the existing railway connections was studied, the lines of restoration were identified, and the ways of extensions with connections to the existing ones were proposed, indicating the possible development of future railway connections in Zakarpattia. It is based primarily on defence needs, which may not be in line with economic feasibility. New lines will increase the significance of cities, towns, and territories. Therewith, environmental, monument protection, legal, and other requirements will

adjust the above provisions. Long-term development of railways requires political will, motivation, and a state vision. The following scientific research should be conducted as a basis for design and implementation.

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CONFLICT OF INTEREST

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Розвиток залізничних сполучень Закарпаття

Анотація. Питання постачання та евакуації гостро постали з вибухом активної фази московської війни проти України у 2022 р. У цьому контексті залізничні перевезення продемонстрували свою стійкість та надійність на усій території держави, а тому дане дослідження є актуальним. Мета статті полягала у дослідженні лінії залізничних сполучень Закарпатської області України як великого господарського, соціального та культурного чинника і її потенціалу в державному та міжнародному контексті. У результатах звернено увагу на потребу надійності транспортних сполучень із найвіддаленішим західним краєм території держави, який у тому числі й через відсутність належних зв'язків через карпатські гори на багато століть опинився у політичній ізоляції по відношенні до решти України. Виявлено можливості та майбутній розвиток ресурсу залізничних сполучень Закарпаття з країнами Європейського союзу. Для цього було використано історичний і географічний аналізи та метод порівняння залізничних сполучень з використанням польових, опублікованих картографічних і супутникових матеріалів. Було проаналізовано усю територію Закарпаття та сусідніх територій, зазначено спільність та особливості розвитку краю; розглянуто усі лінії залізничних сполучень та основні гірські автомобільні. Запропоновано майбутній розвиток залізничного сполучення, який виходить з принципів: відновлення, доповнення, продовження, об'єднання, дублювання, розосередження, варіантності ліній сполучень. На основі різних аспектів дослідження зроблено висновки про можливість такого розвитку, що становить практичну цінність цієї роботи. Наголошено на необхідності залученням досліджень з інших сфер для майбутніх пошуків в руслі військової та економічної доцільності розвитку залізничних сполучень Закарпаття

Ключові слова: вокзал; колія; вузькоколійка; війна; гірські терени

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Defence housing in the 18th century and its genesis in the cultural landscape of the Ukrainian village

Abstract. In Ukraine, the register of monuments that characterise the cultural suburban landscape includes only a few objects. However, the remains of walls or ramparts of defensive dwellings and their territory are not officially recorded, and, in most cases, their historical boundaries are not considered when distributing village land. The purpose of this study was to characterise the planning and spatial solution and genesis of defence housing from the 18th century in the cultural landscape of the Ukrainian village. The study was conducted in the Lviv region. The study was based on a comparative analysis of the functioning of defence housing at three stages of its existence. About 40 objects were analysed for their location in the village structure. The planning and origin of 3 defence housing objects were studied in detail. No small rural defence courtyards exist in the Lviv region as of 2025. However, the land within the defensive walls and on the site of former gardens created during the development of the defensive yard into a residence estate is often undeveloped. Defensive courtyards, which have undergone a long evolutionary path, are a particular type of dwelling in landscape architecture that evolved into the complete opposite – from a walled dwelling to a dwelling with a garden and a park. The defence housing study confirmed Eastern Galicia's intensive urban development. Fixing memory of the region's culture and architecture by marking the territories of former defensive structures is appropriate when creating tourist and educational routes in historical centers of settlement

Keywords: defensive structures; fortifications; countryside; territory planning; castle

INTRODUCTION

As of 2025, no fully preserved objects, such as a dwelling with defensive structures or its later transformation into a residence, exist. However, certain preserved elements of the region's historical and cultural landscape and knowledge about them contribute to forming its established diversity and identity. Documentation of data about an object that does not officially have the status of a monument but is essential in recording the region's historical development is the basis for developing a regional planning strategy and master plans for settlements.

Most studies dedicated to defensive housing primarily focus on the description and classification of such objects. The most comprehensive recent research on the defensive architecture of the western region of Ukraine includes the study by M. Bevz (2020). The scholar introduced into academic circulation the cartographic source titled "Lemberg. General Carta von dem Marche der bey Hommona in Hungarn gestandenen K.K. Trouppen, bis zur Hauptstadt Lemberg in Pollen, 1772." A detailed examination and interpretation of the depiction of the terrain and defensive

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architectural objects presented in this map holds significant academic value, as this cartographic material has not yet been thoroughly analysed by researchers.

The existing descriptions of defensive structures in the region of Galicia have been supplemented, and for certain objects, graphic reconstruction proposals were developed by researchers O. Okonchenko & I. Okonchenko (2022). Their study identified key contradictions arising in typological classification of defensive structures. M. Bevz & T. Pinyazhko (2022) demonstrated that the mid-19th-century fortifications of Galicia represent objects of modernisation within the Venetian-Renaissance tradition in Austrian military architecture. This finding underscores the uniqueness of Galician defensive architecture within the broader context of both Austrian and European architectural heritage. The researchers also proposed three principal methodologies for the contemporary preservation, conservation, and musealisation of mid-19th-century fortification structures in Galicia. These methodologies were provisionally named according to the nature and type of intervention: adaptation-worldview oriented, historically-symbolic, and informational-complementary.

Most studies on defensive housing focus primarily on buildings and their individual elements. Based on the examination of a complex of castles that functioned as fortifications in the mid-16th to 17th centuries in the western region of Ukraine, O. Okonchenko *et al*. (2020) identified and analysed five variants of the spatial and volumetric structure of gate complexes. Their study of castle entrance nodes as dominant architectural elements led to the conclusion that, during the 16th-17th centuries, early forms of tower and bastionette defence systems continued to function alongside bastion-type fortifications. This conclusion regarding the prolonged genesis of defensive structures substantiates the relevance of studying defensive housing within the landscape of the Ukrainian village, as objects with a long evolutionary history serve as the most significant evidence of regional cultural heritage.

M. Rocha *et al*. (2024) investigated the specific features of reconstructing defensive structures based on their original building materials. The researchers provided a rationale for conservation interventions applied to defensive military structures built with rammed earth. The aspect of stabilising the soil form of such defensive structures is particularly important in cases where later architectural additions have a low degree of preservation. The range of combined measures for conservation, reintegration, and reconstruction was classified into four categories: 1. Conservation of walls, which prioritises the preservation of the original material over the restoration of the fortification's original appearance; 2. Consolidation of walls, which involves strengthening the structure using materials similar to the original; 3. Restoration of the structure; 4. Reintegration or replacement of the finishing surface. This data collection method is particularly significant for Ukraine, both for researching historical sites in mountainous areas and for digitising as many monuments as possible that are at risk of destruction during the wartime.

An opposing method in the study of defensive structures is the analytical data collection method. O. Okonchenko & I. Okonchenko (2022) developed a methodology for studying an object based on their characteristics that identify them within a specific system of defensive structure organisation. Defensive structures are increasingly being regarded as cultural tourism objects. S.K. Remya (2024) substantiated the significance of forts, which serve as enduring symbols of the region's history and valuable cultural heritage, highlighting the distinctive features of the local building culture.

The purpose of the present study was to identify the features of the planning and spatial solutions of defensive housing in Ukraine, particularly in Galicia, and to trace its genesis. According to the stated purpose, the key research objectives were defined as follows: to establish and characterise the key stages in the formation of defensive housing systems and their typology; to determine the distinctive features of Galicia's regional defensive architecture, particularly the principles of landscape localisation, from the late 18th to the early 20th centuries.

MATERIALS AND METHODS

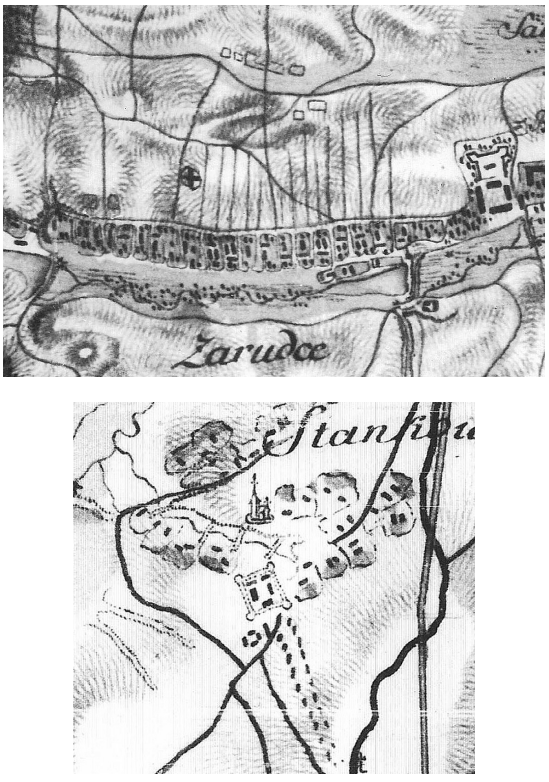
The study was concentrated on the Lviv region. The study was based on the review of scientific papers and archival sources, including cartographic materials, with their subsequent systematisation. The study performed a comparative analysis of the functioning of defence housing at three stages of its existence: of the end of the 18th century, at the turn of the 18th and 19th centuries, in the 19th century. The research methodology was based on the processing of cartographic materials and their comparative analysis. To explore each stage of the object's development, the study analysed exactly those cartographic materials that ensured the reliability of the object's indicators, its parameters, and the planning structure where it was located. Maps by F. von Mieg, made in 1:28,800 scale, record the entirety of housing, both defensive and residential, in the western lands of Ukraine at the end of the 18th century (Petryshyn, 2006).

Buildings, including castles and palaces, are shown on the map as a plan, in contrast to the axonometric depiction of sacred structures. In the study of defensive housing, it is crucial that F. von Mieg's map accurately reproduces the configuration of defensive walls and surrounding ramparts – quadrangular, rarely pentagonal, with towers, bastions, and interior buildings. The abbreviated signatures existing at significant sites, namely E:h (Edelhof), M:h (Mayerhof), z:h, w:h (or simply hof), determine the type of construction – a nobleman's estate or a manor; Schloss – stone castles and palaces; Alte Schanze – abandoned fortifications, ruins (Petryshyn, 2006). Evolution of ancient defensive housing in the 19th century was documented in the following cartographic base covering the entire western part of Ukraine: cadastral maps. Cadastral maps were drawn for each settlement of Galicia in 1830-1860. The scale of 1:2,880 is optimal for analysing the natural

conditions and planning structure of villages (Lisovska, 2000). The territories of the ancient defence courtyards were peculiar in that they were mostly vacant and undeveloped due to their location in the natural landscape. Identification of the former courtyard site was possible by mapping, scaling, and overlaying historical materials on satellite imagery. Georeferencing to satellite imagery helped to obtain the exact coordinates of the objects on the ground.

RESULTS AND DISCUSSION

The first stage of the study analysed network of defence housing facilities as of the end of the 18th century in the Lviv region. On a map, F. Von Mieg recorded the network of defensive housing as of the end of the 18th century (Petryshyn, 2006). Analysis of the map helped to classify defensive housing according to the planning features of its defensive structures. Quadrangular fortresses with bastions and courtyards with corner towers were recorded regularly in Porichchia, Reklynets, Vysotske, Perespa, Hriada, and Zarudtsi villages (Fig. 1, A). Quadrangular fortresses with bastions were found in Stankiv (Fig. 1, B). Lisok, and Romaniv villages. Pentagonal structures with bastions were less common. In the Lviv region, two villages with the same name, Lyashky Murovani (after 1946 both villages were renamed to Murovane), had pentagonal defence complexes.



A

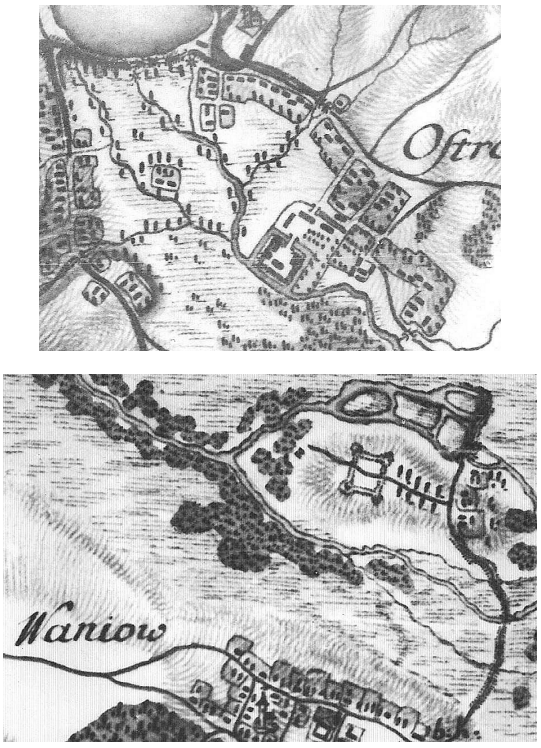
B

Figure 1. Castles and courtyards built in the 18th century, preserving defensive structures

Notes: A – Zarudtsi village, Lviv district, Lviv region, map sheet – 261; B – Stankiv village, Stryi district, Lviv region, map sheet – 218

Source: H. Petryshyn (2006)

The defences of the courtyards consisted not only of defensive walls but were supplemented by hydrologic means. The types of localisation of the defensive structure in the landscape were as follows: type 1 – a river on one side of the object and a canal built from the river on the other three sides, for example, as in the village of Ostriv (in the half of the 20th century the village was renamed to Chornyi Ostriv, Zhydachiv district) (Fig. 2, A); type 2 – the site was surrounded by a river that flooded large areas around it during the flood, reinforced by earthen ramparts, e.g., in the village of Mlyniska, Stryi district; type 3 – the site was located on an island, e.g., in the villages of Honiatychi and Zaderevach, Stryi district. Some of the bastion fortifications were on swamp islands, such as in the villages of Pechikhvosty in the Lviv district, Vaniv in the Chervonohrad district (Fig. 2, B), Novosilky and Koniushkiv in the Zolochiv district. According to the original canons of defence housing construction, some fortifications were localised on the hills. These included the sites in the villages of Volytsia, Hriada, and Ruda (since the 20th century – Zamok) in the Lviv district and Reklynets in the Chervonohrad district.



A

B

Figure 2. Defensive castles and courtyards that included water channels, a river, and a pond in the system of defences

Notes: A – Ostrov village, Stryi district, Lviv region, map sheet – 266; B – Vaniv village, Sheptytskyi district, Lviv region, map sheet – 288

Source: H. Petryshyn (2006)

On the border with Small Polissia, the Podillia Upland forms a ledge up to 200 meters high (Marynych, 1989-1993), in front of which there is a strip of condensation of

ancient family estates of historical origin that developed from a defensive court. Thus, in the Zolochiv district of the Lviv region, defensive courtyards were established in the villages of Khylchytsi, Liatske (now Chervone), Lisok, Vysotsko, Koltiv, Chernytsia, Holoskovychi, Peniaky, Pidhirtsi, Ponykva, and Koniushkiv (Fig. 3). Some had a long-standing origin and developed into representative complexes with a park. One of the factors of development is arguably soil quality. The lands bordering Polissia are among the most fertile and have a soil quality score of 100 (Petryshyn, 1990).

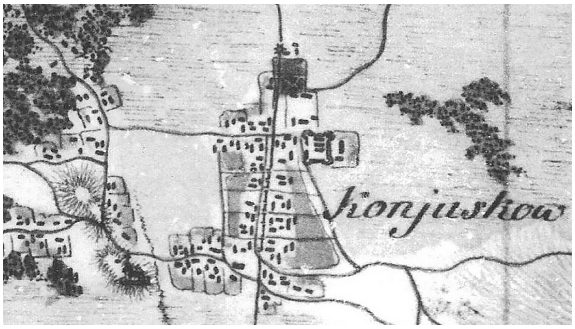


Figure 3. Koniushkiv village, Zolochiv district, Lviv region
Notes: map sheet – 358
Source: H. Petryshyn (2006)

In the second half of the 18th century, changes occurred in the development of Galician architecture. The Tatar-Turkish attacks subside, and the defensive factor ceases to dominate the settlement. The loss of the key factor in the construction of defensive housing – the need for protection – was the basis for a new stage in the functioning of ancient defensive courtyards and castles – the elimination of defensive walls. The liberation of housing from restrictive enclosures gave impetus to developing new principles of open composition in family, noble, and other wealthier settlements. The further development of the former fortified courtyards followed two paths. The first was conservation, which later led to destruction, e.g., in the villages of Zaderevach, Pechikhvosty, Vaniv, and Chornyi Ostriv. The second was adaptation, i.e., turning old defensive courtyards into residential areas, sometimes with their transformation into palace and park complexes, e.g., in the village of Pidtemne, Lviv district (Matsiuk, 1997).

The second stage of the study analysed the transformation of defence housing at the turn of the 18th and 19th centuries. In that period, most of the defensive courtyards in the Lviv region no longer had walls, but the fortifications, such as earthen ramparts, ditches, and ponds, remained. Once redesigned for defence, the terrain did not contradict the new trends in estate construction, especially in those objects built near a river or pond, as water became one of the structural components in the landscape of a new – no longer defensive, but representative – dwelling.

For example, the castles in Mykulintsy, Bessidy, Lahodiv, Koltove, Zamochok, Malchytsi, Medynychi, Pidhorodtsi, Obroshyno, Murovane, Chaplia, and Kolyndiany were rebuilt into larger manor and park complexes of a residential nature. They had a water element included in the territory planning. Some of the defensive objects, after the stage of elimination of the walls and expansion of the living space, still decay over the years. The study found that the defence yards, being based on the defence doctrine and having strongly pronounced natural landscape features, were poorly suited for a new way of living and reconstruction into a residence. The reason for this was the limited territory of the former defence yard, particularly on river islands or hills, which were insufficient for the new type of residence. The same applied to areas that were regularly flooded. Additionally, the floodplain meadows were natural, changing the nature of the landscape situationally, and could not ensure the creation of regular park compositions and a straight access alley, which became a symbol of the new noble housing. The same applied to objects on the flooded peninsulas.

The toponyms of the villages of Ostriv, Richka, and Porichchia indicated that the fortifications on their lands were built using natural elements such as rivers, wetlands, and floodplains as means of defence. Accordingly, the defensive courtyards in the villages of Reklynets (Fig. 4), Vaniv, Ostriv in Chervonohrad district; Porichchia in Yavoriv district; Richka of the Rava-Ruska urban community, Lviv district, which were localised on the remains, did not have a long-standing origin after the elimination of the defensive walls and their remains were not preserved. Due to their defence function, ancient defensive dwellings were often located separately from the village buildings. Such courtyards, located far from the neighboring settlements, also did not often develop into a new type of residential housing. Summarising the second stage of the origin of defence courtyards, the study found that the functioning of objects not developed outside their borders was short-lived, as they were inconvenient as housing. The other two options for a new courtyard structure – adaptation or development – were more suitable for the new form of life and management. The third stage of genesis was marked by courtyards built on the territories adjacent to the old defensive courtyard and not just adapted within the old boundaries.

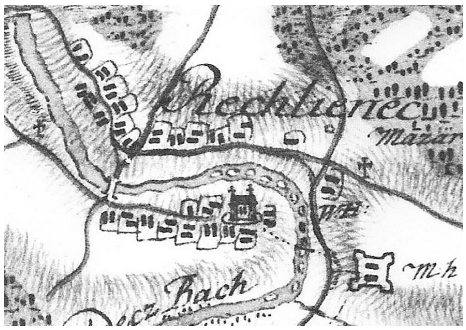


Figure 4. Reklynets village, Sheptytskyi district, Lviv region
Notes: map sheet – 290
Source: H. Petryshyn (2006)

The third stage of the study analysed the development of ancient family estates in the 19th century. The transition from the czynsz system to the manor-pastoral system in the late century prompted the development of family estates in rural areas. This forced many wealthy Galician burghers to move from cities to villages to run their farms. Their family nests were located in various types of defensive courtyards and castles, analogous to the Western European knightly burgs and castles.

