ISSN: 2411-801X
e-ISSN: 2786-7374
UDC 71;72

Lviv Polytechnic National University

ARCHITECTURAL STUDIES

International Journal about Architecture

Founded in 2014
Frequency of issue: 4 times a year

Volume 12, No. 1

Lviv – 2026

ISSN: 2411-801X
e-ISSN: 2786-7374
УДК 71;72

Національний університет «Львівська політехніка»

АРХІТЕКТУРНІ ДОСЛІДЖЕННЯ

Міжнародний науковий журнал про архітектуру

Заснований у 2014 році
Випускається 4 рази на рік

Том 12, № 1

Львів – 2026

Year of foundation: 2014

Recommended for printing and distribution
via the Internet by the Academic Council
of Lviv Polytechnic National University
(Minutes No. 32 of February 24, 2026)

State Registration:
Media identifier R30-01841
Decision of the National Council of Television
and Radio Broadcasting of Ukraine
No. 1335, Minutes No. 26, dated 09.11.2023.

Journal is included in the List of Scientific Professional Publications of Ukraine
Category “B”. Specialties: 0731 – Architecture and town planning, 0732 – Building and civil engineering
(order of the Ministry of Education and Science of Ukraine No. 1693, dated December 23, 2025).

Journal is presented in international scientometric databases,
repositories and scientific systems:
Professional Publications of Ukraine, Crossref, Bielefeld Academic Search Engine (BASE), J-Gate,
Vernadsky National Library of Ukraine (VNLU), GALE, Polish Scientific Bibliography, Dimensions,
UCSB Library, Google Scholar, German Union Catalogue of Serials (ZDB), University of Oslo Library,
University of Hull Library, Search Oxford Libraries Online, European University Institute,
Leipzig University Library (UBL), Cambridge University Library,
WorldCat, Open Ukrainian Citation Index (OUCI), Litmaps

Editors office address:
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
E-mail: info@arch-studies.com.ua
https://arch-studies.com.ua/en

Рік заснування: 2014

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного університету «Львівська політехніка»
(протокол № 32 від 24 лютого 2026 р.)

Державна реєстрація:
Ідентифікатор медіа R30-01841.
Рішення Національної ради України
з питань телебачення і радіомовлення
№ 1335, протокол № 26 від 09.11.2023 р.

Журнал входить до Переліку наукових фахових видань України
Категорія «Б». Спеціальності: G17 (191) – Архітектура та містобудування, G19 (192) – Будівництво та цивільна інженерія (наказ МОН України № 1693 від 23.12.2025).

Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах:
Фахові видання України, Crossref, Bielefeld Academic Search Engine (BASE), J-Gate, Національна бібліотека України імені В. І. Вернадського (НБУВ), GALE, Polska Bibliografia Naukowa (PBN), Dimensions, UCSB Library, Google Академія, German Union Catalogue of Serials (ZDB), Бібліотека Університету Осло, Бібліотека Університету Халла, Search Oxford Libraries Online, Інститут Європейського університету, Бібліотека Лейпцизького університету (UBL), Бібліотека Кембриджського університету, WorldCat, Open Ukrainian Citation Index (OUCI), Litmaps

Адреса редакції:
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
E-mail: info@arch-studies.com.ua
https://arch-studies.com.ua/uk

CONTENTS

ЗМІСТ

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 72.036
DOI: 10.56318/as/1.2026.09

ISSN: 2411-801X
e-ISSN: 2786-7374

Roman Frankiv*
PhD in Architecture
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0003-1100-0930

Bohdan Cherkes
Doctor of Architecture, Professor
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0001-6809-956X

Architecture in the context of socio-cultural polarisation: The case of Lviv (1991-2025)