From the end of the 18th century, some of these defence courtyards were transformed into manor and park complexes. The most striking examples of this transformation included the estate of Countess Borkowska in the village of Ponykva, the palace of Count Mnieszczek in the village of Krysovychi, Yavoriv district, the estate of Horetskyi, which until the 19th century belonged to the Pototsky in the village of Reklynets (Sulimierski *et al.*, 1880-1902), the palace and park complex of Sarnetskyi in the village of Turynka, where Stanisław Żółkiewski was born (Stupnicki, 1864), the estate of Count Stadnitskyi, which later became the property of the Thornitski in the village of Nadyby (Sulimierski *et al.*, 1880-1902). Cadastral maps provide information that many estates with a park, which underwent the first stage of redevelopment from a defence yard to a residence in the mid-19th century, no longer evolved but did not exist at all, or developed with a purely industrial character, and the park is represented only in the form of some park elements (flowerbeds, fragments of the square planted with trees, remnants of linden or hornbeam alleys). Examples include the estates of the villages of Pidhorodtsi in Stryi district, Zhelekhiv Malyi (now Velykosilky), Pechikhvosty and Porichchia in Lviv district, Mlynyshche (now Mlynyska) and Honyatychi in Stryi district.

However, some defence courtyards transformed from a utilitarian defence function to a representative one and continued to develop as manor parks or palace complexes until 1939, e.g., the palace and park complex in the village of Peniaky. In the 19th century, the defensive castles of villages also underwent a long evolutionary path from being closed to being opened into the landscape and developed into a manor and park complex on the site (or near) of an ancient castle: Hriada, Zhovtantsi, Ruda Monastyrok (now Zamok), Zarudtsi, Romaniv, Turynka in Lviv district; Krysovychi in Yavoriv district; Novosilky (Novosilky Zahalchyny in 19th century (Sulimierski *et al.*, 1880-1902), Liatske Male (after 1946 – Chervone), Lisok, Korsiv in Zolochiv district, Horozhana Velyka in Stryi district, Perespa in Chervonohrad district.

Some defensive courtyards stayed in their original location but were rebuilt so radically that nothing remained of the original foundation except for localisation. For example, a typical farmstead replaced a wooden hunting castle in the village of Zamochok. The example of the defensive fortification in the village of Liashky Murovani (from the second half of the 20th century – Murovane, Lviv district, Lviv region) demonstrated the owners' attempts to modernise the defensive castle into a modern type of housing in the 19th century – a residence with a park at a low cost. Bastions of pentagonal configuration protected the residential building in the courtyard. From the north, east, and west, the ramparts and curtains were additionally surrounded by a moat. F. von Mieg's map (map sheet 262) shows the dismantled southern wall and the construction of three new buildings that formed a rectangular semi-open courtyard. A garden was planted downhill from the new buildings (Fig. 5).

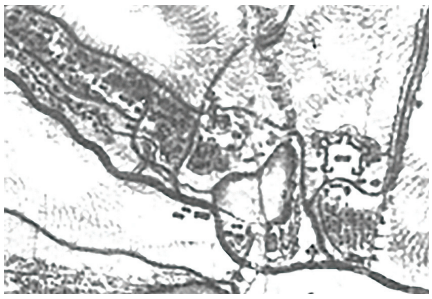


Figure 5. The village of Liashky Murovani, late 18th century
Notes: map sheet – 262
Source: H. Petryshyn (2006)

The estate was rebuilt in the first half of the 19th century, as evidenced by the village's cadastral map. The house was dismantled inside the walls. In addition, the buildings of the previous stage of the castle's development, recorded in the cartography of 1782, were not preserved. Instead, a new palace was built, measuring 40.3 m on the longer side. The eastern side of the walls was handed over to a large farmyard with buildings. A natural park was planned for the southwest of the site (Fig. 6). At the same time, the pentagonal outlines of the defensive ramparts, curtains, and ditch were preserved, demonstrating a balanced adaptation of the terrain without unnecessary costs.

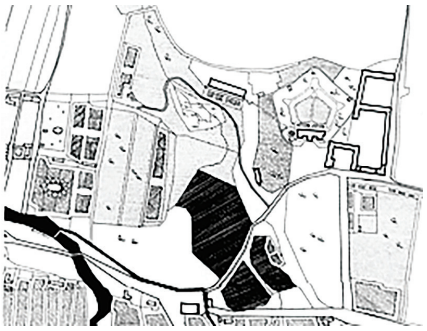


Figure 6. The village of Liashky Murovani, first half of the 19th century
Source: Central State Historical Archives of Ukraine in Lviv (1853); graphic design by the authors

Theorists interpreted the pentagonal organisation of a defensive structure as a ray structure. Following the French construction school, the redesigned castle adapted this geometric form for an axial composition, with

representative dwellings along the axis. Preserving the fortification in the new residential complex can be associated with romantic trends in early 19th-century architecture, when deliberately constructed ruins became the decoration of parks (Petryshyn, 2006). The cartographic comparative analysis helped to compile a typology of defensive housing according to the type of its origin. Thus, the study found that the adaptation of an ancient defence courtyard could take place in several ways:

- to operate within previously established boundaries, such as in the village of Lyatske Male;
- to be included in a new estate's economic or park structure while staying uninhabited, e.g., in Mykulintsy, Tvirzha, Torky, and Zhovtantsy villages.
- build up a new farm and function as a single entity with it, e.g., in the villages of Vysotsko, Lisok, Malyi Zhelekhiv, Penyaki, Stankiv, Ushkovychi, Romaniv.
- to be entirely replaced by a new manor house built on the same site as the castle or nearby, e.g., in the villages of Vaniv, Reklynets, Koniushkiv, Chornyi Ostriv, Hriada (Sosnova, 1998).

The long-established family estates that developed into representative complexes with a park in the 19th century could have been a factor in the transfer of the village where they were founded to the status of a small town. An example is the village of Romaniv, Lviv district. In the second half of the 15th century, the presence of fortifications in the village was twice noted in the records (Pshyk, 2008). F. von Mieg's map shows a quadrangular fortress with bastions. Even small lowland rivers flowing across a relative plain were sometimes challenging to cross, as their branching required crossing them several times through marshy terrain. This might explain the location of the defence yard in the northwestern part of the Romaniv village lands rather than on the top of nearby Kamula Mountain.

At the end of the 18th century, the castle lost its defensive function and began to be built up with new housing and outbuildings. Judging by the image on F. von Mieg's map, a farmyard was formed on the western side of the earthen rampart, and a new building with a tree-lined road was built 300 meters north of the castle. As of the mid-19th century, the earthen ramparts were probably partially preserved, as the cadastral map shows a narrow road that follows the route of the western side (Central State Historical Archives of Ukraine in Lviv, 1854b). In addition, judging by the cadastral data, the buildings of the first stage of the castle's redevelopment did not remain. There was no road connecting the old and new courtyards either. One element that allows identifying the object's location on the cadastral map is the characteristic bend of the entrance to the farmyard on the western side of the fortifications.

Considering the size of the main building and the absence of a park (there was a garden), it can be assumed that in the mid-19th century, there was a farmstead with a developed economy on the site of the defence yard. According to the Geographical Dictionary (Sulimierski *et al.*, 1880-1902), a farmstead and a distillery were located north of the Romaniv village buildings. The so-called "bigger property" in the village – 516 morgans of arable land and 2,247 morgans of forest – belonged to Count Alfred Pototski. Identifying the defensive yard in Romaniv village is possible due to the surviving fragment of the earthen rampart with the geometry of the bastion (Fylypchuk *et al.*, 2014).

As modern researchers described, the defensive castle system "consisted of a central sub-square area with maximum parameters of 40×40 m (oriented almost to the cardinal points). It was surrounded by defensive structures in the form of four basteias and ramparts; the total length of one of the sides of the bastion in its lower part reached 90 m" (Fylypchuk *et al.*, 2014). Based on the above data, the approximate coordinates of the reference to the center of the former castle according to the satellite image (data attribution on September 17, 2018) are as follows – 49°42'40 "N 24°19'54 "E.

Another example of the origin of a defence yard in a village that briefly had the status of a town is the site in the village of Ferleiivka (from 2021 the village of Andriivka, Zolochiv district). In 1638, Ferleiivka received the Magdeburg right, which briefly granted it the status of a town, but this was not reflected in the planning structure. On F. von Mieg's map, a large pond with an island in the middle is located between two sacred buildings in the center of the village of Ferleivka (Fig. 7). The island is surrounded by an earthen rampart and connected to the shore by only one bridge. Within this "defensive land", brick buildings had a "U-shaped" plan configuration, with their courtyard opening towards the entrance gate. There was also a garden with a four-division structure on the island. The part of the island that was farthest from the housing was planted with trees.

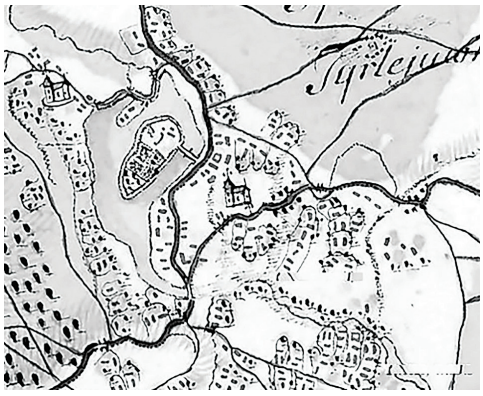


Figure 7. Village of Ferleivka, late 18th century
Source: H. Petryshyn (2006)

The cadastral map of the mid-19th century records dramatic changes in the layout of the defence yard (Fig. 8). Since the defence was no longer required and it was impossible to develop the previous dwelling into a significant residence within the island, the buildings and ramparts were dismantled, and a naturalistic garden was planned throughout the island, corresponding to the character of the natural environment. The layout of a large park at

the pond on the site of the former defence yard was not uncommon. For example, in the village of Ponykva in the Brody community of the Zolochiv district (Lviv region), a high-quality landscape object, a park of about 30 hectares emerged on the site of a defensive castle. The possibility of such a park might be explained by the specific features of the natural landscape. In the floodplains of the tributaries of the Styr River, near the hilly ridge of the Podilska Upland, there is fertile black soil, enabling the creation of a high-quality park.

Figure 8. Village of Ferleivka, first half of the 19th century
Source: Central State Historical Archives of Ukraine in Lviv (1845); graphic design by the authors

The large reservoir in the village covered about 50 hectares. Cartography recorded a defensive type of dwelling on its northwestern bank in the late 18th century – a rectangular courtyard with five buildings. A rampart and a ditch with water from a stream flowing from the north of the estate were used as defensive fortifications on three sides (Fig. 9). Approximately half a century later, the cadastral map shows a new residence with a large-scale park and a water element involved in its planning – ponds and canals that were previously outside the courtyard. The park was laid out at the palace, designed in the English landscape style (Fig. 10).

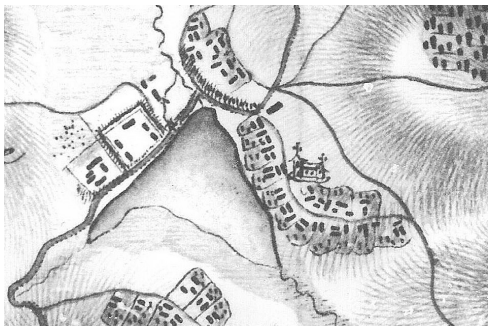


Figure 9. Planning of defence yards the village of Ponykva of the 18th century
Notes: map sheet – 359
Source: H. Petryshyn (2006)

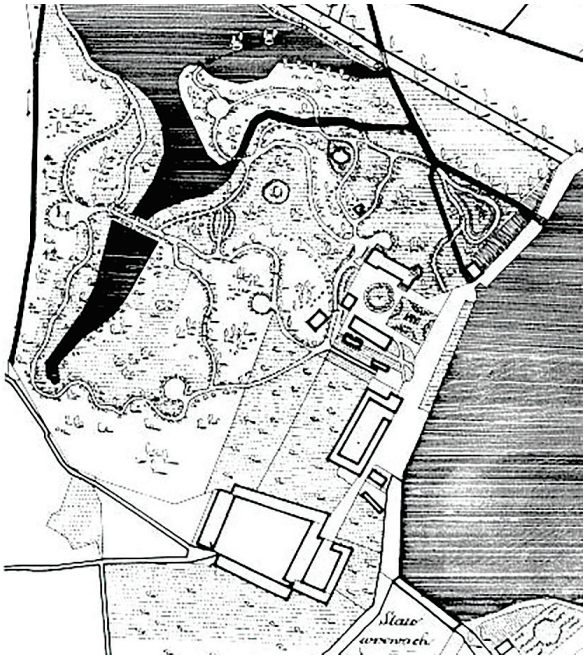


Figure 10. Planning of defence yards the village of Ponykva of the 18th century end Cadastral map
Source: Central State Historical Archives of Ukraine in Lviv (1854a); graphic design by the authors

The old courtyard's moat and fence were removed, and the new residential and representative complex increased in size by 2.5 times compared to the previous one. Despite the complex's evident representativeness, the farmyard stayed in its original location and was expanded in terms of area and new buildings. In the history of Galician courtyards at all stages of their existence, both during the time of the defence function and the period of the representational housing, the economic part was always a significant part of the estate. Together with the dwelling, a complex of outbuildings was built: "barns, stables, breweries for wine production, and other buildings, united compositional with the residence. Such a complex is an example of integrating housing and farming with the landscape of those times in Europe" (Zarebska, 1971). The problematic nature of modern use of such territories complicated the fate of degraded historic landscapes. On the one hand, they are not recognised as monuments of architecture or archeology, but they are essential as objects of the development of region's natural landscape, which was characteristic of past centuries. Examples include objects in villages: Richky, Stankiv, Lisok, and Konyushkiv.

Richky (Riczky, Pziczky) village is located 4.5 km north of Rava-Ruska. The defensive courtyard of the village of Richky, according to the cartographic representation on F. von Mieg's map, was a quadrangular fortress with basteias surrounding two buildings in the courtyard at the end of the 18th century. The site was located on the northeastern outskirts of the village, about 100 meters from the houses. The natural means of defence was a pond adjacent to the western wall of the fortress. However, there was a small hill

on the eastern side of the castle, which made the location of the defence yard questionable from the standpoint of military tactics. Later cadastral maps of the late 19th century show that the old defence yard was not developed into a residence, but it existed. According to the Geographical Dictionary (Sulimierski *et al*., 1880-1902), the village had a farmstead called "Chornyi" at the time, which included 755 morgas of arable land, 237 morgas of meadows and vegetable gardens, 112 morgas of pastures, and 942 morgas of forest. Notably, in the 19th century, Count Kajetan Kicki donated this property for public purposes. The satellite image (data attribution 28.03.2022) shows the contours of the earthen fortification – ramparts and bastions. The eastern rampart was 75 meters long, the southern rampart was 65 meters long, and the defensive structure's parameters were 55 meters along the axis of the southern bastions.

As of 2020, there were vegetable gardens and arable land in the castle yard in the middle of the ramparts. The castle's northeastern bastion coordinates are 50°16'52 "N 23°38'43 "E. The object that allows clarifying the location of the defensive object is a wooden sacral building that existed from 1716 to the 1880s, and now in its place is a wooden church built in 1920 (Slobodian, 1998). Interestingly, the existing church has two stone buttresses, typical of defensive structures. An example of the evolution of defensive housing, which was based on a reservoir, into a residence with a park is the object in the village of *Lisok*. The village of *Lisok* (Lisko) is in the Buska urban community of the Zolochiv district of the Lviv region. According to the map by F. von Mieg, in the late 18th century, there was a castle-fort between the villages of Lisok and Novosilky with quadrangular walls with bastions surrounding a residential building and three buildings in the courtyard.

The facility was on the western edge of the villages, 150 meters from the village houses. The natural means of defence was a small pond (no longer exists today) on the eastern wall of the fortress. The small river Dumnytsia flowed on the castle's south side, and there were mochars on the west side. The fort's inner courtyard entrance was through the eastern gate, via the bridge over the pond. F. von Mieg's map shows that at the end of the 18th century, the defensive courtyard was extended on the south side with a new courtyard of six buildings without dismantling the walls. The area of the newly built estate and the one within the walls was approximately the same – about 4,600 square meters (Fig. 11).

The cadastral map of the village records the changes that occurred to the defensive courtyard as of the mid-19th century (Fig. 12). The defensive structures and buildings were eliminated, and a brick palace was built, oriented towards the entrance via the bridge over the pond. A new road was laid to the palace from the north, connecting it to the village. The old bridge was probably preserved not only for its utilitarian function but also as a decoration of the estate. In the mid-19th century, the construction of bridges over water bodies as an element of a landscape park became widespread.

Figure 11. Defensive castle between the villages of Lisok and Novosilky, Zolochiv district, 18th century
Notes: map sheet – 232
Source: H. Petryshyn (2006)

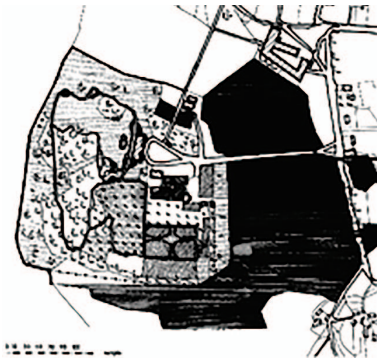


Figure 12. Fragment of a cadastral map the village of Lisko, first half of the 19th century
Source: graphic design by the authors

The former defence yard's territory doubled. On the western side, a naturalistic park was established on the once swampy defence grounds, and a reclamation canal was laid along its border. According to the Geographical Dictionary (Sulimierski *et al*., 1880-1902), 55 people lived in the "estate" in 1880. On the satellite image (data attribution 14.09.2020), the contours of the ancient earthen fortification are very faintly visible, only due to the change in vegetation type. The northern rampart was 110 meters long, and the western rampart was 70 meters long. As of 2020, the territory of both the old defence yard and the residence built in its place was an overgrown marshy meadow. The flooding of the area can be assumed to be the reason the site was not preserved and is not used today. The coordinates of the former northeastern bastion of the castle are 49°42'50 "N 24°19'39 "E (Fig. 13).

The present study contributed to the existing body of knowledge on Galician defensive structures by exploring their origin within the rural landscape. Defensive courtyards and their remnants serve as artifacts that reflect the longstanding experience of Ukrainians in protecting their lands. The outcome of this study is the increased visibility and popularisation of the region's defensive architecture. Studying defensive architecture across various regions

of Ukraine provides a foundation for comparative analysis and helps to identify unique features of local building cultures. In this context, studies of the Volyn region (Mykhailyshyn, 2000) and the Ivano-Frankivsk region (Lukomska, 2015) serve as valuable references for establishing the specific characteristics of defensive housing in the Lviv region.

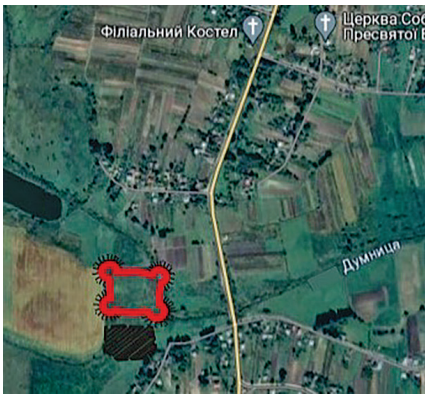


Figure 13. Satellite imagery of the territory of Novosilky, 2024
Notes: coordinates 49°55'39.5"N 24°26'45.6"E
Source: Google Maps (n.d.)

For the first time, researchers of the topography of the town of Kamianky in Podillia are introducing a unique source from the historical map – a map of the Podillia province of 1841-1847. Using the found map source, the authors managed to locate the castle and the fortified town centre, and characterise the type of fortifications (Riazanova *et al.*, 2021). This study also uncovered new information about previously little-known, small but once numerous defensive courtyards in Galician villages. The joint result of work with other researchers of defence construction, particularly with M. Bevz (2020) and O. Okonchenko and I. Okonchenko (2022), is the systematisation of scientific knowledge about the principles of defence architecture. However, the studies of these researcers were aimed at a detailed investigation of architecture, while the current study aimed to explore the transformations of the objects in the landscape. In-depth studies of only certain preserved objects of defence architecture, such as the long-term study by O. Remeshylo-Rybchynska (1994) of the castle in the village of Pidhirtsi, left out the context of the historical period, which is crucial for defence architecture. Namely, the researchers did not cover the entire set of objects that would indicate the density of localisation of defence housing on the lands of the western region of Ukraine.

The available studies of defensive housing mostly concern buildings and defensive structures, for example, the study by A. Cholovsky (1892). The principles of transformation of defence housing have been most thoroughly explored by Ukrainian scientists for the largest or surviving objects. Instead, this researcher's study identified the specific features of their localisation in the landscape and subsequent redevelopment of the territory. A researcher of castles and fortresses in Western Ukraine is the historian O. Matsiuk (1997), who compiled a register of defensive structures in Galicia, described their history and current state, and created tourist routes to the monuments of defensive construction in Western Ukraine. In addition, the study by V. Pshyk (2008) covered a set of defence construction objects of the 13th-18th centuries on the territory of the modern Lviv region, which included about three hundred settlements.

However, in the years since the studies of O. Matsiuk (1997) and V. Pshyk (2008), the condition of the facilities has deteriorated. A threat to the surviving elements, particularly to the earthen ramparts and the underground part of the defence yards, is the failure to include them in urban planning documentation, specifically in the scheme of the village's General Plan. This study outlined the possibilities of identifying the location of the former defence yard as an archaeological site by signs of changes in the shape and type of image on satellite maps. The study demonstrated an example of identifying a historical object by changes in relief readable on Google Maps.

Of the analysed modern studies in the field of architectural inventory, the study by L. Barazzetti *et al.* (2023) opens new possibilities. Recent studies in the field of architectural history have focused on the development of non-contact digital methods for data collection regarding the object of study. One of the practical applications of theoretical research is the digital recording of historical defensive structures in mountainous areas. Drones were used to gather information for reconstructing the appearance of the external surfaces of fortified structures. Drone images and photogrammetric techniques for 3D modeling play a fundamental role in the digital documentation of fortified constructions using non-contact methods. The digital model provides an overall 2D graphic layout for describing a ruined building from geometric, technological, and conservation perspectives. Advanced digital surveying techniques can drive the definition of more reliable 3D geometrical models of built heritage, which is a fundamental step in elaborating analyses that characterise the conservation process.

For Ukraine, this method is relevant because there are specialists familiar with drone control. The ability to identify an object on the territory in real time by comparing maps of different periods and linking them to geodata is essential in the task of planning village development. When developing urban planning documentation for a settlement, it is recommended that the boundaries of the territory of former defence yards, even if they are not monuments, be marked on the plan. Historical sites and even references to them can contribute to the development of a settlement or community.

K. Boguszewska & K. Drobek (2023) explored strategies for adapting the inner courtyards of defensive castles to contemporary functions. Considering that, in most cases, rural fortified yards in Ukraine lost their masonry structures, leaving only earthworks delineating the outline

of the castle, including its courtyard, the study proposed the adaptation of these areas – particularly the inner courtyards – for theatrical use. The activation of historical sites with a minimal degree of physical preservation is intended to attract public attention to their significance and to promote the conservation of these areas as archaeological and historical monuments. The courtyard, as the fortress's focal point, should embody the fortified site's key space. In this context, the defensive courtyard, or even the marking of its location on the site if it has not been preserved, represents a potential for community development. In conclusion, studies on defensive housing predominantly focus on buildings and structures. However, the specific aspects of the localisation of these objects within the landscape and subsequent territorial reconstructions are rarely generalised.

CONCLUSIONS

Since the end of the 18th century, Eastern Galicia has been characterised by the archaic use of regular fortifications and their housing adaptation. By the middle of the 19th century, various types of adaptations of the defensive castle and courtyard were in place, ranging from dismantling only the flank wall to radical reconstruction into a residence with a cultural landscape in the form of a park. The rationality of the way of life led to the long-standing origin of the defensive type of housing, even after the need for defensive structures disappeared. With the elimination of the defensive walls, this type of dwelling was redesigned, and opening into the landscape, it acquired a new utilitarian quality of a manor house with a farm and a cultural landscape. The area's hydrography is also a unique feature in transforming defence courtyards into residences. Fortifications exploited natural elements, such as a river and a marshland, as means of defence, which became elements of the cultural landscape in the reconstructed housing centuries later. The placement of defensive housing in the rural landscape, under the natural structure formed by the lower axes (river, ravine, hollow), upper axes (top of a ridge of hills), and planes (foot of a ledge), captured the regional differences in the cultural and historical landscape that was superimposed on the natural framework of the region. The defence housing study confirmed Eastern Galicia's intensive urban development.

The study of defensive housing confirmed the intensive urban development of Eastern Galicia. Preserving the memory of the region's culture and architecture by marking the sites of former defensive structures is particularly relevant when designing tourist and educational routes through historical settlement centers. One such tourist cluster is being developed in the Zolochiv district, which forms part of the rich cultural landscape of the Lviv region. This district is recognised as a historical settlement hub, rich in archaeological and historical monuments (such as ancient Rus' settlements in Plisnesk, Sasiv, and Olesko, surrounded by satellite villages), architectural landmarks (castles, churches, and monasteries in Pidhirtsi, Olesko, and Zolochiv), and urban planning heritage (many cities and towns preserved the rectangular layout of their centers established in the 15th-17th centuries under Magdeburg Law). The district also features unique ethnographic settlements where regional folk crafts have flourished – e.g., Havarechchyna. Enhancing the area by identifying sites of defensive housing, along with those that later evolved into palace and park complexes in the late 18th to early 20th centuries, will enrich tourist destinations with educational value. Prospects for further research on defence-type housing lie in substantiating its potential for regional tourism development.

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Оборонне житло у XVIII ст. та його генеза в культурному ландшафті українського села

Анотація. В Україні реєстр пам'яток, що характеризують культурний ландшафт передмістя, включає лише кілька об'єктів. Однак залишки стін або валів оборонних споруд та їх території офіційно не реєструються, і в більшості випадків їх історичні межі не враховуються при розподілі сільських земель. Метою цього дослідження було охарактеризувати планування та просторове рішення, а також генезис оборонних споруд XVIII століття в культурному ландшафті українського села. Дослідження проводилося у Львівській області. Дослідження базувалося на порівняльному аналізі функціонування оборонних споруд на трьох етапах їхнього існування. Було проаналізовано близько 40 об'єктів за їхнім розташуванням у структурі села. Детально вивчено планування та походження трьох оборонних споруд. Станом на 2025 рік у Львівській області не існує невеликих сільських оборонних дворів. Однак земля в межах оборонних стін і на місці колишніх садів, створених під час перетворення оборонного двору на житловий маєток, часто залишається незабудованою. Оборонні двори, які пройшли довгий еволюційний шлях, є особливим типом житла в ландшафтній архітектурі, яке еволюціонувало в повну протилежність – від обнесеного стіною житла до житла з садом і парком. Дослідження оборонного житла підтвердило інтенсивний розвиток міст Східної Галичини. Закріплення пам'яті про культуру та архітектуру регіону шляхом позначення територій колишніх оборонних споруд є доцільним при створенні туристичних та освітніх маршрутів в історичних центрах населених пунктів

Ключові слова: оборонні споруди; укріплення; сільська місцевість; територіальне планування; замок

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Problems of the preservation of historical heritage in the context of urban landscape modernisation

Abstract. The relevance of the study is that in the context of accelerated modernisation of urban space in the first quarter of the 21st century, contradictions between development strategies and mechanisms for the protection of historical heritage significantly intensified, which require a scientific understanding of the applied practices and institutional models. The purpose of this study was to identify the factors that determined the success or inefficiency of programmes for the preservation of architectural monuments and the urban environment in the context of growth, investment pressure, and the transformation of regulatory regulations. The research methodology was based on a comparative analysis of legal systems, urban planning approaches, and empirical cases in three cities: Bishkek, Prague, and Rome. The results of the study demonstrated that the effectiveness of conservation strategies directly depended on a combination of the rigidity of the legal status of cultural heritage sites, the availability of economic incentives (subsidies, tax incentives, financing programmes), the level of digital support for monitoring the condition of monuments, and the degree of involvement of local communities in urban planning decisions. Institutional instability and legal dualism were recorded in Bishkek, which contributed to the reversibility of the protected status and the accelerated loss of iconic objects. Prague has shown the viability of a multi-stage conservation model based on zoning and coordination mechanisms, while Rome has demonstrated the potential of digital technologies and the integration of cultural policy with the logic of a smart city. It was concluded that the stability of the historical landscape was ensured in the presence of an integrated management model that includes three interrelated components, regulatory protection, economic feasibility, and technological adaptation. Under the conditions of urban pressure, it was the synthesis of legal, technical, and socio-cultural mechanisms that allowed not only to preserve the material layers of historical memory, but also to integrate them into the strategic development of the modern urban environment

Keywords: architectural authenticity; globalisation; digital monitoring; restoration; cultural identity

INTRODUCTION

The relevance of preserving historical heritage in cities is determined by the fact that in the first quarter of the 21st century, it was the tangible and intangible layers of the past that served as a resource of cultural identity, a source of competitive advantages in the economy of impressions and a factor in the sustainability of the urban environment. Their loss invariably led to the erosion of social capital, accelerated featureless dense buildings, and exacerbated environmental risks. The urbanisation of the modern period is characterised by an unprecedented rate of demographic growth, large-scale consolidation of central territories, and expansion of transport and logistics infrastructure. These processes increased the need for new residential and commercial spaces, created additional stress

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on engineering networks, stimulated vertical development and thereby transformed the silhouette of historical centres, while reducing aeration corridors. The global tourism market increased the operational burden on iconic sites, increased rental pressure, and initiated the displacement of indigenous populations from protected areas (Zatsepina & Pruss, 2023). There is an institutional complication of urban planning regulation, public-private partnership schemes, digitalisation of cadastres, and the introduction of the concept of "historical urban landscape" changed the traditional logic of protection. Insufficient law enforcement practice, the contradiction between economic interests and restoration expediency, and the fragmentation of public participation led to the fact that the legally fixed status of the monument became reversible, and the height regulations were constantly revised.

F.A. Adenaike *et al*. (2023) analysed the causal relationships between structural transformations and the sustainability of historical centres, emphasising the importance of preliminary object typologisation and coordination between stakeholders in the modernisation process. The researchers highlighted the need for regulatory clarity in the renovation policy and the integration of heritage into the economic cycles of the city. A. Astore & L. Tricarico (2024) investigated the transformation of the San Lorenzo district in Rome, revealing the conflict between gentrification and urban policy programmes. The paper proposed an attempt at a conceptual systematisation of urban changes as a result of the interaction of cultural, institutional, and market factors. C. Bryant (2021) presented a multi-layered analysis of the processes of social belonging in modern Prague, focusing on the role of the architectural environment as a mediator between personal identity and collective memory. The study enriched the discourse of urban memory by showing how urban heritage shapes the experience of everyday life.

C. Francini & T. Rozochkina (2024) examined the application of the "historical urban landscape" approach in the context of fragile territories, demonstrating its effectiveness in integrating cultural heritage into sustainable development. The researchers insisted on interdisciplinarity and flexibility of management models, especially in conditions of institutional instability. F. Kavak & M. Soleimani (2024), using the example of the Iznik Theatre, showed how tourist and hotel functions can be combined with the preservation of archaeological sites. The study was characterised by a practice-oriented approach and an emphasis on architectural adaptation as a way to ensure accessibility while maintaining authenticity. F. Liu *et al*. (2022) applied visual analysis in the historical centre of Prague, revealing which elements of the architectural environment attract the most attention of visitors. The study confirmed the importance of visual perception in shaping the value of heritage and offered tools for planning visual corridors.

V. Orcígr (2024) analysed post-socialist Prague through the prism of hegemonic discourse, revealing how ideological attitudes transformed the urban development agenda. The study was characterised by a critical approach to spatial planning policy and revealed the mechanisms of institutional dominance in decision-making. P. Schröder (2022) investigated the phenomenon of courtyard spaces in Central Asian cities, including Bishkek, considering them as forms of stable local self-organisation capable of resisting fragmentation of the urban structure as a result of intensive investment and construction activity. The study emphasised the importance of cultural practices of cohabitation, interpreted as an element of intangible heritage that preserves social stability in the face of increasing urban pressure. M. Vaishnavi & A. Kumar (2025) investigated the perception of the historical urban landscape by local communities and visitors, showing that the collective assessment of aesthetics and cultural significance has a direct impact on the sustainability of security solutions. The work highlighted the need to include empirical data on perception in the strategic planning of cities seeking to integrate heritage into everyday urban planning. The study confirmed that the introduction of technological tools can effectively support the preservation of cultural heritage, especially in conditions of high anthropogenic pressure.

Previous studies have described in detail individual cases of conservation and adaptive use, but have left unresolved the issue of the complex interrelationship of legal, economic and technological factors that shape the stability of the historical landscape during modernisation. The purpose of the study was to identify the systemic conditions under which heritage protection could be integrated into the development of urban infrastructure. To achieve this goal, the following tasks were formulated, to analyse regulatory and legal mechanisms and their practical effectiveness in selected jurisdictions, to compare economic incentives and financing models that affect the fate of historical sites.

MATERIALS AND METHODS

The study was aimed at a comprehensive understanding of the mechanisms for preserving historical heritage in the context of accelerated urban transformation. The cities of Bishkek, Prague, and Rome were chosen as comparative cases. This choice was explained by the fundamental difference in the institutional protection regimes, Bishkek was characterised by a weak regulatory framework and limited resource provision. Prague demonstrated the sustainable integration of heritage policy into municipal planning, Rome was an example of a city with a multi-level protection system combining international commitments and national restoration standards. This approach allowed comparing the forms of management of the cultural landscape in conditions of different legal maturity, tourist load, and the level of involvement of civil society. The National Commission of the Kyrgyz Republic for UNESCO (2010) was used as the main source for Prague, which documented the risks of loss of authenticity due to the growing tourist load and modernisation of urban infrastructure. Publication by A. Niborski Nadel (2023) covered restoration practices in Rome, including technical approaches and regulatory aspects. The document about cultural exchange programme

between the Republic of India and the Kyrgyz Republic provided an opportunity to analyse the impact of international programmes on security policy in Kyrgyzstan, with an emphasis on the participation of TIKA and UNESCO organisations (Cultural Exchange Programme..., 2022).

The analytical method was used to decompose the regulatory framework and urban planning regulations into functional blocks, which allowed identifying the internal logic of their construction and trace the mechanism of reversibility of the protected status of objects. The method ensured the operationalisation of key research categories (security mode, adaptive use, buffer zone), so that the results acquired clear comparability criteria. The historical and genetic method was used in the reconstruction of the phased formation of the urban landscape. It allowed tracing the evolution of security institutions and the transformation of spatial structure in relation to socio-political factors. The chronological stratification of the data provided the identification of cause-time relationships between changes in demographic burden, modernisation waves and correlating legal revisions of the status of cultural heritage.

The comparative method was used to compare three cities of Bishkek, Prague, and Rome, which differ in scale, economic and legal system of heritage regulation, degree of institutionalisation of security policy, level of involvement of civil structures, and depth of stratification of the historical landscape. A systematic comparison allowed separating the universal mechanisms of interaction between modernisation and protection from context-specific manifestations. The structural and functional comparison matrix provided an opportunity to extrapolate the findings beyond the territories under study and formulate recommendations considering the wide variability of urban regimes. The programmatically implemented encoding of semantic units allowed quantifying prevailing narratives and identifying conflicts of interest between security and investment logic. The results of the content analysis ensured the stability of interpretations, minimising subjectivity when reading text sources.

The system approach served as the integration framework of the study. It allowed synthesising the results of all the above methods into a single multi-level model, where legal norms, economic incentives, technological solutions and socio-cultural practices were considered as interrelated subsystems of the urban environment. This model allowed assessing not only the direct effects of individual regulatory or engineering measures, but also their indirect impact on environmental, social, and cultural sustainability parameters. Architectural and typological analysis was used to classify historical buildings according to morphological and stylistic features, which made it possible to identify the most vulnerable groups of objects and correlate them with conservation priorities.

RESULTS

Heritage and urbanisation: Institutional and spatial challenges in Bishkek. Since the beginning of the 21st century, the issue of preserving historical heritage in the context of urban landscape modernisation has been studied as a multi-level process in which legal norms, economic mechanisms, and spatial transformations interacted (Chen *et al*., 2023). Demographic growth and increased building density led to an increasing need for new residential, transport, and engineering structures, which regularly came into conflict with protection regimes based on the principle of immutability of the urban planning context, in the absence of updated cadastral registers and clear regulations for changing the functional purpose of buildings, the status of a cultural heritage site became reversible, recognition of architectural buildings as technically dilapidated made it possible to deduce to remove it from protection and carry out major reconstruction (Hmood, 2022).

However, the financial attractiveness of the central territories stimulated the consolidation of the urban core, which increased the load on engineering networks and led to a reduction in aeration corridors, negatively affecting the microclimate and the condition of the stone material. At the international level, rulemaking was based on the concept of the "historical urban landscape", which interpreted heritage as a stratified system, including both tangible and intangible components. The concept of adaptive reuse has been established in academic discourse, according to which outdated structures were involved in modern economic turnover without loss of authenticity (Feng, 2024). Special attention was paid to the impact of mass tourism, the increase in short-term rental space and the density of pedestrian flows contributed to accelerated erosion of cladding material, vibration effects on foundations, and the social transformation of historical neighbourhoods (Kalla & Metaxas, 2024). Mechanisms for territorial diversification of attendance were proposed, the introduction of dynamic environmental fees and the development of green infrastructure integrated into protected areas, the lack of comprehensive monitoring of the technical condition of monuments prevented timely damage prevention, while the introduction of digital models and remote monitoring systems made it possible to predict deformations and optimise the allocation of restoration resources (Rössler & Lin, 2018).

Bishkek's historical appearance consisted of a layered overlay of the pre-revolutionary Vernon-Frunze manor quarters, the Soviet modernism of the pre-war and Brezhnev decades, and the post-socialist development of the turn of the 20th-21st centuries. In the structure of the historical buildings of the central part of the city, there are objects with symbolic and town-forming significance. These include the architectural ensemble of Ala-Too Square, which includes the State Historical Museum, the monument to Manas, and the preserved sculpture of V.I. Lenin Square, and the adjacent landscaped area with a park sculpture from the 1980s (Fig. 1). In addition, significant objects include the buildings of the printing house Erkin-Too, the Ak-Kula hippodrome, the Issyk-Kul hotel, and a complex of residential buildings from the period of Stalinist

architecture forming the spatial structure of the central quarter of the city (Li *et al.*, 2025).

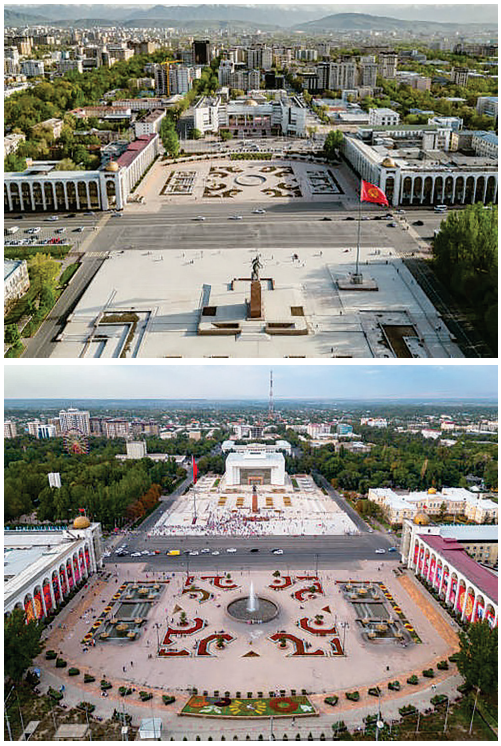

Figure 1. Ala-Too Square
Source: prepared by the author based on research by G. Aitapaeva (2023)

The cultural and memorial value of these structures was determined not only by their artistic merits, but also by the function of urban "anchors of memory". Through material markers, the city "returned" fragments of the difficult 20th century to residents, including the colonial and Soviet modernist experience, thereby becoming a platform for public conversation about its own identity. Urbanisation processes intensified after 1991, when the capital's population increased over 250,000 people in twenty years, and the UNECE forecast for 2021 expected another 400,000 migrants by the 2040s. With a shortage of city coffers and political turbulence, the authorities consistently sold plots for multi-storey shopping malls and residential complexes, and the sanitary reserve zones provided for by the Soviet master plan were considered as potential sites for development. The lack of an updated inventory register made the procedure for revoking the monument's status a technical formality, which was confirmed by the fate of the Erkin-Too printing house. The facility was taken out of protection in 2015 and returned at the request of the State Committee for National Security in 2021, but in fact support was reduced to preserving the facade wall, which was gradually destroyed by bad weather (Li *et al.*, 2025).