Abstract. The relevance of the research lay in examining the contemporary architectural governance of Lviv, which required a developed media component and an established dialogue between groups with opposing cultural and aesthetic views. The aim of the study was to determine the dependence of urban architecture stylistics on the moderation of public opinion and the prevention of antagonistic and hostile narratives in professional and public environments. The article examined the relationship between sociocultural polarisation and stylistic evolution of urban architecture in Lviv during 1991-2025. The example of Lviv showed that the lack of effective mediation between traditionalist and liberal positions in architectural discourse led to conflicts of values and a decline in the quality of design decisions. Based on an analysis of media and professional materials, two main phases of architectural development have been identified: postmodernism (1991-2010), characterised by a rejection of Soviet modernism and a romanticisation of historical forms, and neomodernism (2011-2025), in which modernism was reinterpreted as a symbol of European identity. Sharp criticism of neomodernist projects by the public had become a social phenomenon that had influenced architectural decisions. An example of this was the conflict surrounding the reconstruction of St. George's Square, which ended with a compromise solution and initiated a trend toward "neutral" and prosaic forms. The practical value of the article lies in demonstrating how establishing mutual understanding between proponents of different architectural approaches can improve the quality of design decisions, avoid excessive simplification, and preserve architecture as a carrier of urban identity

Keywords: prosaic architecture; simplification; neomodernism; traditionalism; design moderation; aesthetic conflict; urban identity

INTRODUCTION

Architectural design has become closely linked to narratives emerging within urban communities connected through horizontal networks. These narratives shaped the symbolic meanings of architectural projects, reflecting the transient mindset of society. Public engagement with architecture had turned into a tool of political positioning, media influence, and cultural negotiation, making design itself a mirror of social reality. In Lviv, the historical traditionalist mentality and the aspiration for European reintegration entered into sharp opposition, resulting in two

Suggested Citation:
Frankiv, R., & Cherkes, B. (2026). Architecture in the context of socio-cultural polarisation: The case of Lviv (1991-2025). *Architectural Studies*, 12(1), 9-17. doi: 10.56318/as/1.2026.09.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 9-17
Received: 21.10.2025 Revised: 19.01.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

stylistic phases – postmodernist and neomodernist. The latter became the centre of polarised discourse, whose political and reputational consequences shifted neomodernist architecture toward neutrality and restraint. The architecture of Lviv in 1991-2025 appeared as a space of value interaction, where design was not only a technical act but also a reaction to the dynamics of the urban community. J. Kelly (2023) noted that a passive and reflective moderation between two poles of communication led to the dominance of "neutral" and compromise solutions in the spirit of prosaic architecture, and the absence of contemporary objects equivalent in symbolic role to historical monuments that identified the city. The interaction between architecture and public opinion was not new, but in modern media environment, it reflected the convergence of professional and mass cultures. With the growth of information exchange, public opinion began to position itself as more legitimate than the professional stance of architects. In a period of developed social communications, key architectural decisions were influenced not only by spatial or functional considerations but also by socio-cultural context. H. Jannière & P. Scrivano (2020) emphasised that society had become an active participant, contributing to the authenticity of design. The prestige of architecture and its authors often depended on their acceptance by public criticism, as noted by M. Tempestini (2025), who highlighted the spontaneity of public opinion and the need to establish boundaries for its effectiveness.