In practice, this meant that the registry became dynamic and the status reversible. An illustrative case was the building of the Kurenkeev Music School, which was deprived of its protection index in April 2024, a decision explained by the loss of "original function and integrity", although the expert community insisted on the possibility of revitalisation. A similar algorithm has already led to the dismantling of the Issyk-Kul hotel, the Manas Aiily complex, and the removal of the VDNH-Frunze facilities. Thus, some successful cases proved that heritage protection could be combined with modernisation. The competitive reconstruction of the State Historical Museum, completed in 2021 and opened in 2022 after a five-year closure, transformed the Soviet modernist cube into a multimedia platform, preserving the original volume and including 90 thousand objects in the exposition (Zinna, 2020). The project was implemented with funding from the budget of the Kyrgyz Republic and a grant from TIKA, and subsequent investigative journalism corruption schemes have not negated the museum value of the renovated complex, which has once again become the main tourist attraction of the capital. Another example of positive interaction between the state and traditional protection mechanisms was the Manas Ordo Mausoleum complex, a study by the World Heritage Centre documented the stable condition of 14th-century structures due to direct subordination to the government and the synthesis of official protection with local ritual practices (National Commission of the Kyrgyz Republic for UNESCO, 2010).

By the end of the 2010s, the role of the civil sector had increased in the controversy over the fate of "old Bishkek". The Urban Initiatives Foundation implemented a collaborative design methodology. In 2022, the square was modelled and equipped, demonstrating that the involvement of local communities can form a demand for the environment, and therefore, for the preservation of historical markers that define the identity of the place. The Esimde platform, initiated by Nogoibayeva, was engaged in digitising oral histories, linking the preservation of tangible artefacts with intangible memory practices. Meanwhile, destructive scenarios continued to manifest themselves in targeted examples. The Ala-Too hotel, the Erkin-Too printing house, and the wooden bread kiosks of the 1930s stood abandoned, demonstrating the mechanism of "degradation of waiting", the object stopped maintenance, fell into disrepair and after several winters qualified as "not subject to restoration" (Alymbaev, 2024).

Thus, in the first quarter of the 21st century, the preservation of Bishkek's historical heritage found itself at the epicentre of conflicts between investment modernisation, institutional weakness of security mechanisms, and increased civic engagement. The state declared the protection of monuments, but simultaneously initiated legal instruments for their alienation, the professional community proposed a systematic revision of the register and differentiated restoration, but faced fragmented solutions; citizens showed willingness to participate in the creation of new public spaces if they respected the historical context. The experience of reconstruction of the State Historical Museum and the Manas-Ordo Complex has shown the viability

of a model combining state control, international resources and local cultural practices. The experience of the demolition of Issyk-Kul and Naryn demonstrated the cost of lost time, when the monument was ignored until interest in the land became fatal. Taken together, these examples formed the understanding that the preserved heritage increased the cultural capital and environmental sustainability of the capital, while the lost objects were replenished only by accelerating impersonal development and increasing social distrust of urban strategies.

Urban planning policy and preservation of historical heritage in Prague. The historical centre of Prague was formed from the 11th century, and Prague became a city in which the Romanesque foundations of Prague Castle were combined with the Gothic verticality of St. Vitus Cathedral, the Renaissance palaces of Mala Strana, the Baroque plasticity of Charles Bridge, and the Bohemian Cubism of the House of the Black Madonna (Fig. 2). In 1992, UNESCO has included 866 hectares of the Old Town, Mala Strana, Grad, Novy Gorod, and Visegrad in the World Heritage List, the organisation described Prague as "an exemplary European ensemble reflecting all the key styles of continental architecture without interruption" (Ministry of Culture of Czech Republic, 2001). This status did not negate the pressure of modernisation; the post-war population growth almost doubled, the development of mass tourism and the post-socialist transformations of the market economy required a compromise between preserving the unique historical foundation and the infrastructural demands of a modern city.

Figure 2. House of the Black Madonna
Source: prepared by the author based on research by A. Tóth *et al*. (2022)

The key monuments set the framework of the cultural identity of the capital. Prague Castle, the world's largest medieval fortress, remained the political and symbolic centre of the country, St. Vitus Cathedral, completed only in 1929, encapsulated six centuries of building techniques, and Old Town Square with its astronomical Orla clock became the "hallmark" of the Czech Republic. The cultural layer of modernism manifested itself in the functionalist Valetrzhni Palace, in the Dancing House of F. Gehry and V. Milunits. The Josefov Jewish quarter, rebuilt during the era of Habsburg urbanism at the end of the 19th century, preserved the oldest functioning synagogue ensemble in Europe, and the associated memory of the Holocaust gave the area a special memorial status. The city's heritage protection policy was formed within the framework of a dual system, the Act of the Czech National Council No. 20/1987 Sb. (1987) established the regime of state ownership of cultural property, while the International Building Code of International Code Council (2021) consolidated responsibility for preservation at the municipal level.

Nevertheless, UNESCO criticised the project for the lack of clear height parameters and visual corridors between the hills that define the silhouette of the "golden city". In response, the Mayor's Office established a Standing Committee on Monuments in 2023, obliging it to provide opinions on each major project in the buffer zone. The reconstruction of industrial Karlín after the devastating 2002 flood turned the ČKD factory into a complex of offices and restaurants in Corso Karlín, where the historical foundation was combined with the glass insert of the atrium. A private initiative by Leos Valka reinterpreted a 1930s factory building in the Holeszowice area, creating the DOX Center for Contemporary Art in 2008, and in 2016 the Gulliver wooden-steel airship landed on the roof, which became a symbol of the discourse between architecture and literature (Stanojević & Keković, 2019).

In Smikhov, the territory of the Staropramen brewery was turned into a quarter with creative offices, retaining malt towers as panoramic dominants, the project was funded through the European Fund for Regional Development. Government initiatives were based on the National Institute of Monuments, the largest organisation of the Ministry of Culture, which managed over a hundred palaces and castles and developed restoration standards. The "Long-term renovation strategy to support the renovation of the national stock of both public and private residential and non-residential buildings" by Ministry of Industry and Trade (2018) delineates a framework to facilitate energy-efficient renovations throughout the Czech building inventory, encompassing historical structures. It facilitates renovation initiatives for both public and private assets, and it promotes comprehensive energy renovations that honour heritage values and enhance building performance. The National Museum (2018) on Wenceslas Square, after a five-year renovation, opened on October 28, 2018, connecting the historic Joseph Schultz building and the former Federal Assembly House with a glass underpass, an example of the equal coexistence of the Neo-Renaissance monument and the brutalist inserts of the 1970s.

The World Monuments Fund included the historical centre of Prague in the watch list for 2002 and 2010, emphasising the risk of losing the "authenticity of the panorama" in the absence of strict height regulation. The European Union has funded the digitalisation of archives, the

restoration of Charles University frescoes, and pilot energy efficiency projects in historic buildings in the country. Nevertheless, the modernisation pressure remained palpable. Prague Airport registered 14.8 million passengers in 2019, with 80% of visitors concentrated in the "golden kilometre" between Charles Bridge and Old Town Square. The city responded by diversifying its flows. In 2024, they launched the Beyond the Old Town project, subsidising excursions to Visegrad and Trosky Castle, and tightened the rules for short-term rentals, reducing the number of available Airbnb apartments by 12%. Post-industrial territories remained the frontier for the integration of heritage into the new landscape. The plan for the reconstruction of the Zhizhkovsky Freight station provided for 50 thousand m² of housing, schools, the National Film Archive and cultural spaces in a historic brick volume in 1936. The mayor's office acquired the complex for CZK 1.43 billion, obliging the developer to preserve the characteristic "jagged" silhouette of the platforms (Prague unveils ambitious…, 2024).

Similarly, the Landscape 2024 festival demonstrated the potential of abandoned railway lands for temporary park installations and art pavilions, emphasising the role of creative industries in the regeneration of voids (Fodor, 2024). The limited urban budget required multi-level financing. In 2014-2023, the National Institute of Monuments has raised more than CZK 6 billion through European funds, directing them to the restoration of the Church of St Anežka Česká, the strengthening of the Charles Bridge's foundation and the digital scanning of the Visegrad complex. Municipal and national programs in the Czech Republic have subsidised significant amounts of the costs of renovating historic building facades, frequently covering between 40% and 75% of eligible expenses (Ministry of Industry and Trade, 2024).

In general, the experience of Prague in the first quarter of the 21st century demonstrated that heritage preservation has become not a static "open-air museum", but a dynamic strategy in which government regulation, private investment, and international mechanisms interacted on a platform of integrated planning. The success of the revitalisation of Karlin, Golesovice, and Smikhov, the reconstruction of the National Museum and strict height restrictions in the buffer zone proved the viability of the model of "embedding" modernity in the historical context. The disputes over the skyscrapers on the Pankratsky Plateau, rising rental pressure and the risks of tourism promotion showed how fragile the balance between development and security is. The preserved heritage increased the cultural capital and economic attractiveness of the city, while the loss of authenticity threatened to erode the unique image of Prague in the global consciousness.

The historical heritage of Rome in the context of urban transformation. The historical landscape of Rome developed as a kind of "paleontological section" of Western civilisation, from the republican temples in the Forum to the multi-level palaces of the Medici era and the modernist interventions of the 20th century. UNESCO, which included the centre of Rome and the enclaves of the Holy See in the World Heritage List in 1980, qualified the combination of ancient, Christian and Baroque topography as "unique spatial evidence of cultural continuity" (UNESCO World Heritage Site…, n.d.). By 2025, the protected area was 1,430 hectares, and the buffer zone was about 10,000 hectares more, but the protected status did not eliminate the stress caused by tourism, infrastructural modernisation, and demand for luxury real estate. The monumental matrix of the city included iconic objects of world culture. The Colosseum, which ended with the 2013-2023 restoration cycle with the construction of a retractable wooden podium, once again presented the antique look to the viewer (Fig. 3).

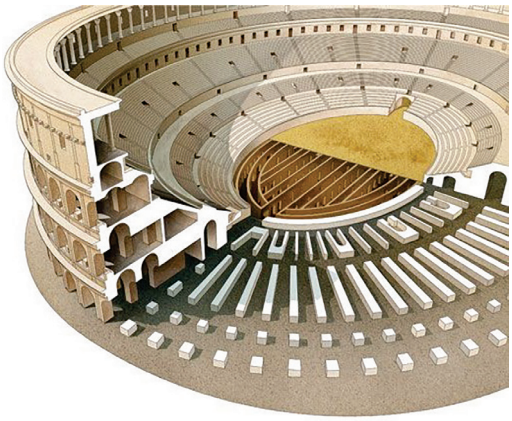

Figure 3. Reconstruction of the Colosseum
Source: prepared by the author based on research by C. Marshall (2021)

The Pantheon remained the world's largest non-reinforced concrete dome structure, and its experimental management model, which allowed for an entrance fee from 2023, set a precedent for financing conservation through the tourist flow. The Romanum Forum and Palatine, united in the Parco Archeologico del Colosseo, implemented a digital twin for monitoring microcracks and sediments. The Baroque ensemble of the Fontana di Trevi was under pressure from crowds of millions. In 2024, Mayor Roberto Gualtieri proposed a pilot fee of EUR 1-2 for the right to enter the observation platform, arguing that it was necessary to regulate the flow and restoration costs. Modernisation challenges were manifested primarily in the tourist load. After the pandemic recession of 2020, the city received 15 million guests in 2022 (an increase of 176% by 2021), and by August 2023 recorded 13 million arrivals, predicting an absolute record. Estimates by the Lazio Department of Tourism showed that there were five times more tourists than permanent residents inside the GRA ring road, and the over-density of visits was associated with the "crowding out effect" – an increase in rental rates and the replacement of housing stock with short-term accommodation. Urban projects generated the paradox of "archaeological delay"; the construction of the third metro line C, launched

in 2006, was repeatedly halted due to the discovery of Hadrian's temples, Praetorian barracks, and a late Antique theatre – each find increased the budget and deadlines (Celesti-Grapow & Ricotta, 2020).

Urban planning policy has found a systemic response necessary. "The Management Plan for the historical centre 2024-2030", approved by the City Council and coordinated with UNESCO, set four goals, conservation, sustainability, communication, and improvement of the quality of the urban environment (UNESCO World Heritage Site..., n.d.). The document prescribed integrating the assessment of visual corridors into the permit procedure, and the new volumes should not disrupt the panoramic discourse of the seven hills. The plan allowed for the reconversion of the monastery complexes into university dormitories and creative hubs.

The Metropolitan Archdiocese continued the programme of adaptive use of small churches of the 17th century, transferring them from the status of rare places of worship to full-fledged socio-cultural centres of suburban areas. This "ethical reprogramming of the sacred space" compensated for the shortage of libraries, halls for clubs and non-formal education facilities on the periphery, while preserving liturgical elements, that is, it demonstrated that the security regime could be combined with the transformation of functions if the intervention was reversible and visually declared (Khader & Fusco, 2022). The Italian legal framework enshrines the principle of preserving cultural heritage as material patrimony through Legislative Decree of Italy No. 42 (2004), which consolidates and governs the protection, conservation, and enhancement of monuments, historic sites, and cultural assets throughout Italy. Any relocation or restoration intervention in an artefact older than seventy years required coordination with the relevant ministry. Formally, this tightened the bureaucracy, but in practice it provided a transparent chain of responsibility and allowed the development of a digital registry, which by 2024 included more than 260 thousand objects.

Cooperation with international experts has strengthened the technological side of conservation. Specialists were trained at annual courses in restoration sciences, where methods of non-contact laser diagnostics and injection of lime-nano solutions into microcracks of frescoes were practiced. These technologies were first tested on the pilot sites of the Sistine Chapel, which allowed stabilising the colour layer without the traditional removal of ancient coating varnishes (Magar *et al.*, 2022). Experts remotely monitored fluctuations in temperature and humidity inside the monuments using sensor networks that transmit data to the city's metrics storage centre, an approach that became part of the concept of a "smart" security perimeter. Large religious complexes were switching to a new content model. The facade restoration of the Great Synagogue, completed in 2024, combined traditional masonry with composite reinforcement elements, which ensured minimal interference with the historical foundation and increased earthquake resistance (Niborski Nadel, 2023).

During the same period, the basilica outside the Aurelian walls received a modern geothermal heating system, which reduced energy costs by almost a third and became the first example of integrating renewable sources into a high-security facility. The concept of "selective trusting" has become stronger in the professional community, suggesting the limitations and visual readability of any modern supplement (Iudova-Romanova, 2025). The illustration was a glass elevator built into the arcade of the Colosseum, the new design did not disguise itself as antique marble, but emphasised the time gap, while allowing wheelchair users to climb to the upper tier of the amphitheatre. In this way, the ethical transparency of the intervention was implemented – the principle according to which the modern stratum is obliged to demonstrate its own era. The hotel industry in Rome receives considerable economic advantage from its closeness to cultural landmarks, significantly enhancing the city's tourism-related value (Joint Research Centre, 2025). This progress is accompanied by obstacles, escalating housing costs associated with the proliferation of short-term visitor accommodations, which have led to the eviction of certain permanent residents. The growing number of tourist buses and shuttles puts pressure on aged urban infrastructure, such as basalt slab pavements, potentially accelerating their deterioration and creating concerns regarding sustainable tourism management.

The municipality responded by quoting souvenir trade licenses and restricting single-use plastic in the protected area, while distributing tourist flows through the development of the "small ring" routes, which included lesser-known but no less significant monuments. Despite the successes, infrastructure projects continued to experience difficulties. The construction of the new metro line was delayed due to archaeological finds, each stop required rescue excavations, and sometimes the integration of open fragments into the design of the station. These delays raised the issue of commensurate costs and public benefits, but demonstrated the city's commitment to the principle of "archaeology first". Collectively, the described processes showed that the sustainable development of the historical centre depended on a balance between regulatory rigidity, innovative technologies, and the economy of impressions. Digital monitoring, selective restoration, and social reprofiling of religious buildings strengthened cultural capital, but required constant revision of regulations and flexible adaptation to changing visitor flows (Karyy *et al.*, 2025). Rome confirmed that its preserved authenticity, enhanced by openness and inclusivity, not only maintained its status as an "eternal city", but also served as a resource for sustainable urban development in the face of increasing external pressure. Table 1 is a comparison of the historical heritage preservation policies of Bishkek, Prague, and Rome. It underscores the disparities in institutional methodologies, legal regulatory frameworks, civil society participation, and the use of modern technology in the conservation of cultural assets among these cities.

Table 1. Comparative analysis of historical heritage preservation policies in Bishkek, Prague, and Rome

Aspect	Bishkek	Prague	Rome
Institutional approach	An unstable regulatory framework, limited resources	Deep institutionalisation of heritage protection	Integration of cultural policy with smart city approach
Legal regulation mechanisms	Lack of updated inventory, reversibility of protection status	National legislation, UNESCO World Heritage obligations	Principle of material patrimonialism, strict regulations for objects older than 70 years
Civil society participation	Increased by the late 2010s, limited public control	Active involvement through state programmes and public initiatives	Limited, but evolving, with the adaptive reuse of religious buildings
Use of innovative technologies	Minimal use, limited by legal and technical resources	Active use of European funds for restoration and digitalisation	Digital twins, sensor networks, nanomaterials in restoration
Revitalisation and development	Fragmented, dependent on external grants and volunteer initiatives	Systematic, part of sustainable development strategy	Integrated with tourism and infrastructure development, balancing authenticity
Tourism pressure	Increasing urbanisation, tourist attractions at risk	High, but managed through diversified tourist routes	High, with efforts to reduce impact through regulation of short-term rentals and tourist flow diversification

Source: prepared by the author based on research by J. Xia *et al*. (2024)

A comparison of the three cases showed that the key factor in the sustainability of the protection of historical heritage was the degree of institutional integration of security policy into the overall urban development strategy. In Bishkek, legal dualism and institutional weakness combined with high investment pressure contributed to the erosion of the historical environment and a decrease in public confidence in modernisation policies. In Prague, the institutionalisation of protection, the existence of clear procedures for public participation and the use of multi-level financing allowed maintaining a balance between the development and protection of historical identity. In Rome, the sustainability of conservation was ensured by a combination of strict regulatory regulation, the introduction of digital monitoring technologies and selective restoration programmes, but infrastructure projects periodically faced challenges from archaeological finds and mass tourism.

Thus, differences in conservation policies were explained not only by economic or cultural contexts, but also by the quality of administrative procedures, the level of civil society involvement, and the ability of government institutions to integrate innovative approaches into conservation practices. Bishkek demonstrated the need to consolidate security legislation and strengthen public control. Prague was a successful example of strategic planning and comprehensive protection of the historical environment. Rome illustrated the possibilities of technological adaptation of security activities to the modern challenges of globalisation and mass tourism while preserving the principle of historical continuity.

DISCUSSION

The study revealed differences in institutional approaches to the preservation of historical heritage in Bishkek, Prague, and Rome. In Bishkek, the main problems were the lack of an updated registry, legal instability, and investment pressure, which contributed to the loss of cultural sites through the mechanism of "degradation of expectations". Despite some successful projects, it was not possible to form a systematic approach to security. In Prague, heritage protection was based on a multi-level legislative framework, international commitments, and the active use of European funds. The revitalisation of post-industrial areas and strict regulation of the urban environment ensured a balance between development and preservation of authenticity (Chernyshev *et al.*, 2020; Demessie & Yakovets, 2025). In Rome, strict regulatory regulations were combined with the introduction of digital monitoring and innovative restoration technologies, but mass tourism and archaeological finds slowed down infrastructure projects. In all three cases, the sustainability of conservation depended on the degree of integration of conservation policy into urban planning and on the availability of mechanisms for public participation.