The influence of social media on architectural design had been widely examined. G. Lindsay *et al.* (2025) noted that online platforms can redefine architectural meaning and interpretation. In their introduction to a special issue, the authors emphasised that digital platforms have become not only a tool for disseminating information but also an active environment that redefined the meaning and interpretation of architecture. The study focused on how the virtual representation of objects shaped perceptions of them before, during, and after realisation, indicating a shift in the architect's role within the media space. I.B. Kosasih & M.A.G. Sangaras (2022) demonstrated that clients shaped their design preferences under the influence of Instagram trends. This study showed a direct link between visual trends in social media and the formation of clients' design preferences, who increasingly came to architects with ready-made ideas inspired by aesthetics popular online. Thus, Instagram functioned as a powerful, yet often informal, regulator of style in contemporary design. Likewise, B. Topdağı Yazıcı *et al.* (2025) analysed how social media aesthetics – light, colour, and framing – affected public reception of heritage restoration projects in Istanbul. The authors emphasised that a project's success may depend less on its historical authenticity and more on its ability to generate positive "media content". This illustrated how the visual appearance for social media became an integral part of assessing an architectural object in the age of advanced communication. Public media activity had become a decisive tool for shaping architectural outcomes. M.E. Linko (2020) documented how strong public opposition led to the rejection of the Guggenheim Museum project in Helsinki. Researcher documented how media debates, which went far beyond professional circles, turned the architectural project into a political issue related to the use of public funds and urban identity. This case served as an important example of how public media activity became a decisive tool for shaping architectural outcomes, capable of leading to the cancellation of even high-profile international projects. J. Kubik (2024) emphasised that the growing divide between traditionalist and liberal positions reflected a broader reaction challenging Western liberal-democratic dominance through counter-narratives, sometimes neo-feudal in tone. Scientist I. Krasnodemska (2022) analysed the redevelopment project of St. George's Square, intended to install a monument to Metropolitan Sheptytsky, a religious leader of Ukraine's national revival. The project's symbolism provoked a confrontation between liberal activists seeking preservation and traditionalists advocating transformation. Protests and online debates culminated in a compromise solution. Paradoxically, liberals defended historical continuity, while conservatives demanded change, referencing the square's 19^{th}-century origins (Petryshyn *et al.*, 2016) The aim of the study was to explore how the stylistic choices in urban architecture were influenced by the mediation of public opinion and the avoidance of conflicting and adversarial narratives in both professional and public spheres.

MATERIALS AND METHODS

The methodology applied in this study was based on the integration of three interconnected analytical components: the relevance of architectural form within the professional design community, its perception in mass culture, and its actual morphological and symbolic content. These components were examined together within a chronological framework that covered the period between 1991 and 2025, allowing the research to trace the evolution of stylistic preferences, cultural attitudes, and socio-political tensions that shaped architectural decision-making in Lviv. This temporal lens made it possible to observe how architectural forms and their interpretations changed in response to broader socio-cultural polarisation. To achieve this, the study incorporated a wide range of heterogeneous sources. Professional publications from sources such as the Architectural Herald (n.d.), and Building Differently (n.d.) provided insights into expert discourse, while public debates, media narratives, manifestos, and residents' reactions offered a broader cultural perspective. These sources revealed a consistent pattern: a widespread public rejection of the Soviet past, which resulted in a corresponding rejection of modernism and a reorientation of architectural form-making. Additionally, opinion-based materials – including user posts, detailed comments, and visual criticism found in Facebook groups such as Lviv Architects Forum (n.d.), Controversial Developments in Lviv (n.d.), and Save Historical Lviv (n.d.) – supply valuable data on public sentiment and conflict between opposing cultural positions. The combined use of these materials allowed for tracing the dynamics of socio-cultural polarisation and its impact on architectural form-making.

The methodology also included a detailed analysis of communicative and morphological materials in order to identify the main phases of this process. Particular attention was given to shifts in semantic fields related to the reception of architectural projects, ranging from the romanticisation of historical heritage to the re-evaluation of modernism as a symbol of reintegration into the European cultural sphere. A binary structure of public debate – between liberal and traditionalist viewpoints – was examined to understand how ideological oppositions influenced architectural preferences and decision-making. For the conditional postmodern stage of development (1991-2010), the methodology incorporated a two-step analysis of semantic field interactions. Firstly, the narratives associated with the positive semantic field and its vectors of opposition were identified. Secondly, the architectural techniques that materialised these narratives in the built environment were outlined, focusing on how it shaped reality in accordance with contemporary ideals.

RESULTS AND DISCUSSION

Architectural form in Lviv after 1991 cannot be considered outside the context of social attitudes and media interaction. During 1991-2010 period that social and cultural influence became more polarised, conflicts arose, and attempts were made to neutralise them by changing the dominant style. The main platform here was social media, which was forming a new, more inclusive, and multifaceted space for communication aimed at changing architectural reality. The information landscape of architectural discourse in Lviv from 1991 to 2025 was heterogeneous due to the rapid evolution of the media, primarily in terms of content creation and authorship. In the beginning, the dominant media were traditional print media, including specialised architectural magazines and daily newspapers. It generally featured one-way communication from authors on specific topics, and discussion could only take place between authors, who were given the opportunity to express themselves. This format shaped the understanding of both urban development initiatives and the preservation of historical heritage. This fperiod can be considered a step forward compared to the previous Soviet experience, as free professional criticism became possible after Ukraine gained independence. In this sense, Lviv's architecture became similar to that of the West, where important architectural structures became not only physical but also media events (O'Regan, 2013).