G. Foster & R. Saleh (2021) demonstrated that the inclusion of cultural heritage sites in circular urban plans reduced the carbon footprint, increased the resource autonomy of neighbourhoods, and served as a catalyst for the "green" growth of the construction industry. The researchers identified an institutionally consistent three-tier model of "inventory, life cycle assessment, modular reconfiguration," which minimised the risks of loss of authenticity. The study revealed that even with similar protocols in place in post-socialist agglomerations, the fragmentation of competencies between municipal departments and private entrepreneurs remained a key barrier. The analysis showed that the lack of a single financial instrument slowed down eco-renovation, while, according to G. Foster & R. Saleh, circular funds, and tax incentives accelerated adoption. When comparing, it was found that the method of G. Foster & R. Saleh relied on a high maturity of civic engagement, whereas in the cities studied, similar practices were still at the experimental pilot stage. In addition, G. Foster & R. Saleh considered cultural heritage as an element of a "closed" material cycle, while the study involved a broader socio-cultural continuum that included intangible assets. This confirmed that the sustainability of restoration projects was determined not only by environmental metrics, but also by the degree of institutional coordination of management regimes.

The approach by T.-S. Kim (2024) was based on the analysis of the visual environment as a communicative structure of signage, facades, and language codes were considered as elements of public representation of identity. This approach was based on the assumption that visual conflict arises from a discrepancy between the new cultural content and the established symbolic order of the city. In contrast, the conducted research was based on an administrative and functional approach. Visual transformations are not considered as autonomous cultural utterances, but as the product of a certain mode of coordination. Where there is a mechanism for prior coordination with residents and regulatory authorities, facade changes take place without conflict, regardless of their symbolic saturation. Thus, the difference between T.-S. Kim and the present study consists not only in the interpretation of the visual changes themselves, but also in analytical optics, the first model focuses on signs, the second on procedures. The question of the permissibility of changes is not solved at the level of symbolic content, but at the level of institutional manageability. Hence the discrepancy in conclusions, if in the interpretation of T.-S. Kim, new visual codes were in conflict with the historically established semiotic structure of the city, so within the framework of this study they were considered as a manageable part of institutional adaptation.

Spatial alienation, which occurs at the junction of tourist expectations and local experience, was treated in the study by M. Šnorbert (2022) mainly in terms of visual dissonance. The researcher considered Prague Castle and the surrounding territories as zones of symbolic overload, where representative images replicated by media and digital tourism platforms came into conflict with the everyday environment. According to this interpretation, conflict is defined as a discrepancy between the external symbolic projection and the internal perception of a place by residents. However, the results of the study suggest a different model of causality. Spatial conflict manifests itself not as a consequence of excessive visualisation, but as a result of the functional transformation of the urban environment – first of all, the transition from long-term residence to short-term rental. This indicates the importance of a regulatory framework that can shift the regulatory vector from symbolic measures (for example, visual corridors) to functional space management. There is also a different approach to identifying entities capable of stabilising the urban environment. In the model by M. Šnorbert, the main regulator is the state authorities, in particular, the structures related to the protocol management of historical heritage. The study highlighted the active role of non-governmental actors – initiative associations and non-profit organisations that are able to interfere in planning processes and ensure a contour of coordination of interests between residents, entrepreneurs and municipal authorities. Thus, the difference between approaches was determined not only by the level of analysis (visual or operational), but also by assumptions about how urban conflicts were formed and regulated. Model by M. Šnorbert proceeded from a representative logic, where the image had an independent impact, while this work pointed to the need to consider the infrastructural and regulatory conditions in which such an image arises and is perceived. As a result, strategic regulation should include not only control over visual perception, but also tools aimed at managing functional flows and sustainable spatial load distribution.

In the context of a post-Soviet city, collective memory functioned not as a closed system, but as a set of diverse practices in which administrative, local, and international actors intersected (Ivashko *et al.*, 2020; Dzyba & Saveliev, 2023). The study showed that the policy regarding monuments in Bishkek did not have a centralised source and did not follow a single regulatory logic. Memorial sites, including Ala-Too Square and the Manas Ordo complex, were preserved, reconstructed, or interpreted depending on the balance between government initiatives, public demands, and external sources of support. Such an institutional structure assumed a stable coexistence of competing forms of memory. It was in this multiplicity of subjects and forms that the specifics of the city's memorial policy were contained; no one level had monopoly power over the interpretation of the past.

B. Soukupová (2020) proposed a typology of "wars" for public space, classifying conflicts by duration, material costs and number of actors. The Prague study revealed the dominance of slow conflict cycles with rare b ursts of escalation. The researcher interpreted the public square as an arena of struggle between commercialisation, memorialisation, and civic activism. The study noted that negotiation models prevailed in the squares of Bishkek, in which situational coalitions of historians and residents made it possible to reach a compromise before an open conflict. The comparison showed that B. Soukupová gave priority to the symbolic capital of the place, while this study revealed the crucial role of tax-equity mechanisms and flexible urban planning expertise. It was also established that the methodology of territorial diversification of attendance (disclosed in the study through the Beyond the Old Town project Prague) can be adapted to Bishkek to redistribute flows between Ala-Too and peripheral monuments. The conducted research has documented that the implementation of projects for the preservation of historical heritage in Bishkek depended primarily on administrative predictability, regulatory certainty, and the availability of functionally justified modes of use of buildings. Successful examples, such as the reconstruction of the State Historical Museum, have demonstrated that the sustainability of monuments was ensured not by visual authenticity, but by a legally established law enforcement status, access to stable financing and public legitimisation of the project.

This configuration was opposed to those models in which the main focus was on architectural integrity and visual conformity. In particular, in the study by K. van Knippenberg & B. Boonstra (2022) called the aesthetic

consistency of objects with the surrounding buildings and the active participation of residents in maintaining the visual identity of the area the main condition for the successful restoration of the historical environment in Warsaw. These parameters were accompanied by combined financing measures, including municipal subsidies and micro grants. However, architectural integration was not a leading criterion in Bishkek. In the absence of targeted subsidies and insufficient regulatory framework, preference was given to preserving the functional significance of buildings. Historical objects involved in active use proved to be more stable regardless of their visual transformation. Thus, the main support mechanism was not stylistic conservation, but ensuring continued operation within acceptable legal and sanitary standards. In addition, the degree of participation of the local population in the restoration and reconstruction processes also differed. In the Warsaw case, the involvement of residents was organised and supported, whereas in Bishkek, citizen participation was limited to individual initiatives and was not institutionalised. This reduced the possibility of horizontal coordination and called into question the sustainability of projects without direct government or international donor support. Unlike the model proposed by K. van Knippenberg & B. Boonstra, a study on Bishkek has shown that successful renovation does not necessarily require preserving the architectural appearance. It is possible if there are legal guarantees, stable regulations for land use and mechanisms for the inclusion of citizens at the decision-making level, even if significant external changes are allowed. Aesthetic continuity may be significant, but it is not a determining condition for the sustainability of an object in an institutionally unstable environment.

CONCLUSIONS

The study emphasised significant obstacles in safeguarding historical treasures in Bishkek amid increasing urbanisation. A significant problem was the absence of a current inventory of cultural monuments, resulting in the reversible designation of protected places. Numerous structures lost their protected status owing to assertions of deterioration or outdated functionality. Accelerated urban densification diminished sanitary zones, heightened engineering stresses, and degraded the microclimate, hence worsening the maintenance of monuments. Successful conservation initiatives, like the State Historical Museum and Manas Ordo Complex, exemplify the efficacy of integrating governmental backing, international collaboration, and reverence for native memory practices.

Conversely, Prague exhibited enhanced institutional stability and a holistic strategy for cultural protection. The city integrated historical landscape preservation into urban development by employing a multi-tiered security system, explicit height limitations, and visual corridors. Prague received European money for restoration and digitisation initiatives, while civic engagement and collaborative design bolstered public legitimacy in the transformation of the urban landscape. Despite tourism demands, Prague preserved a balance between expansion and originality through transparent planning and urban oversight.

Rome's circumstances presented more intricate issues owing to its elevated monument density. Strict legal constraints, encompassing the notion of material patrimonialism, provided substantial protection for cultural sites exceeding 70 years of age. Technological advancements, like digital twins, sensor networks, and nanomaterials, improved conservation initiatives. Nonetheless, the city faced challenges in infrastructure improvements owing to archaeological findings and the expansion of tourists. Efforts to diversify tourist itineraries and regulate short-term rentals have been beneficial. Yet, the difficulty of reconciling the preservation of authenticity with economic sustainability persists.

Promising areas of further research include the development of digital registers of monuments, the analysis of the impact of investment projects on the loss of heritage, and the creation of models for integrating green infrastructure into protected areas. It is also necessary to investigate the mechanisms of participatory planning in post-Soviet cities. The limitations of the study were the lack of full access to the internal documentation of government agencies, the changing regulatory framework in the course of research, and insufficient availability of long-term data on the technical condition of monuments, which limited the depth of empirical analysis.

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Проблеми збереження історичної спадщини в умовах модернізації міського ландшафту

Анотація. Актуальність дослідження полягає в тому, що в умовах прискореної модернізації міського простору в першій чверті XXI століття істотно загострилися протиріччя між стратегіями розвитку і механізмами охорони історичної спадщини, що вимагає наукового осмислення застосовуваних практик та інституціональних моделей. Метою цієї роботи було виявлення чинників, що визначали успішність або неефективність програм збереження пам'яток архітектури та містобудівного середовища в умовах зростання, інвестиційного тиску і трансформації нормативно-правових регламентів. Методологія дослідження спиралася на порівняльний аналіз правових систем, містобудівних підходів і емпіричних кейсів у трьох містах: Бішкеку, Празі та Римі. Результати дослідження продемонстрували, що ефективність охоронних стратегій безпосередньо залежала від поєднання жорсткості правового статусу об'єктів культурної спадщини, наявності економічних стимулів (субсидій, податкових пільг, програм фінансування), рівня цифрової підтримки моніторингу стану пам'яток, а також ступеня залученості місцевих громад в ухвалення містобудівних рішень. У Бішкеку фіксувалася інституційна нестабільність і правовий дуалізм, що сприяло оборотності охоронного статусу і прискореній втраті знакових об'єктів. Прага показала життєздатність багатоступеневої моделі охорони, заснованої на зонуванні та узгоджувальних механізмах, тоді як Рим продемонстрував потенціал цифрових технологій та інтеграції культурної політики з логікою «розумного міста». Зроблено висновок про те, що стійкість історичного ландшафту забезпечувалася за наявності комплексної моделі управління, що включала три взаємопов'язані компоненти: нормативний захист, економічну доцільність і технологічну адаптацію. В умовах урбанізаційного тиску саме синтез правових, технічних і соціокультурних механізмів давав змогу не тільки зберігати матеріальні шари історичної пам'яті, а й інтегрувати їх у стратегічний розвиток сучасного міського середовища

Ключові слова: архітектурна автентичність; глобалізація; цифровий моніторинг; реставрація; культурна ідентичність

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Mathematical modelling and factors affecting aerated concrete with floating ash cenospheres

Abstract. Incorporating floating ash cenospheres from thermal power plants in aerated concrete and other construction materials is crucial for addressing environmental and economic challenges. The principal objective of the research was to explore the incorporation of fly ash cenospheres sourced from Kazakhstan into the production of aerated concrete. The study used mathematical modelling employing methods such as analysis, comparison, synthesis, and a systematic approach. Significant findings were obtained from investigation into the properties of aerated concrete incorporating floating ash cenospheres. Through rigorous mathematical modelling and experimentation, vital correlations were uncovered between various factors, such as composition, curing conditions, and production methods – and the resulting properties of the concrete. Observations revealed that the utilisation of floating ash cenospheres led to tangible

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improvements in multiple key properties of aerated concrete. Notably, a substantial increase in compressive strength, a significant decrease in density, and a remarkable enhancement in thermal insulation properties were noted compared to conventional concrete formulations. Furthermore, the efficacy of mathematical modelling in accurately predicting and optimising concrete properties was showcased. By leveraging this approach, not only could the impact of different factors on concrete performance be anticipated, but production processes could also be refined to achieve desired outcomes efficiently. The results of this study carry practical significance for the construction sector, presenting avenues to refine the manufacturing process of aerated concrete and elevate its efficacy

Keywords: construction materials; sustainable building; engineering applications; properties analysis; mechanical behaviour

INTRODUCTION

In construction landscape, the utilisation of aerated concrete with floating ash cenospheres presents a promising avenue for sustainable building practices. However, understanding and optimising this innovative material is essential to address contemporary environmental challenges and meet the demands of modern construction. Failure to do so may hinder progress towards sustainable construction goals and impede the adoption of eco-friendly building materials.

Cenospheres, also known as fly ash cenospheres (FAC), widely utilised as fillers in artificial materials and other products, cenospheres offer promising opportunities for addressing environmental challenges associated with fly ash disposal as M.F. Banda *et al*. (2024) and M. Kowsalya *et al*. (2024) mentioned. In article by Z. Tauanov *et al*. (2022) and also D. Sunjidmaa *et al*. (2019), the authors investigate the problem of ash formation as a by-product of coal combustion at power plants, while emphasising the prospect of ecological application of this waste. In this context, special attention was paid to the synthesis of zeolites using modern production approaches and their applications, including heavy metal removal and catalysis. However, among the advantages, the disadvantages of the synthesis of zeolites from ash were also investigated, which leaves an open question. A. Satayeva *et al*. (2022) investigated the environmental problems associated with the accumulation of FAC. The paper provided a detailed comparison of the physical properties and chemical composition of cenospheres from Kazakhstan power plants and presented impressive approaches to help reduce mercury pollution problems.

In the Pavlodar region of Kazakhstan, Ekibastuz State District Power Plant (SDPP)-1 and SDPP-2 thermal power plants (TPP) generate significant volumes of fly ash, much of which comprises floating ash, accumulating along the lakeshores of ash storage facilities. These floating ash cenospheres present a unique resource for exploration in the construction industry. S.K. Tanirbergenova *et al*. (2023) endeavoured to explore the capacity for augmenting the strength attributes of concrete materials by leveraging ash waste sourced from TPP in Kazakhstan. Their focus was on altering the chemical composition of these materials, with cenospheres emerging as the most impactful additive. The inclusion of cenospheres led to a notable enhancement in compressive strength, surpassing samples without additives by more than twofold. But the question of assessing their long-term durability remains open. A. Shokanov *et al*. (2020) used Mössbauer spectroscopy and X-ray diffraction analyses to investigate fly ash samples derived from coal combustion in the Ekibastuz basin, specifically at TPP-2 and TPP-3 in Almaty, Kazakhstan. These analytical techniques provide valuable insights into the structural and chemical composition of the fly ash, offering essential data for understanding its properties and potential applications. For example, R. Ibrasheva *et al*. (2021) investigated the synthesis of catalysts from cenospheres extracted from fly ash and their performance in hydrocarbon processing. Results demonstrate the efficacy of the synthesised catalysts in producing light gas oil and achieving high selectivity in methanol conversion. Further research is needed to optimise the isolation of microspheres and understand the mechanistic aspects of catalytic reactions under different temperature conditions.

In the context of using aerated concrete with floating ash cenospheres, careful consideration of the chemical composition of cenospheres is crucial for maximising their effectiveness as additives in concrete applications, as it directly impacts their properties and performance (Makyeyeva *et al*., 2024). The analysis highlights correlations between chemical composition, grain size, and refractoriness of the cenospheres, suggesting potential benefits in classifying cenospheres into grain-size classes for extended industrial applications. Several problems exist within the industry and research landscape regarding the utilisation of aerated concrete with floating ash cenospheres (Nenastina *et al*., 2024). Firstly, there is a lack of comprehensive understanding regarding the long-term durability and performance of aerated concrete incorporating these cenospheres in real-world construction applications. Additionally, questions remain regarding the scalability of mixtures containing cenospheres for sustainable concrete manufacturing practices. Furthermore, the environmental implications of coal fly ash disposal and the potential hazards associated with improper handling need to be thoroughly examined. If these issues are not explored, it could result in setbacks in achieving sustainability goals, hinder progress in construction practices, and exacerbate environmental concerns.

While existing research has provided valuable insights into the potential of cenospheres as additives in concrete materials, several aspects remain unexplored as long-term durability and performance of lightweight concrete incorporating cenospheres, the scalability of mixtures containing cenospheres, the environmental implications of coal fly ash disposal and the potential hazards associated with improper handling. In this case, the primary aim of this study was to investigate the integration of fly ash cenospheres obtained from Kazakhstan into the manufacturing process of aerated concrete.

MATERIALS AND METHODS

To investigate the effects of factors on the properties of aerated concrete derived from floating ash cenospheres, methods such as analysis, comparison, synthesis, mathematical modelling, and a systemic approach were utilised to achieve a comprehensive understanding of the subject matter. Through meticulous analysis, the composition, structure, and performance characteristics of the aerated concrete samples were thoroughly examined. This method provided a detailed understanding of the material's properties. Synthesis played a crucial role in this study as well. By integrating data from diverse sources, including experimental results by J. Shi *et al*. (2022a; 2022b) and V. Kavinkumar *et al*. (2023), literature reviews by Z. Tauanov *et al*. (2022), A. Satayeva *et al*. (2022) and A.D. Johar *et al*. (2024), and theoretical models by W. Chen *et al*. (2020) and S. Banerjee (2021), an understanding of the elements impacting the characteristics of aerated concrete was developed. Comparison was then conducted to discern how different factors impacted the properties of the aerated concrete. By comparing various formulations or production methods, patterns and variations in material performance were identified.

Furthermore, mathematical modelling served as a powerful tool in research. Survey data underwent rigorous mathematical and statistical analyses to derive average values of numerical indicators from the studies. These values were manipulated within defined parameters to construct a mathematical model of the study. Subsequently, optimisation methods were employed to identify the most efficient study approach. Through the formulation of mathematical equations and computational models, the behaviour of aerated concrete under various conditions was simulated. This research methodology primarily investigated the interrelation between influencing factors, production technology, and product characteristics. The mathematical representation of the general form of the model was denoted as follows:

$$Y=A(X), \quad (1)$$

where Y – the output parameter, signifying the primary characteristics of the product, often termed objective functions or optimisation parameters; A – the input parameter, serving as an operator defining the mathematical operation transitioning to the output factor; X – the input factor, commonly referred to as arguments.

In prior stages of planning the mathematical modelling experiment, adjustments in ash, lime, and water temperature quantities were guided by earlier experiments investigating the impact of these factors on aerated concrete properties incorporating a floating ash mixture from Ekibastuz SDPP. The composition of the aerated concrete included Portland cement as the primary binder, with sand as the aggregate and aluminium powder as the blowing agent. Standard samples in the form of 10×10×10 cm cubes were prepared for testing purposes. These samples were demoulded following a heat-moisture treatment period at 80°C for 14 hours, allowing for proper curing and strength development. Subsequently, compressive strength and bulk density data were collected post-hardening, measured within a 28-day period under standardised conditions. This meticulous approach ensured that the aerated concrete samples experienced realistic environmental conditions, providing accurate insights into their long-term performance.

This methodical approach facilitated a thorough exploration of the intricate interplay between influencing factors and concrete properties, enabling the development of effective strategies for optimising production processes and achieving desired outcomes in aerated concrete production. Utilising the findings garnered from the experimental endeavour's, the multifactorial mathematical regression model, encapsulating the variability in aerated concrete strength, is meticulously formulated within a comprehensive three-factor matrix (2):

$$Y_R = 2.41 - 0.38X_1 - 0.1166X_2 + 0.031X_3 - 0.05X_1X_2 + \\ + 0.045X_1^2 - 0.0734X_2^2 - 0.093X_3^2, \quad (2)$$

where X_1 – the quantities of ash; X_2 – amount of lime; X_3 – the temperature of water.