So, research was divided two separate time phases: early – conditionally postmodernist (1991-2010) and late – conditionally neomodernist (2011-2025). This periodisation reflected not only the shift in the nature of public discourse and media accessibility but also a change in the dominant stylistics and ideas about the ideal lifestyle (Architectural Herald, n.d.). The former referred to the idea of the normality of architectural form, while the latter referred to a negative alternative that was intended to reinforce the belief in the truth of normality. Therefore, the analysis of the interaction of semantic fields helped to investigate the nature of socio-cultural polarisation and its influence on the architecture of Lviv, which underwent changes due to the radicalisation of the opposition vector. It should be noted that the influence of socio-cultural polarisation occurred through the evaluation of already constructed objects, which then influenced the nature of subsequent projects. Therefore, it was identified the key structures that provoked the greatest public reaction and analysed the content of the arguments put forward by various actors in media interaction. In particular, the most discussed object of the postmodernist trend was the Ukrsotsbank building on Mitskevych Square in Lviv (Kos & Kharambura, 2017), and the neomodernist trend was the Ibis Hotel on Shukhevych Street. Several forms of discursive messages and determination of their percentage of distribution in the total mass of journalistic material related to the description of modern architectural problems of the period before 2010 were depicted in Figure 1.

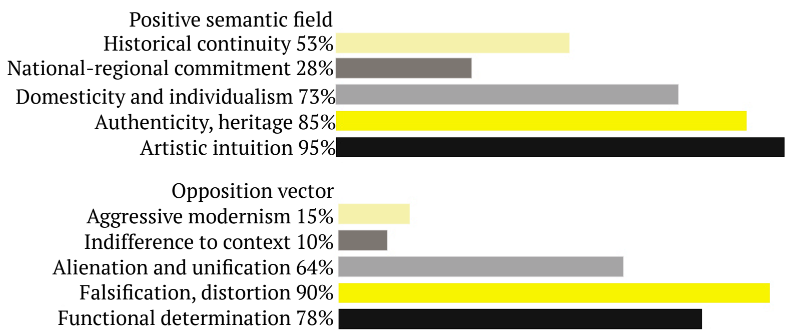


Figure 1. Forms of discursive messages

Source: Save Historical Lviv (n.d.)

At the second stage of the research, it became important to determine the semantic fields related to the project proposals of Lviv architects in 1991-2025. In this context, it was determined the shift towards the use of techniques that clearly signaled a break with modernist form creation and gave architecture not only postmodern but also anti-modern features. Textual and visual material of 1991-2025 formed a positive semantic field, which had an openly pre-modern and romantic character, based on the idealisation of the past and the desire to revive the artistic significance of architectural form (Building Differently, n.d.). All these discursive messages should be seen as part of the overall process of "healing" architecture from the pathologies of the totalitarian past and a kind of decommunisation process, which remained relevant at least during 1991-2025 (Vlasenko & Ryan, 2022). The great attention paid to artistic intuition, not determined by a specific identity testified to a deeper sense of the crisis of modernism, not solely conditioned by political and ideological positions. Also, it was worth mentioning the characteristic styles of Lviv architects, which stemmed from their previous experience and ideas about "good architecture", which had three trends: a) dynamic composition of geometric forms (a trend parallel to neo-futurism); b) postmodernist interpretation of classical form creation; c) postmodernist interpretation of traditional housing. Many objects showed signs of several of these trends at the same time. Traditionalist compilations were generally well received by the urban community, as it was perceived as a positive alternative to the limited and predictable lifestyle of Soviet dormitory districts built according to standard designs in a manner of radical utilitarianism (Gentile, 2015). The popular genre of sacred architecture of 1990-2000 testified to the existence of social expectations of linking the semiotic content of architecture with the means of realistic decorativism and straightforward artistic expression, including on the basis of classical order templates, as an expression of spirituality and extraordinary nature (Znak & Znak, 2023).

The 2015-2025 period in Lviv architecture was characterised by a significant change in the positive semantic field, which had shifted towards integration with Western, and European design reality. Among influential professional circles, a new consensus emerged regarding a return to modernism as a style that reflected a more desirable lifestyle and liberal-progressive values. At the same time, the traditionalist camp relied on the conservative worldview of a significant part of the urban community, which had developed as a result of the specific historical development of the region (Lekhniuk, 2019). The emergence of new forms of public social communication significantly complicated the landscape of discourse around architecture. Now its participants included community activists, cultural figures, interested residents, amateurs, political and business actors, and others. A new information field had emerged, which had gradually gained the ability to influence decision-making by government institutions and project initiatives (Treffers, 2023). As a result, traditionalist and liberal views have become two opposing poles of assessment of architectural phenomena. Figure 2 indicated the percentage results of the types of public comments on architecture, which were divided into five main types: aggressive (threats, radical evaluative judgments, accusations of crimes), confrontational (accusations of bad taste, lack of professionalism, lack of necessary aesthetic qualities, distortion of the environment), neutral (opinions about the objectivity of changes in architecture without personal approval, the non-priority of architectural topics in general, transfer of problems to another sphere – politics, economics), positive (approval within the framework of passive contemplation), euphoric (opinions have a strong emotional component, which indicated a readiness for active support).

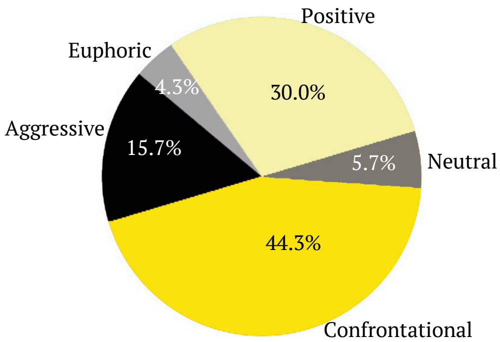


Figure 2. Types of public comments on architecture
Source: Controversial Developments in Lviv (n.d.)

So, data from Figure 2 indicated that for most members of the urban community, who participated in the discussion and evaluation of architectural projects, the formative content of modernism itself was not associated with art and cultural value. Accusations of destroying the historical image and authenticity of the environment were used as the ideal weapon to discredit modernist projects. Although the first experiments with neomodernist form creation in Lviv date back to the early 2000s, it became widespread in the mid-2010s, when two trends emerged: expressive-dynamic and static-geometric. At the initial stage, neomodernist objects gravitated toward the tradition of artistic content that had developed in postmodernism. Therefore, it was characterised by experiments with dynamics and expression, attempts at individualisation. It was at this time that a new polarisation model of urban discourse on architecture gradually emerged, focusing on criticism of projects that arose within the historical area of the city, as well as the lack of charisma and cultural value in new architecture equivalent to historical architecture (Habrel *et al.*, 2020).

One of the objects that received a noticeable reaction was the Ibis Hotel on Shukhevych Street, completed in 2015, built in the style of expressive neomodernism with elements of deconstructivism (Fig. 3, a). An analysis of reactions in thematic and professional discussions on Facebook showed a predominance of negative assessments, which were expressed mainly by representatives of the active non-architectural community (Lviv Architects Forum, n.d.). Positive assessments were generally not unambiguous, but came with certain reservations regarding individual spatial elements. As a result of acute polarisation, which also had political consequences due to criticism of the authorities and city leadership, the expressive manner underwent reduction. A trend of prosaic neomodernism with a laconic and austere geometric language became widespread. It manifested itself, in particular, in the subsequent Ibiz Hotel, for which a building on the neighboring Ivan Franko Street was reconstructed in 2022. Its facade was distinguished by its one-dimensionality and predictability, the simplicity of its geometric and compositional design, and conservatism in the use of materials (Fig. 3, b). The regularity of this process was also confirmed by the fact that both buildings were designed by the same design company "Shvets and Partners".


a) b)