Subsequent to the experiment's culmination, a comprehensive three-factor mathematical regression model has been meticulously devised to explicate the nuanced fluctuations observed in the volumetric mass of concrete (3).

$$Y_p = 830 - 24.71X_1 - 13.28X_2 - 8.87X_1X_2 - 4.37X_2X_3 + \\ + 11.28X_1^2 + 8.06X_2^2 - 4.87X_3^2. \quad (3)$$

The amalgamation of theoretical studying and experiment yielded optimal results in establishing a mathematical model for research. The theoretical studying scrutinised the structural properties of the study object and the product to deduce the equation's general form. However, to ascertain the numerical coefficients of the calculated part or equation and validated theoretical conclusions, the experiment was indispensable. When the result of the research gave a stochastic number, and the input parameter kept a fixed value, and was not stochastic, then the mathematical model was called regression. The experiment planning matrix was a numerical table illustrating the variation in factor values across different experiment sequences. Experimental multi-factor planning entails simultaneous was changed in all factors. If the resulting equation

representing the research object in the form of a mathematical model was nonlinear, then a second-order mathematical model was developed. Lastly, a system approach was employed to study aerated concrete properties within a broader context. By considering factors such as raw material sourcing, production methods, structural design considerations, and environmental impact, insights into the interconnectedness of various aspects of aerated concrete production and application were gained.

RESULTS

Through careful examination and testing, important information about how different elements affect the characteristics of concrete is discovered, revealing the effectiveness of incorporating floating ash cenospheres into construction materials. Ensuring consistency between the findings of initial and primary experiments was accomplished through meticulous mathematical modelling, a process that involved comprehensive analysis and validation of the experimental data (Banerjee, 2021). The design of the experiment focused on two key output parameters: the compressive strength and average density of aerated concrete, which are fundamental indicators of its structural integrity and quality. Three influential factors were identified: the quantities of ash X_1, lime X_2, and the temperature of water X_3, each playing a significant role in shaping the properties of the concrete. By systematically varying these factors within a predetermined range, researchers were able to observe their individual and collective effects on the final characteristics of the aerated concrete. Using these criteria, a planning matrix was constructed, which is shown in Table 1, outlining the specific combinations of factors to be tested in the experiments. Additionally, its corresponding test matrix is depicted in Table 2, providing a detailed roadmap for executing the experiments with precision and accuracy. These matrices served as not only a guide for experimental setup but also as a means of organising and analysing the vast amount of data generated throughout the study.

Table 1. Matrix for experimental planning

Influencing factors (code)	Unit	Level of influencing factors					Midpoint value, J_i
		$-X_{remote}$ -1.682	X_{ilower} (-1)	X_{io} 0	X_{iupper} (+1)	$+X_{remote}$ 1.682	
X_1	%	14.7	25	40	55	65.2	15
X_2	%	1.6	5	10	15	18.4	5
X_3	°C	53.2	60	70	80	96.8	10

Source: compiled by the authors

Table 2. Experiment matrix and findings

n	N	Coded factor values			Actual data			Outbound metrics (MPa), trial repetition				$\sigma N^2(Y)$	$\bar{Y}_R$ (MPa)	$\bar{Y}_{\rho(V)}$(kg/m³)
		X_1	X_2	X_3	X_1	X_2	X_3	Y_1	Y_2	Y_3	$\bar{Y}$			
n_h	1	+	+	+	55	15	80	1.4	1.33	1.28	1.34	0.0073	1.73	790
	2	+	+	-	55	15	60	1.28	1.31	1.36	1.31	0.0017	1.73	810
	3	+	-	+	55	5	80	1.79	1.72	1.81	1.77	0.0021	2.08	880
	4	+	-	-	55	5	60	1.66	1.6	1.83	1.7	0.0142	2.08	861
	5	-	+	+	25	15	80	2.65	2.59	2.67	2.63	0.0016	2.61	844
	6	-	+	-	25	15	60	2.58	2.54	2.65	2.59	0.0031	2.61	835
	7	-	-	+	25	5	80	2.8	2.83	2.87	2.83	0.0012	2.72	877
	8	-	-	-	25	5	60	2.78	2.82	2.84	2.81	0.009	2.72	872
n_r	9	-1.682	0	0	14.7	10	70	2.92	2.97	2.9	2.93	0.0013	3.17	932
	10	+1.682	0	0	65.2	10	70	2.68	2.6	2.61	2.63	0.0019	1.9	783
	11	0	-1.682	0	40	1.6	70	2.62	2.53	2.5	2.55	0.0039	2.39	840
	12	0	+1.682	0	40	18.4	70	2.4	2.37	2.36	2.34	0.0014	2	857
	13	0	0	-1.682	40	10	53.2	2.3	2.31	2.31	2.31	0.0001	2.14	819
	14	0	0	+1.682	40	10	96.8	2.45	2.44	2.44	2.47	0.0031	2.14	805
n_0	15	0	0	0	40	10	70	2.4	2.49	2.4	2.43	0.0027	2.41	831
	16	0	0	0	40	10	70	2.4	2.35	2.42	2.39	0.0013	2.41	826
	17	0	0	0	40	10	70	2.37	2.39	2.41	2.39	0.0005	2.41	833
	18	0	0	0	40	10	70	2.35	2.48	2.43	2.42	0.0043	2.41	834
	19	0	0	0	40	10	70	2.36	2.4	2.35	2.37	0.0007	2.41	828
	20	0	0	0	40	10	70	2.4	2.43	2.41	2.41	0.0002	2.41	833
											46.62	0.0534		16791

Notes: n_h – number of trials at extreme points; n_r – number of trials at remote points; n_o – number of trials at the central point; $\bar{Y}$– average of outbound metrics; $\sigma N^2(Y)$ – variance of outbound metrics; $\bar{Y}_R$ – average of outbound metrics at remote points; $\bar{Y}_{\rho(V)}$ – – predicted average of outbound metrics

Source: compiled by the authors

The experiment comprised a three-factor matrix consisting of a total of $N = 20$ trials. Among these, $n_0 = 8$ trials were conducted at the central point, while $n_h = 6$ trials were executed at the extreme point. Furthermore, $n_r = 6$ trials were carried out at the remote point, with the corresponding values for the remote point of the lines indicated as $a = (-)(+)1.682$. These experimental configurations were carefully designed to cover a wide spectrum of conditions and variables, ensuring thorough and dependable data collection for subsequent analysis and interpretation.

Based on the experimental results obtained within the three-factor matrix, a mathematical regression model was developed to capture the effects of second-order interactions, notably the type $X_2 \cdot X_3$ interaction, on the compressive strength and average density of aerated concrete. The model quantitatively described the relationships between influencing factors and concrete properties. Specifically, within the experimental ranges, ash content (X_1) varied from 14.7% to 65.2%, lime content (X_2) from 1.6% to 18.4%, and water temperature (X_3) from 53.2°C to 96.8°C. Analysis of the model indicated that the maximum compressive strength reached 2.93 MPa at an optimal combination of 14.7% ash, 10% lime, and 70°C water temperature, while the minimum strength observed was 1.31 MPa at 55% ash, 15% lime, and 60°C water temperature. Similarly, the average density ranged between 783 and 932 kg/m^3 depending on the mixture parameters.

Validation of the proposed mathematical models was carried out by comparing the predicted values of compressive strength and density of aerated concrete with the actual experimental data obtained from 20 test trials. The average variation of predicted strength values from experimental data did not surpass 5%, whilst for density it was roughly 4%. This analysis showed a good degree of agreement between the model and actual observations. For materials science multifactor regression models, these variations are within allowable error ranges. High repeatability of data was ensured by parallel repeats (8 trials at the centre of the design), as shown by the low variance in strength values (coefficient of variation less than 2%). This shows that the production parameters are stable and that the statistical results are adequate. By optimising the model output parameters through the application of objective functions (formulas (2) and (3)), the aerated concrete's qualities were enhanced. Sensitivity study showed that while the relationship between ash content and lime content mostly influenced material density, ash content and water temperature had the greatest effects on strength metrics. This made it possible to precisely define the parameter ranges needed to produce the required material properties. For instance, density was reduced between 790 and 840 kg/m^3 without sacrificing compressive strength below 2.4 MPa.

For the optimisation of mathematical models describing the experimental results, an analytical method of multivariate objective function was employed. The minimum compressive strength value $Y_R = 2.41$ MPa was found at a specific point in the factor space (a combination of X_1, X_2, X_3) corresponding to fixed factor values at the central level of the experimental design. Similarly, the maximum average density value $Y_\rho = 916$ kg/m^3 was determined as the highest value of the density function within the experimental data range. These results were obtained through a mathematical search for the extremal values of the respective second-order regression functions. For this purpose, based on the constructed polynomial models of strength and density in the three-dimensional factor space – ash content, lime quantity, and water temperature – an analytical calculation of critical points (extrema) was carried out within the experimentally defined factor ranges. The execution of six parallel trials at the central level of the experimental design enriched the dataset used to assess the accuracy and reliability of the developed models.

The analysis of the experimental data revealed several key insights into the factors influencing the properties of aerated concrete. Trends and patterns in the data were identified, highlighting the significant impact of factors such as ash content, lime quantity, and water temperature on concrete strength and density. Moreover, the examination of interaction effects between these factors provided a deeper understanding of their combined influence on concrete properties. The validation process entailed meticulous examination, comparing the forecasts generated by the mathematical models with the empirical data collected during the experiments. This scrutiny uncovered a remarkable level of alignment, signifying that the models effectively encapsulated the discernible patterns and fluctuations observed in the data. Additionally, employing statistical techniques furnished quantitative evidence affirming the reliability and resilience of the conclusions drawn. In sum, the validation procedures fostered assurance in the precision and prognostic prowess of the mathematical models underpinning the study.

The examination of experimental data and the validation of mathematical models have provided invaluable insights into the determinants affecting the characteristics of aerated concrete (Sidliarenko, 2023). Through meticulous statistical scrutiny and alignment with experimental findings, the precision and dependability of the mathematical models have been affirmed. These revelations not only deepen comprehension of concrete manufacturing processes but also furnish pragmatic directives for refining concrete attributes in practical contexts. Ultimately, the outcomes of this investigation pave the path for progress in the innovation and utilisation of eco-friendly construction materials. The discoveries from this study bear promising prospects for advancing the development and enhancement of aerated concrete materials for real-world utilisation. By elucidating the influence of key factors such as ash content, lime quantity, and water temperature on concrete properties, this research provides valuable insights for engineers and materials scientists seeking to enhance the performance and sustainability of construction materials. Furthermore, the validated mathematical models offer a powerful tool for predicting and optimising

concrete properties in diverse production scenarios, facilitating the design of more efficient and cost-effective construction processes.

DISCUSSION

The study's findings contribute to understanding of aerated concrete production processes and offer valuable insights for optimising concrete properties. By confirming the significant influence of ash content and curing conditions on concrete strength and density, the study reinforces the importance of these factors in concrete production. However, discrepancies with previous research regarding the impact of lime quantity on concrete strength emphasise the necessity for further exploration into the underlying mechanisms. Furthermore, the study's novel exploration of water temperature's role in aerated concrete production opens avenues for future research and underscores the complexity of concrete formulation. Advancing ahead, integrating these insights into concrete production practices holds the potential to foster the development of more sustainable and high-performance construction materials.

Significant attention has been directed towards the separation of cenospheres from fly ash, given their distinct properties and potential applications. A.D. Johar *et al*. (2024) mentioned that, cenospheres, valued for their lightweight and versatile properties, can be separated from fly ash using wet or dry techniques, involving methods such as submersion in solvent mixtures or cyclone separation, respectively. In comparison this investigation also focuses on the utilisation of these cenospheres in aerated concrete and their impact on its properties and gained the same conclusions but in another way. Understanding the properties and separation methods of cenospheres is crucial for investigation into their utilisation in lightweight concrete production was mentioned in this research. Also, their unique properties, such as thermal insulation and reduced density, make them particularly suitable for the production of lightweight concrete as S. Takibai *et al*. (2022) wrote. J. Yang *et al*. (2023) also studied that incorporating cenospheres into concrete mixtures enhances its mechanical properties while reducing overall weight, offering advantages in construction projects where weight reduction is crucial.

In study, cenospheres were utilised as a lightweight additive to substitute a portion of fly ash in the formulation of ultra-lightweight foamed geopolymer concrete (UFGC). The investigation aimed at elucidating the correlation between the fresh properties of the geopolymer paste and the stability of the UFGC mixture, with particular emphasis on controlling its hardening behaviour. The result is informative for comparison and further research, since this study did not consider UFGC. Findings from J. Shi *et al*. (2022a) revealed that the incorporation of cenospheres into the slag-fly ash system effectively mitigated the reaction rate of the geopolymer paste, thereby decelerating the decomposition rate of H_2O_2 and influencing the initial size of the decomposed foams. Additionally, with the increase in cenospheres content, there was a noticeable decrease in the density of the geopolymer foams, resulting in enhanced mechanical properties and thermal insulation performance (Zhangabay *et al*., 2023). This effect was particularly pronounced when the substitution ratio of cenospheres reached 50%.

Moreover, the study by J. Shi *et al*. (2022b) explored the potential of cenospheres and fly ash as substitutes for sand in light-weight concrete (LWC), investigating their impact on the strength characteristics of concrete structures. Through experimental research, it was determined that using fly ash up to 25% and cenospheres up to 30% as sand replacements. In research by V. Kavinkumar *et al*. (2023), LWC resulted in improved strength properties, indicating the viability of utilising these waste materials for sustainable construction practices. Further research and development in the extraction and utilisation of cenospheres hold promise for advancing the production of lightweight concrete and addressing environmental concerns associated with coal fly ash disposal.

In this particular investigation, cenospheres proved to be a promising additive for enhancing the properties and suitability of cement-based composites (Strzałkowski *et al*., 2023). The incorporation of cenosphere in lightweight cement-based composites resulted in favourable outcomes, including reduced density, enhanced compressive and flexural strength, and decreased shrinkage. However, W. Chen *et al*. (2020) observed a decrease in fracture energy and negative effects on tensile strain capacity and strength, which attributed to the inadequate interface strength between the aggregate and cement paste. Although faced with these challenges, the internal curing effect induced by cenospheres led to a reduction in shrinkage, accompanied by a notable decrease in the overall embodied energy and global warming intensity of the composites (Bugaevsky *et al*., 2020; Dovhopolov *et al*., 2020). These findings underscore the potential of cenosphere-enhanced cement-based composites as a sustainable solution for mitigating environmental costs in construction practices.

This research explores the potential for enhancing the strength properties of concrete materials by utilising ash waste sourced from TPP located in Kazakhstan. This approach is rooted in the notion of sustainable resource utilisation, aiming to repurpose industrial by-products to enhance the performance of construction materials while concurrently addressing environmental concerns associated with waste disposal. By exploring methods to modify the chemical composition of ash/slag waste, the study seeks to unlock the latent potential of these materials and contribute to the development of innovative and eco-friendly construction solutions. A significant discovery of the study is that cenospheres, distinguished by their spherical particles and smooth vitrified surface texture, emerged as the most effective additive. This finding underscores the significant role of cenospheres in enhancing the mechanical properties of concrete, highlighting their potential as a valuable resource in construction applications. In this context, the

conclusions by G. Koshlak & A. Pavlenko (2021) and M. Orfanova (2023) are also useful.

Moreover, the study sheds light on the process of obtaining cenospheres from ash waste through thermal plasma treatment. This innovative approach offers a sustainable means of generating cenospheres while concurrently mitigating the environmental impact of ash waste disposal (Dzhusupova *et al*., 2024). The compositions of ash waste and the morphological structures of the resulting cenospheres were comprehensively analysed, providing valuable insights into the underlying mechanisms governing the transformation process. Furthermore, the study elucidates the relationship between cenosphere incorporation and the mass reduction of concrete materials. While the addition of cenospheres led to a decrease in concrete mass, the strength characteristics exhibited a significant improvement as was investigated by T. Gupta & P.S. Bokare (2021), A. Jaworek *et al*. (2023) and U.S. Agrawal & S.P. Wanjari (2023). This trade-off between mass reduction and strength enhancement highlights the potential for achieving lightweight yet durable concrete structures through the strategic utilisation of cenospheres.

The study highlights the need for more research into the effects of lime quantity and water temperature on the material's properties while also confirming the significance of ash content and curing conditions in determining the strength and density of aerated concrete using floating ash-slag cenospheres. The connections found between the cenospheres' shape, chemical makeup, and the end properties of the concrete mixture point to the components' encouraging potential for producing strong, lightweight building materials. The findings of the study show how cenospheres may be used as an environmentally friendly additive to reduce structural weight while also enhancing mechanical and thermal insulation qualities.

CONCLUSIONS

As a result of twenty experimental tests, including six repeated experiments at the central point of the design, it was established that the maximum compressive strength of the aerated concrete reached 2.93 MPa at a factor combination of 14.7% ash, 10% lime, and 70°C water temperature, whereas the minimum strength was 1.31 MPa under conditions of 55% ash, 15% lime, and 60°C. The average density varied within the range of 783 to 932 kg/m^3 depending on the mixture parameters. The developed second-order polynomial regression model clearly reflects the interaction of factors, notably revealing a significant effect of the interaction between lime content and water temperature ($X_2 \cdot X_3$) on the properties of the aerated concrete. The model demonstrated high accuracy, with deviations between predicted and experimental values not exceeding 5% for strength and approximately 4% for density, which corresponds to standards for multifactor regression models in materials science. High reproducibility of results was confirmed by a low coefficient of variation below 2% in control tests. By means of analytical search for extremal values of the secondary polynomial regression functions, the minimum strength value of 2.41 MPa was determined at a point corresponding to the central level of the factors, as well as the maximum average density of 916 kg/m^3 within the studied ranges. Sensitivity analysis showed that strength depends most significantly on the interaction between ash content and water temperature, whereas average density is predominantly influenced by the ratio of ash content to lime amount. The obtained results allow precise determination of optimal parameter ranges to achieve the required properties of aerated concrete, particularly reducing density to 790-840 kg/m^3 without substantial strength reduction below 2.4 MPa. However, the study also pointed out several drawbacks. The cenospheres that were utilised had a texture that was comparatively coarse-grained and were composed of 90% mullite with a low percentage of quartz and calcium oxide. This kind of chemical specificity limits the material's ability to reach its optimum strength by decreasing its reactivity. Future research must address practical issues with raw material properties and the necessity for more study of long-term performance and behaviour under actual operational settings.

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Математичне моделювання та фактори, що впливають на газобетон з плаваючими зольними ценосферами

Анотація. Включення плаваючих зольних ценофер із теплових електростанцій у газобетон та інші будівельні матеріали має важливе значення для вирішення екологічних і економічних проблем. Основною метою дослідження було вивчення можливості використання ценофер з летючої золи, добутих у Казахстані, у виробництві газобетону. У роботі застосовувалось математичне моделювання з використанням методів аналізу, порівняння, синтезу та системного підходу. Було отримано суттєві результати щодо властивостей газобетону з плаваючими зольних ценоферами. За допомогою строгого математичного моделювання та експериментальних досліджень було виявлено важливі залежності між різними факторами, такими як склад, умови твердіння, методи виробництва, і властивостями кінцевого матеріалу. Спостереження показали, що використання плаваючих ценофер призводить до помітного покращення ключових властивостей газобетону: суттєвого зростання міцності на стиск, значного зниження щільності та відчутного покращення теплоізоляційних характеристик порівняно з традиційними бетонними сумішами. Крім того, було продемонстровано ефективність математичного моделювання у точному прогнозуванні та оптимізації властивостей газобетону. Використання цього підходу дозволяє не лише передбачити вплив різних факторів на характеристики матеріалу, але й удосконалити виробничі процеси для досягнення бажаних результатів з максимальною ефективністю. Результати дослідження мають практичне значення для будівельної галузі, відкриваючи шляхи вдосконалення технології виробництва газобетону та підвищення його ефективності

Ключові слова: будівельні матеріали; сталеве будівництво; інженерні застосування; аналіз властивостей; механічна поведінка

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Challenges of urban development in providing temporary housing for internally displaced persons: Lviv experience

Abstract. This study highlighted the contradictions that arise when addressing the housing needs of internally displaced persons and analysed their impact on the sustainable development of the city. The purpose of this study was to identify the urban planning problems caused by the establishment of modular settlements in the already developed urban environment of Lviv, where four such settlements were organised in 2022 and to assess their impact on urban structure and sustainable development. To fulfil the purpose of the study, theoretical methods were applied, particularly the logical-philosophical approach to studying temporary housing as a process that occurs in specific socio-economic conditions. An urban planning and comparative-typological analysis of these settlements was performed, evaluating their potential in the context of urban development and the provision of temporary housing. A negative impact on urban structures was identified due to the mismatch between the needs and challenges of sustainable development, particularly in terms of functional identity and the integration of such settlements into the existing environment. Based on the results, it was proposed to consider modular settlements as part of multifunctional structures that must be flexible and adaptive to changes in the socio-economic context. The practical significance of this study lies in the development of recommendations for urban planners on implementing adaptive approaches in designing temporary settlements, ensuring the sustainable development of urban areas, and fostering social interaction between internally displaced persons and local communities

Keywords: modular town; regional centre of Western Ukraine; urban environment; contextuality; sustainability

INTRODUCTION

Security is one of the key factors forcing the population to leave their homes, escaping the consequences of military actions, temporary occupation, manifestations of violence, human rights violations, and anthropogenic disasters. In the context of forced displacement, such individuals acquire the status of internally displaced persons (IDPs) (Law of Ukraine No. 1706-VII, 2014). An adequate living environment plays a crucial role in the adaptation and social integration of IDPs. Housing shortages, mismatches with their needs, or the temporary nature of their housing arrangements can negatively affect urban development, complicate adaptation processes, increase social isolation, and influence the economic activity of displaced persons. This issue became particularly acute in Ukraine after 2014 and reached a critical level in 2022 due to the full-scale war. A. Pleshkanovska *et al*. (2024) emphasised that urban recovery strategies should be based not only on the physical restoration of housing but also on the preservation of cultural heritage, energy efficiency, and the formation of an inclusive environment. Analysing the housing needs of IDPs, C. Jayakody *et al*. (2022) highlighted that housing plays a key role in community recovery and determines the long-term satisfaction of displaced persons. Viewing housing solely as a physical resource without considering social,

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economic, and psychological aspects may lead to various problems, including marginalisation and spatial segregation of IDPs. V. Borysenko (2023) addressed the lack of focus on integration processes in the pre-war period and stressed the significance of fostering a culture of hospitality and a sense of belonging during the adaptation of IDPs.