Figure 3. An example of the transformation of neomodernist language
Note: a – the facade of "Ibis" 2015, on Shukhevych Street, in the style of expressive neomodernism; b – the facade of "Ibis" 2022, on Ivan Franko Street, in the style of prosaic neomodernism
Source: photos by the authors

In the context of the shift in architectural design towards prosaicness as a result of conflicting socio-cultural polarisation, it was also worth considering the development of Mitskevich Square, which had undergone a shift towards historical reproduction as a result of criticism of the Ukrsotsbank building. In 2023, the construction of a hotel designed by Kuryłowicz & Associates in the style of prosaic neomodernism was completed. Although the fate of the development on this site had long been a subject of intense interest and disagreement between supporters of the restoration of the historic building that previously stood there in the historicist style and the new building with a cut facade. As a result, the laconic, lapidary form of the new building significantly reduced the level of criticism and the effectiveness of counterarguments. During the period of conditional neomodernism (19^{th}-20^{th} centuries), criticism was directed not only at modernist objects, but also at some postmodernist ones, such as Ukrsotsbank building on Mitskevich Square (Fig. 4, a). While the journalism of the conventional postmodern period expressed neutral and positive opinions about the future implementation at the design stage, after the emergence of social networks, the critical attitude of some residents and interested parties towards its architecture and cladding technology became apparent. As a result, during the subsequent reconstruction of the neighboring building for the needs of Ukreximbank, a strategy of returning to historicism was chosen, giving the functionalist facade a decorative language of eclecticism (Posatskyy, 2015). A similar transformation also took place with other initiatives that shifted toward prosaicness. For example, between 2016 and 2018, a building was inserted into the historic development of TzOV Nova Motel (architect O. Suvorov) on Hnatyuk Street in the manner of prosaic historicism, which provoked virtually no public reflection (Fig. 4, b). In 2008 this site had been the subject of heated debate provoked by neomodernist proposals for the planned Bristol Plaza hotel and office complex (architects B. Cherkes, E. Voronich, with the participation of M. Dubova) (Fig. 4, c).


a) b) c)

Figure 4. Examples of the transformation of Lviv's architecture under the influence of conflict discourse
Note: a – on the right is the postmodernist building of Ukrsotsbank, and on the left is a prosaic neomodernist building; b – house insert on Hnatyuk Street in the style of prosaic historicism; c – neomodernist proposal for the Bristol Plaza hotel and office complex on Hnatyuk Street
Source: photos and sketch by the authors

When considering the transformation that Lviv architecture underwent between 1991 and 2025, it was focused on the role of the contrast between traditionalist and modernist tendencies, which manifested themselves in different ways in the phases of postmodernism and neomodernism (Fig. 5). In the context of the former, it was found itself in the role of an unquestionably positive alternative to Soviet pathology, an expression of local values, humanism, and individualisation. This position did not provoke resistance based on a general social consensus. The rethinking of modernism as a European and Western style of liberal society changed the vector of traditionalist positioning. Modernism began to be attacked as architecture that destroys the authenticity of the environment, and the approval of projects was seen as corrupt.

1991-2010	2010-2025
Modernism = Soviet legacy	Modernism = West/Europe
Value via ornamentation	Value via quality materials
Indifference to heritage	Heritage sensitivity
No civic response mechanisms	Civic critique shapes projects
Traditionalism unchallenged	Modernism opposed by traditionalism
Postmodernism naturally fading	Neutral design avoids conflict

Figure 5. Contrast between traditionalist and modernist tendencies
Source: developed by the authors

A new consensus gradually emerged regarding the optimal architectural form in Lviv. Both traditionalist and modernist projects received a prosaic interpretation without distinctive details or compositional twists. The style of strict laconicism made it possible to avoid attacks from various sides of the polarised urban discourse on architecture, reducing information tension and reputational risks for political actors. In addition, such projects reduced the costs of construction company owners, who stopped spending money on the implementation of complex projects and artistically motivated details. The main focus shifted to maintaining the existing image of the city (Idak, 2023) and ensuring the isolation and safety of residents through the creation of closed communities of residents. In addition to stylistic differences, it was also worth noting a change in typological orientation. While in 1990s, considerable attention was paid to sacred buildings, which appeared in all districts of Lviv, later on, residential construction and trade became dominant. Significant volumes of new housing often led to conflicts with local communities, which further radicalised polarisation and, consequently, activated mechanisms for its reduction.