Since February 24, 2022, Lviv has been one of the main places of concentration for IDPs. As of the end of January 2023, 251,000 IDPs were registered in the Unified Information Database in the Lviv region. However, their real number is much greater (The real number is..., 2023). Most IDPs are children, women, and people with disabilities. The problem of providing housing prompted the development of certain regulations (Resolution of the Cabinet of Ministers of Ukraine No. 495, 2022) and led to the formation of temporary residential centres. Various shelters (Kostyk, 2022) and modular towns (Press service of the Lviv Regional State Administration, 2022) were created, focused on providing temporary housing for IDPs. As a result, distinct communities emerged, united territorially and bound by shared problems and interests.

The idea of housing provision appeared to be resolved; however, social issues and challenges related to the harmonisation of the newly formed urban environment began to intensify. The official website of the UNICEF in Ukraine (2023) noted that due to the abrupt change in their place of residence, physical isolation from the outside world, and the loss of familiar social connections, internally displaced persons experienced significant social and psycho-emotional challenges. The creation of clusters that are uncharacteristic of the existing residential environment – functioning as typical territorial units with clearly defined boundaries and a minimal set of infrastructure elements – disrupts established urban structures, some of which have a deep historical context. As a result, O. Panchenko (2022) pointed out that this issue became a subject of controversy among architects and urban planners, particularly in discussions about the appropriateness and correctness of hasty decisions. This is especially relevant in cases where the long-term impact of such decisions stays uncertain. The phrase "Nothing is more permanent than the temporary", cited in the study by B. Etzold *et al*. (2022), is central to this discussion and particularly underscores the urgency of the issue at hand.

It is essential to consider that the lack of experience and theoretical foundation in addressing such issues is natural, as the situation in Ukraine is unprecedented. Research on social integration and the spatial organisation of the residential environment for IDPs is based primarily on previous experience, particularly on conceptual and empirical studies published before 2022. Z. Senkiv (2021) attempted to outline the phenomenon of spatial segregation in Lviv and identified its influence on the current situation. Yu. Idak & R. Frankiv (2022) raised the same issue. While examining the formation of gated communities, the researchers traced the relationship between the level of social isolation and the structure of the urban environment. The researchers noted that such enclosed residential complexes exacerbate the divide between local residents.

The issues of integrating IDPs into society and harmonising all elements of the urban environment are important and require thorough research in various sectors. These aspects concern the development of specific approaches and recommendations that would facilitate the creation of favourable conditions for their living and interaction with other residents, as well as the preservation of the integrity of the already formed urban environment. To supplement the theoretical base on this topic, the present study explored the experience of forming temporary housing and examined the problems that the city faced after establishing a residential environment for IDPs. The study also described the mechanisms that influenced the socialisation of these individuals and fell within the competence of urban planners. Additionally, the study addressed the issue of forming a temporary residential environment for IDPs in cities, which had not been addressed in urban planning. This can help improve their quality of life and ensure sustainable development of the city overall.

LITERATURE REVIEW

Due to the complexity and multidimensionality of the problem of displacement caused by war, there is a need for sectoral prioritisation of this issue. Considering the specificity of each situation, it is necessary to address the issues of socialisation of IDPs with consideration of the context in which they arise. R. Patel *et al*. (2020) argued that to better understand how political, social, economic, and environmental factors interact in cities, it is vital to combine multiple disciplines and approaches. To address urban risk issues, integrated strategies must be employed that would account for the interaction of various factors influencing specific challenges. Such research will help to understand how different risks can amplify each other and how these risks may affect particular communities and groups in cities.

A. Mitchell (2022) emphasised that during 2010-2020, there has been a renewed interest in time within human geography. This trend is particularly pronounced in migration studies. The researcher explored sanctuary practices, which can alter the rhythm and flow of time, deviating from the linear, progressive perception of time that dominates modern state systems. E.L.-E. Ho (2021) covered contemporary ways of conceptualising the connection between time and temporality with space to analyse social relations, social inequality, and social justice. The researcher argued that temporal frameworks and strategies for how people interact with unequal socio-spatial relations were central to ongoing issues for social geographers.

G.W. Tefera & A. Gamlen (2024) analysed three approaches to migration research, criticising the conventional use of classical time categories. To problematise and dereify these categories, the researchers proposed using the term "temporal logic", which enables a more detailed analysis of time in the processes of migration, mobility, and displacement. A. Sisson (2021) examined the

phenomenon of territorial stigmatisation, particularly in the context of its development in the 21st century. The researcher explored how territorial stigmatisation is used to explain the negative reputation of certain places, as well as the processes that lead to the creation of this reputation.

The study of Ukrainian experience allowed analysing the internal approaches to functional-planning optimisation of cities (Ustinova & Pleshkanovska, 2023), which ensure more efficient use of their territories and development towards sustainable development. Attention was also drawn to the fact that in modern conditions, the socio-psychological factor, namely the attitude of the population as consumers of the urban environment towards the city, is becoming increasingly significant. Additionally, there is a growing need to develop comprehensive approaches aimed at preserving urban landscapes in various urban contexts (Yatsenko *et al.*, 2024). Of particular significance are issues related to the adaptation of urban areas to changes in socio-economic and environmental conditions, requiring a synergy between functional, aesthetic, and ecological aspects of planning.

Mentioned studies emphasised the necessity of an integrated approach to addressing issues related to urbanisation challenges, social integration, and the adaptation of urban areas to conditions caused by population displacement. Existing sources highlight the multifaceted nature of these processes, encompassing social, economic, spatial, and temporal dimensions, as well as the development of effective strategies for urban environment management. However, the issues of functional and planning development and optimisation of urban territories, aimed at enhancing their efficient use and ensuring sustainable development under the influence of internal and external factors, pose a challenge for urban planners. This challenge involves striking a balance between the needs of diverse social groups, preserving cultural and natural heritage, and integrating innovative approaches into spatial planning. It requires consideration of local specificities, adaptability of design solutions to changes in the socio-economic environment, and the creation of conditions for sustainable urban development that not only respond to challenges but also leverage them to improve the quality of urban life.

MATERIALS AND METHODS

This study was based on an analysis of three modular settlements and one winter settlement IDPs in Lviv: the first one is located in the Stryskyi Park area, the second one is situated on undeveloped plots of land in a residential area formed in the 1980s on Puliuia Street, the third one is located on the territory of the Ukrainian Greek Catholic Church, and the fourth, the winter settlement, is situated nearby. Each of them can be considered a relatively independent object in terms of complex urban planning and according to their physical and social context. They are located in a developed urban environment and consist of standard residential modules equipped with all the necessary amenities for comfortable living. Additionally, they have infrastructure for social support of residents, such as medical points, kitchens, laundries, recreational areas, educational spaces, childcare facilities, psychological support centres, and community meeting halls. The territories of all settlements are landscaped, including inner courtyards with modern street furniture, flower beds, and planted trees.

The study was based on an interdisciplinary approach that allows investigating the declared problem in the interrelation of different scientific fields, such as psychology, sociology, architecture, urban planning, etc. In this context, the study analysed the risks through which war-related migration of citizens to less affected regions may disrupt the integrity and harmony of the existing urban environment. The study was conducted in several stages using the following methods: logical-philosophical, urban planning, comparative-typological, and hypothetical-deductive.

The study begun with the application of logical-philosophical analysis to investigate the problem of the temporal aspect in the formation of the material-spatial environment, which is necessary to ensure human life. The logical-philosophical analysis was performed in two stages: first, the problem was formulated, which consisted of establishing the connection between the temporal aspect and the formation of the material-spatial environment; second, the arguments and evaluation of ideas existing in the context of the formulated problem were studied. The outcome of the logical-philosophical analysis was the identification of key arguments that offered a better understanding of the problem of temporality, which extends beyond the usual fixation of a limited time period. Based on critical literature (Hajjari & Sarvestani 2017), it was noted that this problem is perceived as a universal one, through which a person experiences and understands time. In addition, the logical-philosophical analysis was applied at the stage of discussion, where, based on critical reflection and evaluation of arguments regarding the stated problem, ways to solve it were proposed.

A city planning analysis was further conducted on four modular towns and based on its results, a comparative-typological analysis was performed. Their essence was to determine the strengths and weaknesses of the delineated territories, their potential and limitations, as well as to establish connections between various aspects of IDPs living in an already developed urban environment, such as social, ecological, transport, etc. The analysis results enabled a formal evaluation of the causes of disharmony in the developed urban environment.

Considering the problems of interaction between humans and the environment, as well as the consequences of intervention in the already developed urban structure using Lviv as an example, a hypothesis was put forward that solving the problem of housing for IDPs should be linked to the formation of multifunctional structures. These structures positively influence the city's development and their participants enrich their social experience and can enjoy social connections. Such a hypothesis expands the understanding of the problem of forming temporary housing

environment for IDPs and the possibilities of its solution without disrupting the formed material-spatial environment of human life. The hypothetical-deductive method was applied to test the hypothesis.

Accumulation of information about the organisation of living environments for IDPs and their comparative-typological analysis were made possible by an updated source base. It included photo and video materials, observations, generalisations, graphic representations, and diagrams regarding the problems of IDPs in the Lviv region, as well as available recommendations, catalogues, and manuals (Official website of the World Health Organisation, n.d.), the International Organisation for Migration (IOM) (2023), the Council of Europe (2006), the UN Refugee Agency (2024) and the United Nations Economic Commission for Europe (UNECE) (2021). Considering the large amount of available and diverse materials, as well as for the sake of consistency, their scope was limited. Therefore, sources related to refugees, social housing, and construction solutions were excluded. Statistical data obtained from official sources became significant for determining the real state of such territories.

RESULTS AND DISCUSSION

Prerequisites for studying the impact of migration processes on the organisation of the residential environment for internally displaced persons. The most widespread and accessible sources of information on the problems of integrating IDPs and organising their living environment are documents from the UN (Council of Europe, 2006) and IOM (2023) – a leader in the study of IDPs issues. There are also recommendations developed based on these documents (Paraskeva, 2017) and mechanisms for ensuring the rights of IDPs in the context of national security protection and deepening European integration of Ukraine (Buletsa *et al.*, 2017). In 2022, specialised organisations and experts focused on summarising European standards useful for assessing Ukraine's legislative framework for the protection of IDPs.

As early as the beginning of the 21st century, scientific studies (Castles, 2010; Castles *et al.*, 2013) demonstrated that the growth of migration processes is one of the reasons for the complication of the situation for temporarily displaced persons. An increase in the number of migrants leads to an increase in demand for housing and social support, which complicates housing affordability. In this regard, the development of effective strategies and policies for organising the territory (residential environment) for temporarily displaced persons requires considering migration processes as one of the aspects of this issue and accommodating their specific features when making urban planning decisions.

The category of temporariness in the context of philosophical principles. One of the central concepts applied in relation to IDPs within the framework of the UNHCR approach in Ukraine is "durable solution". A durable solution to IDP problems is considered a situation where the needs and threats associated with displacement disappear (Titar, 2016). Notably, the issue of housing for IDPs in Lviv is viewed as a "temporary phenomenon", requiring time-limited measures to stabilise the situation. Therefore, it is relevant to analyse the category of temporariness in a philosophical context, as this will allow reflecting the essence of the problem in the long term.

In literature, the term "temporary" is applied to various objects, including things, situations, and events that have an impermanent nature, do not last long, or are not intended to last long. It has numerous synonyms, which are determined by diverse contexts and ways of use (Cambridge Dictionary, n.d.). In philosophical discourse (Bedoya, 2004; Hawley, 2004), the term "temporary" can be replaced with "transitional", "fleeting", "ephemeral", or "short-lived", while in the context of technical systems, words like "portable", "mobile", or "movable" are used. Thus, the definition of temporary may vary depending on the discipline and context of its use.

Throughout different historical epochs, many people have observed the impermanence of the world as a constant phenomenon. This observation was characteristic not only of ancient Eastern philosophy of the 6th-5th centuries BC but also of the Romantic era (Hajjari & Sarvestani, 2017), which was characterised by emotionalism, individualism, and expressiveness in the creation of artistic works (Encyclopædia Britannica, n.d.). Within the phenomenological tradition, the thesis was analysed that temporality is time that manifests itself in human existence and is its subjective experience (Hoy, 2009). For the ancient Greeks, time was closely related to natural phenomena, such as the movement of the sun or the change of seasons, rather than abstract concepts as in the modern world. Therefore, something temporary for them meant a natural and limited span of existence, not something artificially created or forced (Martineau, 2020). Philosophers Henri Bergson (Price, 2019) and Gilles Deleuse (Jancsary, 2019) argued that the world consists of a stream of energy that constantly flows and transforms. There is nothing in it that can be identified as stable, substantial, or essential. Therefore, the apparent stability and strength of the world are illusory, and the only reality is the process of change and becoming.

Temporality, as a philosophical category, is linked to the concept of time and its perception. However, in the context of the prolonged war in Ukraine, its understanding takes on new characteristics. Internal displacement, particularly as a result of the full-scale military invasion, is marked by unpredictability and the rapid destruction of urban spaces in the affected areas. This calls into question the conventional interpretation of temporality as a short-term situation, as the housing needs of IDPs may not align with the anticipated timeframes for their return to their original places. Therefore, temporality, in the context of housing solutions for IDPs, becomes a more flexible and long-term process that depends not only on time but also on a range of interconnected factors, including social, economic, and infrastructural conditions. In this context, temporality refers to the need for organising housing for the time being, until the conditions for permanent residence and

integration into an unfamiliar environment are created, which may take much longer than conventionally expected.

Temporary housing in the city: typological features. The housing strategy immediately after the displacement of IDPs should provide solutions for emergencies as well as more long-term solutions over time. Its organisation cannot be considered in isolation; any response must factor in the locality or context (The UN Refugee Agency, 2024). The problem of providing adequate living conditions for IDPs is one of the central issues that arose in 2014 and became particularly relevant in 2022 due to the open full-scale armed aggression against Ukraine. Considering the need for prompt action on the existing issue, the organisation of temporary housing is the most effective and immediate measure to ensure necessary living conditions (Johnson, 2007). In Lviv, this included the construction of temporary buildings – so-called mobile settlements, providing rental housing in apartment buildings and the private sector, as well as in hotels, motels, or campsites, along with the organisation of hostels and shelters. Thus, the organisation of temporary housing for IDPs became a moment when uncertainty transformed into confidence, allowing families to feel safe and gain social recognition (Bedoya, 2004).

In the context of increasing political conflicts and negative consequences of climate change, an increase in demand for temporary housing is observed. This contributes to the deepening of scientific discourse (Albadra *et al.*, 2018), which considers a wide range of ecological, economic, social, technical, moral, and other characteristics. Mostly, they are based on research on shelters and housing in post-crisis situations (Davis, 1978; Quarantelli, 1995). Within this discourse, many theoretical problems related to the definition of concepts (Pezzica *et al.*, 2018) and typological characteristics are being addressed, including structural-spatial (Stocker *et al.*, 2021), socio-economic and temporal (Johnson, 2009), quantitative (Kronenburg, 2014), and other features.

The problem of terminological nature is being addressed by clarifying existing definitions and expanding the established terminology (Pezzica *et al.*, 2018). M. Stocker *et al.* (2021) proposed a classification focused on temporal, technical, and technological aspects. It offers a more detailed consideration of the functional and spatial features of the territorial organisation of such types of residential objects. In the end, the researchers identified two formations, four classes, fifteen orders, twenty-two alliances, and twenty-six types. The key feature for structuring various residential formations was the "foundation" – the element that transfers loads from the building to the ground.

C. Johnson (2009) provided a definition of "temporary housing" that can help to obtain an extended understanding of the specificities of its functioning and organisation. The researcher considered temporary housing as a unit that allows for the restoration of everyday activities and distinguishes it, depending on the stage and state of the situation where a specific problem is being addressed. In her arguments, C. Johnson accounted for the need to differentiate concepts such as emergency sheltering, temporary sheltering, temporary housing, and permanent housing, proposed earlier by E.L. Quarantelli (1995). The first stage is an emergency situation, where emergency shelters are deployed; the second is temporary sheltering, which is formed; the third is planned living for a period of six months to three years, which is organised through temporary housing; and the fourth is the move to rebuilt or new permanent housing. According to this understanding, temporary housing is described as an object that represents a physical structure where people live after a disaster; a part of a housing recovery programme after a disaster; and a place that serves as a shelter for people during the period from the disaster until they are resettled in a permanent place of residence (Félix *et al.*, 2013). Such a classification is based on socio-economic factors and an understanding that distinct types of temporary housing can be applied depending on the situation. This approach helps to manage the housing recovery process and ensures the efficient use of resources and efforts.

Features of organising mobile settlements in Lviv. During 2022, four modular settlements were opened in Lviv. They are located on a territory consisting of residential blocks, utility zones, and specially equipped places for recreation for adults and children. Modular settlements are a general term used to describe modern solutions for the rapid and efficient placement of residential modules on limited land plots. Residential modules, which are the basic element of such settlements, have a temporary nature and consist of small blocks mounted on the basis of panel systems kits, which represent one of the forms of modular constructions (Seidu *et al.*, 2021). Components that comprise modular settlements are small, light, and easy to handle, making them convenient for transportation and local assembly (Félix *et al.*, 2013).

The blocks, which are the main structural elements of the mobile settlements, have a standard size and are equipped with all the necessary components. Their composition is based on modularity as an innovative concept that involves creating full-fledged structures. To obtain more complex structures, they can be arranged in any desired order. In the 21st century, modularity is increasingly being used worldwide, particularly in the construction and public sectors. Examples include student dormitories, private and social housing, hotels, military housing, healthcare buildings, educational buildings, prisons, production facilities, and bathrooms (Lawson *et al.*, 2014). Modular construction is widely promoted as the future of the construction industry, as it promises to offer a better advantage over conventional construction in terms of speed, quality, and cost (Seidu *et al.*, 2021).

According to the classification by C. Johnson (2009), modular settlements in Lviv, organised with the consideration of the specific needs of IDPs, correspond to the third stage. Such settlements are a place where planned residence is provided for a period of six months to three years. During the analysis of the classification by

M. Stocker *et al*. (2021), some inconsistencies were found. They are related to the specific features of the structural organisation of the modular settlement in Lviv. According to the classification, it belongs to the first type of demountable housing environments of planned temporary presence (F1) and the first class – accommodations without foundations intended for residential use (C1). However, the characteristics of the examples used to identify the first class, such as tents, cabins, and mobile homes (on wheels or water), do not correspond to the real situation in Lviv. Here, residential blocks can be characterised as multi-apartment buildings without foundations, which are not provided for in this classification.

Modular settlements in the structure of the city of Lviv. Modular settlements for IDPs in Lviv have become a significant solution in the field of residential construction and development of the city's social infrastructure (Press service of the Lviv City Council, 2023) (Fig. 1).

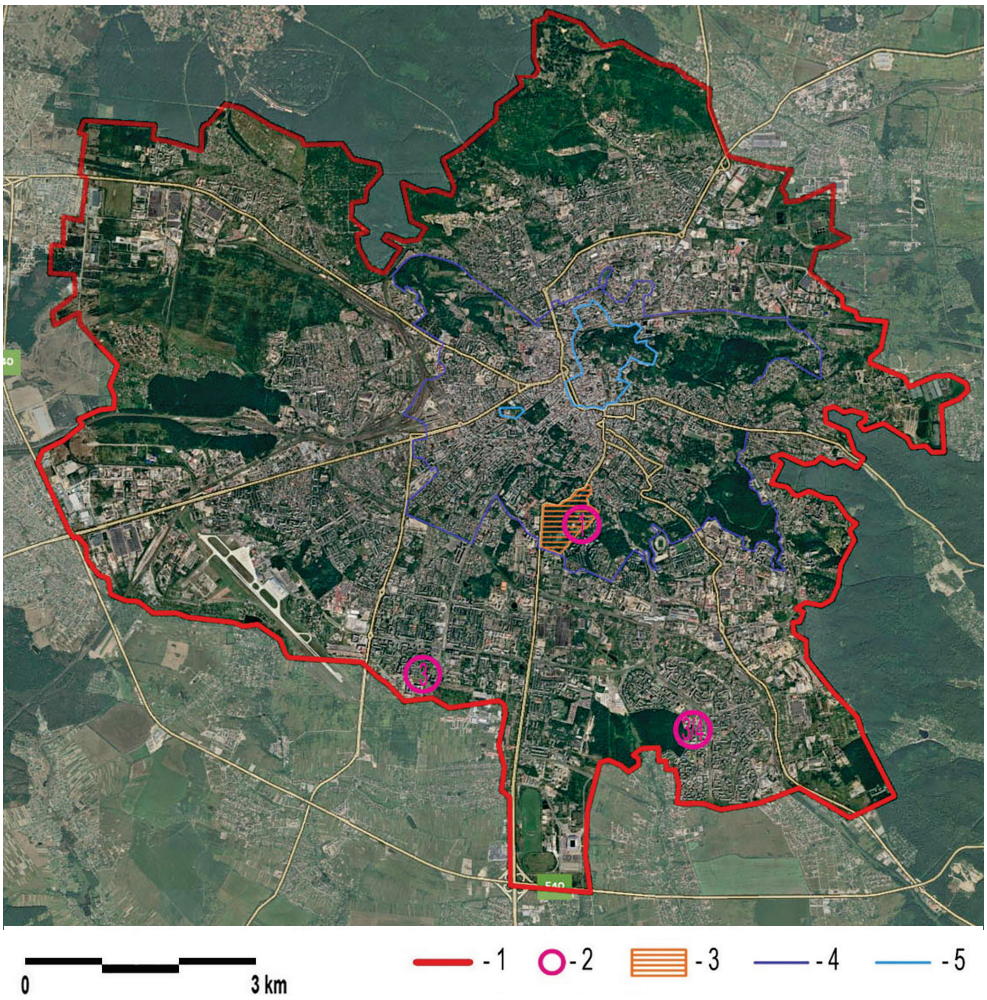

Figure 1. Placement of modular settlements in various parts of Lviv and in the context of different component
Notes: I – first modular settlement, city park area; II – second modular settlement, residential quarter; III – third modular settlement, private territory; IV – winter modular settlement; 1 – administrative city boundaries; 2 – modular settlements; 3 – territory of Stryiskyi Park; 4 – boundaries of the historical area; 5 – territory under the protection of UNESCO
Source: developed by the author of this study

In April 2022, with the support of the Polish government, the first modular settlement was opened in the Stryiskyi Park in Lviv, designed for 350 residents. It consisted of 88 modular houses with a separate kitchen, bathrooms, showers, and a laundry room (Hryniuk, 2023). The territory of the settlement covers about 0.2 hectares. It is fenced and equipped with necessary infrastructure facilities, such as electricity, water supply, sewerage, air conditioning system, as well as playgrounds for adults and children.

Notably, the territory of Stryiskyi Park is a monument of landscape art of national significance, located in the central part of Lviv and covers an area of 51.4 hectares (Lviv City Council, n.d.). For the city residents, it is not just a place of rest and recreation, but an integral part of the urban history, preserving a unique natural and cultural heritage. Specifically, there are monuments of landscape art and historical objects concentrated here, which became symbols of Lviv: the lower terrace, formed according to the

principles of a picturesque landscape park; the upper terrace, arranged for the Regional Exhibition of 1894, has a regular structure (Maksymiuk, 2008; Zhuk, 2012). According to the law, construction, recreational, and other activities that may lead to disturbance of natural processes and a decrease in the natural value of objects are prohibited on the territory (Law of Ukraine No. 2456-XII, 1992). Later, analogous settlements were deployed on Puliuia Street and in Sykhiv. In total, over 1,000 forced migrants from different regions of Ukraine were resettled there (Hryniuk, 2023).

The second modular settlement appeared on Puliuia Street. It covers approximately 0.6 hectares with a total of 120 houses and a capacity of 320 people (Press service of the Lviv City Council, 2022). Like in the previous version, the territory is fenced and equipped with necessary infrastructure facilities. The specified territory is an example of extensive urban development that took place in the 1960s-1980s. It was initiated by the state in response to a dramatic housing shortage and later built with hundreds of homogeneous residential units. The evaluation of the success or failure of residential formations depended not only on their physical structure but also on the formation of the ideological significance of the modernist residential formation and its perception by experts from various fields, including politicians, ideologists, urban planners, and residents themselves. The results of the study by O. Chabaniuk (2004) revealed that such areas have a series of negative characteristics: low level of social control over the territory of residential areas, insufficient safety of living, emptiness and transitiveness of intra-block spaces, functional conflict of the environment, lack of personalisation of the space around buildings, and a low level of psychological comfort of living. Since 2010, these areas are undergoing transformation and the formation of a new identity (Mysak, 2014).

The third modular settlement is located in Sykhiv with a total of 94 houses and a capacity of 300 people. The land where the town is located belongs to the Order of the Salesians of St. John Bosco, Ukrainian Greek Catholic Church. Representatives of the church expressed a desire to take the town under their spiritual care and become its patrons (Fig. 2).

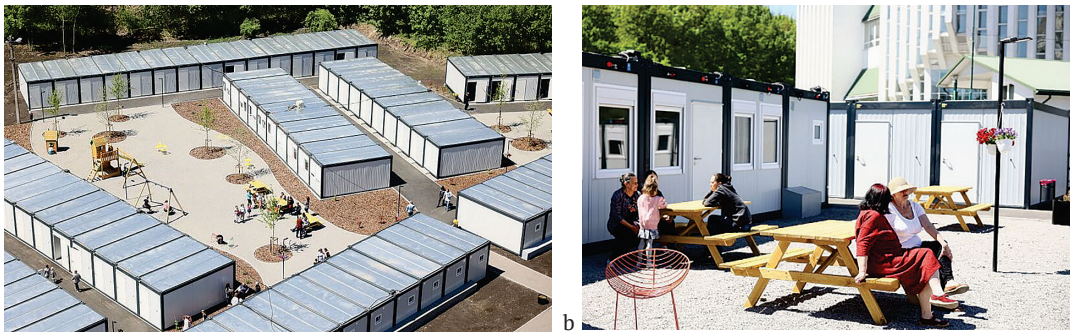

Figure 2. Third modular town in Lviv
Notes: a – general view; b – view of the multifunctional recreational centre
Source: photo by Roman Kaiman (Press service of the Lviv City Council, 2022)

The area of the land plot is approximately 0.7 hectares. As in the previous version, the territory is equipped with necessary infrastructure facilities, as well as a children's and sports playground. With the arrival of cold weather, the issue of heat preservation arose, as the residents, mostly women with children and elderly people, needed warm accommodation. Therefore, in Lviv, a modular settlement was deployed on Sykhiv, near the third quarter, called the "winter" settlement. However, temporary housing in the territory of the Stryiskyi Park, Puliuia Street, and the Salesian Fathers of St. John Bosco Congregation was temporarily "conserved". It is the largest of all existing settlements in Lviv and can accommodate 1,400 people. In total, there are eight two-story buildings on the site, each consisting of 80 modules (Hryniuk, 2023).

"Sykhiv", where the third and later the "winter" settlement were initially located, is a planning district of Lviv that began to take shape in the 1970s and 1980s. With the onset of Ukraine's independence, there were significant transformations in urban planning. As a result, the district changed its structure and was supplemented with new functions. Starting from the 21st century, the territory was in a state of intensive development and transformation. In the 2020s, Sykhiv district continued to be the largest in Lviv. One out of five residents in Lviv lives in this district and identifies with this area (Cherkes & Mysak 2013). Having undergone a change in ideological foundations and developed in architectural, ecological, economic, historical, cultural, educational, social, tourist, and other areas, it became a fully-formed entity with a functional-planning structure and unique identity.

Modular settlements became a noticeable element of the already-developed urban environment in various regions of Ukraine. They are implemented through donor funds from government and international organisations, as well as Ukrainian and foreign companies. For instance, through the initiative and cooperation with Polish partners, four modular settlements were arranged in Lviv since April 2022. The example of Lviv showed that the implemented programme became a flexible and effective tool for addressing urgent issues of temporary housing for IDPs. Due to the growing demand, the issue of temporary

housing and modular settlements is becoming increasingly relevant and actively discussed in international communities among theorists and practitioners. This is done to develop effective strategies and recommendations for creating temporary housing facilities and their management in the context of socialising IDPs and refugees (UNECE, 2021).

To better understand and address such problems, a scientific debate has risen to a new level of research regarding the correctness of the use of the term "temporary housing" and other aspects related to this concept. In the present study, the author used studies where the terminology was under special scrutiny. Thus, C. Pezzica *et al*. (2018) emphasised that the term "temporary housing" does not always accurately reflect the essence of the problem. In her arguments, the researcher relied on the findings of I. Davis (1978) and E.L. Quarantelli (1995), the authors of one of the first theoretical studies on shelters and housing in post-crisis situations. E.L. Quarantelli (1995) emphasised the ambiguity and inconsistency in the use of the terms "shelter" and "housing" in the literature. In turn, I. Davis (1978) emphasised that the term "temporary houses" falls within the purview of politicians, slick salesmen, and some officials who provide assistance. In Quarantelli's opinion, solving the problems should not be limited to a narrow circle of specialists and any donor should be aware of the long-term consequences of their actions. C. Johnson (2009) defended the same opinion and proposed to consider temporary housing as a transitional and short-term process aimed at restoring or obtaining permanent housing.

A special place in the declared problematic is occupied by the definition of the essence of concepts related to the category of temporariness. The concept of temporariness is based on philosophical and worldview approaches and is substantiated by understanding the temporary as a transitional and non-permanent phenomenon, which is determined by the temporal factor. The classification issue continues to be understudied. For example, C. Johnson (2009) and M. Stocker *et al*. (2021), while systematising their own empirical material, relied on the conclusions of E.L. Quarantelli (1995). It should be recalled that the author proposed to distinguish between different forms of temporary housing depending on the stage and condition of the situation that requires solving a certain problem. Analysis of such literature (Johnson, 2009; Stocker *et al.*, 2021) and available catalogues (The UN Refugee Agency, 2024) revealed that the systematic basis for classifying different types of temporary housing includes such features as building material, building structure, capacity, mobility, and type of engineering networks. They fall within the scope of architecture and construction. Classifications based on structural features help standardise terminology and provide a collective understanding of the terms and concepts used when discussing temporary housing. Despite expanded classifications (Johnson 2009; Stocker *et al.*, 2021), they are not universal and require further clarification to accommodate the context of concrete places and their specificity. To specify, residential modules in Lviv can be characterised as multi-apartment buildings without a foundation, designed for short-term residence.

Within the competence of urban planners, there are several issues related to effective ways and approaches to organising temporary housing at the territorial level and their connection to the already formed material-spatial environment of human life. The absence of such knowledge, norms, and standards raises doubts about the safety and comfort of living not only for the residents of the created housing environment (e.g., in Lviv's Sykhiv or the Puliuia Street area) but also for the residents of new structures. Studying this spectrum of issues can help researchers, policymakers, and practitioners to identify the strengths and weaknesses of each type of temporary housing and develop effective models for its territorial organisation in the context of the created housing environment. This falls within the scope of urban and social issues.

The city planning element. Modular settlements, like any other form of temporary housing, can have a crucial role in the urban environment, especially in situations where the availability of quickly deployable mobile structures is necessary, such as during emergencies that force people to leave their homes or during mass events. The experience of organising modular settlements in Lviv showed that compact organisation of the territory is an effective solution that contributes to achieving maximum functionality and comfort. This effect was achieved by implementing the following principles:

- zoning: the territory is divided into distinct zones depending on their purpose (e.g., residential, technical, recreational). This allows optimising the use of space;
- use of multifunctional spaces and organisation of green areas: the territory is designed considering the possibility of using the created space for various functions at different times of the day;
- application of the principle of pedestrian accessibility: the choice of the territory was made considering the possibility of ensuring pedestrian accessibility to key objects (such as public centres of social security, cultural and spiritual centres, entertainment centres, public spaces, educational and preschool institutions).

Social element. A prominent aspect of successful socialisation of IDPs lies in providing conditions for free choice and access to various social groups, including those that are already developed. This requires the application of a social approach and careful study of the specific features of social relations, which are based on intuition, interdependence, and interrelatedness among various individuals, not just among IDPs. One of the means of implementing such an approach is a theoretical model (Idak, 2022) built on the principle of a three-tier hierarchical organisation of the urban environment:

- the first tier – micro-level, describes an individual's private space that functions only with their participation, e.g., a living room;
- the second tier – meso-level, describes the private space of a certain social group to which the individual feels

a sense of belonging and identifies as their own. Social control takes place here, which is guided by a certain set of rules and standards, limiting certain actions of the individual, but directing them towards the acquisition of clear cultural norms and the choice of a social role. This tier can represent a residential building or neighbourhood;

- the third tier – macro-level, describes a public space that belongs to the community or is available for use by different social groups, e.g., a city district or settlement.

It should be emphasised that the organisation of modular towns requires a separate approach in relation to an already formed urban environment. It is vital to consider compatibility with urban development and infrastructure, as well as probable consequences for adjacent areas and residents. It is also necessary to have an adequate legislative and regulatory framework to ensure safety and housing quality in modular towns, as well as to ensure legal protection for their residents.

Finally, modular settlements are not always harmoniously integrated into the existing urban environment. Their placement can disrupt the ecological balance and create transportation and other problems. Furthermore, modular settlements are often promoted as temporary territorial objects, which can lead to careless preservation and maintenance, which can subsequently affect the environment and reflect on the overall quality of life of local residents. To harmonise the organisation of the living environment, it is also essential to consider the principles of ecology and sustainable development.

Despite their significance, the solutions that were implemented in Lviv have both positive and negative aspects. Research revealed that negative aspects are caused by a misunderstanding of basic categories and the absence of a regulatory framework when decisions must be made promptly. When making decisions regarding the placement of modular settlements, it is vital to apply a comprehensive approach to design and strike a balance between social needs and the preservation of the urban environment to ensure proper city development and comfortable living for all its inhabitants. A comprehensive approach may include not only the placement of modular settlements but also the creation of multifunctional structures that positively influence the city's development and provide the opportunity to gain social experience and establish social connections for its participants. This assumption expands the understanding of the problem of forming temporary residential environments for IDPs and the possibilities for its solution without interfering with the already developed material and spatial environment of human life.

CONCLUSIONS

The creation of temporary housing for IDPs involves a wide range of problems that affect the experience of various fields of activity, including architecture, urban planning, and sociology as interrelated and complementary scientific disciplines. The following problems can be identified: consistency in terminology for designating and describing key concepts for research; in-depth understanding of temporary housing, its characteristics and interactions with other categories; inconsistencies in existing typological classifications of temporary housing; consideration of urban planning components when organising modular settlements for IDPs; absence of comprehensive approaches to the formation of the urban environment in unforeseen situations. The temporariness was updated as a significant category of various spheres of human life, which necessitates planning and organisation for successful adaptation to changes.

The term "temporary housing" and approaches to its classification were explored. It became clear that this concept should not be regarded as an object. Instead, it is a process aimed at a certain degree of certainty and happens only once. Here, resources and opportunities become decisive. Therefore, an effective mechanism that proposes an algorithm of actions and a universal concept for solving problems related not only to the formation of housing as a unit, but also to the creation of a proper living environment, appears prudent. It was noted that existing classifications are incomplete and unable to cover all possible options. For example, temporary housing in the modular settlements of Lviv does not fit into any existing type, suggesting the need to create new classifications or improve the existing ones. There are also no classifications regarding the organisation of temporary housing at the territorial level.

A formal approach was applied to the territorial organisation of four modular settlements in Lviv and the specific features of their functioning and interaction with the surrounding environment were determined. The specific experience gained in Lviv provides valuable insights and lessons for other cities and regions facing comparable challenges. Both successes and negative impacts are present here. Success is associated with the development of a reliable basis for an effective strategy for solving housing problems for IDPs. To achieve maximum functionality and comfort, the territory of the modular settlements in Lviv is compactly organised. The zoning principle and the formation of multifunctional spaces and green areas, as well as pedestrian accessibility, are implemented here. This can ultimately lead to more equitable solutions for IDPs and contribute to the overall development and sustainability of cities.

The project of modular neighbourhoods in Lviv demonstrated its effectiveness and potential for development. Specifically, it was successfully used to address the urgent problem of providing housing for the local population in the short term. However, considering the long-term perspective, questions arise concerning the project's controversial aspects, such as environmental sustainability and integration with the existing urban environment. Therefore, the negative aspects are driven by the absence of a legal framework for shaping the living environment in crisis situations and the created urban environment. Modular neighbourhoods in Lviv are organised in areas with certain characteristics. These characteristics express

a unique context that is present in each specific situation. It is expressed through the historical, natural, and heritage categories. Theoretical research should be further developed to increase the depth and volume of knowledge about the problem under study, identify certain regularities in approaches to providing temporary housing, and develop new principles for its organisation at the territorial level.

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CONFLICT OF INTEREST

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Виклики міського розвитку у забезпеченні тимчасовим житлом внутрішньо переміщених осіб: досвід міста Львів

Анотація. Це дослідження висвітлило суперечності, що виникають при вирішенні житлових потреб внутрішньо переміщених осіб, та проаналізувало їхній вплив на сталий розвиток міста. Метою цього дослідження було виявити проблеми містобудування, спричинені створенням модульних поселень у вже розвиненому міському середовищі Львова, де у 2022 році було організовано чотири таких поселення, та оцінити їхній вплив на міську структуру та сталий розвиток. Для досягнення мети дослідження було застосовано теоретичні методи, зокрема логіко-філософський підхід до вивчення тимчасового житла як процесу, що відбувається в конкретних соціально-економічних умовах. Було проведено містобудівний та порівняльно-типологічний аналіз цих поселень, оцінивши їхній потенціал у контексті міського розвитку та забезпечення тимчасовим житлом. Було виявлено негативний вплив на міські структури через невідповідність потреб та викликів сталого розвитку, зокрема в плані функціональної ідентичності та інтеграції таких поселень в існуюче середовище. На основі отриманих результатів було запропоновано розглядати модульні поселення як частину багатофункціональних структур, які повинні бути гнучкими та адаптивними до змін у соціально-економічному контексті. Практичне значення цього дослідження полягає у розробці рекомендацій для містобудівників щодо впровадження адаптивних підходів у проектуванні тимчасових поселень, забезпечення сталого розвитку міських територій та сприяння соціальній взаємодії між внутрішньо переміщеними особами та місцевими громадами

Ключові слова: модульне місто; регіональний центр Західної України; міське середовище; контекстуальність; сталий розвиток

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