So, analysis of the development of architecture in Lviv during the period 1991-2025, especially its neomodernist phase, demonstrated the importance of moderating public discourse around architectural projects, especially those that affected the interests of a significant number of people. At the same time, it should be noted that the socio-cultural polarisation was a consequence of the unique historical development of Lviv and the entire Carpathian region. Although the Ukrainian population constituted a relative majority in the region, it effectively had only one "own" institution, which was the church. The region's long-standing provincial status provoked a compensatory movement toward forced reintegration into the cultural space of Europe, assimilating liberal and democratic social and artistic models, as well as corresponding ideas about lifestyle, which were directly related to architecture. As a result of neutralising the polarisation tension through the use of prosaicness, the overall state of architecture in Lviv underwent changes in its development. Unlike cities with similar historical development, such as Vilnius, Warsaw, Krakow, Bratislava, as of 2025, Lviv had not seen the emergence of high-rise areas or new spatial accents, nor have buildings appeared that could complement the already established associative series of iconic identifiers (Fig. 6). Attempts to develop high-rise construction, faced with sharp criticism from a polarised society, either ended up with modified and simplified implementations in a prosaic manner, or do not reach the stage of completion.

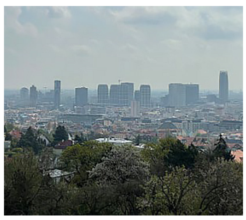
a)  b)  c)  d) 

Figure 6. Panoramas of European cities and high-rise construction in Lviv
Note: a – panorama of Vilnius with a view of the historic centre and modern high-rise buildings; b – panorama of Warsaw with a view of the historic centre and modern high-rise buildings; c – panorama of Bratislava with a view of modern high-rise buildings; d – construction of high-rise building in Lviv
Source: Kapsuła Hostel (2019), Ateitis.lt (2024), Wanderlust Welsh (n.d.), Encyclopedia Novobudov (n.d.)

The practice of public debate on issues in a particular professional field had ceased to be seen as a problem and was regarded as a manifestation of democracy and freedom. As a result, the range of possibilities for political struggle had expanded significantly, with society's reflections on various areas of services and social security also being added to the mix. J.N. Druckman *et al.* (2013) noted that this process also had a reverse effect, when, under the influence of political struggle, certain highly specialised professional discussions underwent transformation and polarisation. R. Luck (2018) emphasised that attempts to respond to the media and social component of contemporary design became the source of the concept of participation, but it only partially balanced the two poles of interaction and remained an uncertain and controversial phenomenon. This was probably due to the fact that participation itself was not a priority goal, unlike the opportunity to express an opinion and saw it as important. Since public opinion was a political asset, the assessment of aesthetics had become an act of giving preference to the side, with which a particular decision in the public sphere was associated. R.-A. Thietart & J. Malaurent (2024) noted that criticism in traditional and social media caused major revisions to Paris's Tour Triangle and contributed to the cancellation of the Munger Hall dormitory in Santa Barbara after viral backlash on TikTok and Twitter. M. Lizzio-Wilson *et al.* (2022) explored the relationship between social media use and affective polarisation, focusing on how online exposure to political content can deepen emotional divides and hostility between groups in society. The authors highlighted mechanisms such as selective exposure and echo chambers that reinforced partisan sentiments on digital platforms, and proposed the thesis that social media dynamics played a significant role in intensifying social and political polarisation. Y. Lin & S. Geertman (2019) provided a systematic literature review on the role of social media in urban planning, showing that social media data have increasingly been used for urban analysis and modelling (e.g., activity patterns, land use, transport) and that social media platforms had emerged as new spaces for public participation, communication, and collective action in planning practices. However, researchers also identified challenges in using social media for planning – such as population and spatial biases, privacy issues, and difficulties in extracting useful information – and highlighted the need for careful methodological handling of such data.

CONCLUSIONS

So, in research two main phases of the Lviv architectural development in the period 1991-2025 (postmodernist and neomodernist), the origin of the process of media influence on different ways of expressing traditionalist and liberal views was determined. The intensification of the polarisation process after the emergence of the neomodernist trend, which provoked a sharp reaction on social networks and among media-active citizens, who gained additional leverage with the development of public communication technologies, was emphasised. Confrontational rhetoric, which occupied a significant part of the information interaction field, gradually turned into a tool for political lobbying. So, in order to reduce the negative projection of the traditionalist trend, the architecture of neomodernism in Lviv underwent changes towards greater prosaicness and ordinariness. It also affected projects that were still being carried out in a postmodernist manner, giving architectural solutions a strict laconicism and taciturnity. Therefore, the architecture of Lviv in the period 2015-2025 lacked spatial and symbolic accents, charismatic plots, and solutions that could complement the visual associative series of the city. The analysis showed that the Ibis Hotel on Shukhevych Street in 2015, the Ibis Hotel on Ivan Franko Street in 2022, the building on Mitskevich Square, and the new object on Hnatyuk Street underwent a transformation towards prosaic neomodernism due to polarisation in Lviv's architectural environment. Various initiatives to construct high-rise buildings became impossible in the city, as happened in other Eastern European cities (such as Vilnius, Warsaw, Bratislava) with similar histories and architectural heritage. The prosaic design style also had an impact on residential construction, which grew significantly due to the city's popularity as a cultural, business, and educational centre. The new districts had come closer to the aesthetic heritage of typical Soviet projects of the 1970s and 1980s. In further research, it is worth paying attention to the experience of overcoming alienation and the convergence of conflicting views on architectural form, by expanding the concept of ideal presence and ways of its architectural representation.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Architectural Herald. (n.d.). Retrieved from https://architectureherald.com/.

[2] Ateitis.lt. (2024). *Emigrate? Or maybe immigrate to Lithuania?* Retrieved from https://www.ateitis.lt/emigruoti-o-gal-imigruoti-i-lietuva/.

[3] Building Differently. (n.d.). *LinkedIn*. Retrieved from https://surl.lu/srsprj.

[4] Controversial Developments in Lviv. (n.d.). *Facebook*. Retrieved from https://www.facebook.com/groups/388861717938338/?locale=uk_UA.

[5] Druckman, J.N., Peterson, E., & Slothuus, R. (2013). How elite partisan polarization affects public opinion formation. *American Political Science Review*, 107(1), 57-79. doi: 10.1017/S0003055412000500.

[6] Encyclopedia Novobudov. (n.d.). *New building, Lviv, Lukash – Ostrogradskyy – photo of construction and planning*. Retrieved from https://novobudovy.com/arkhiv/zhitlovij-budinok-po-vul-lukasha-1?jbquickview=quickview.

[7] Gentile, M. (2015). The post-Soviet urban poor and where they live: Khrushchev-era blocks, "bad" areas, and the vertical dimension in Luhansk, Ukraine. *Annals of the Association of American Geographers*, 105(3), 583-603. doi: 10.1080/00045608.2015.1018783.

[8] Habrel, M., Habrel, M., & Lysiak, N. (2020). Spatial change of Lviv in the post-Soviet period and their assessment by the residents. *IOP Conference Series: Materials Science and Engineering*, 960, article number 022098. doi: 10.1088/1757-899X/960/2/022098.

[9] Idak, Y. (2023). "Habitus of the city" as a sign of the invariance of the historic city and the variability of its structure. *AIP Conference Proceedings*, 2490(1), article number 060013. doi: 10.1063/5.0123187.

[10] Jannière, H., & Scrivano, P. (2020). Public debate and public opinion: Notes for a research on architectural criticism. *Clara*, 7(1), 18-29. doi: 10.3917/clara.007.0018.

[11] Kapsuła Hostel. (2019). *The end of the summer holidays in Warsaw*. Retrieved from https://kapsulahostel.pl/zakonczenie-wakacji-w-warszawie-2/.

[12] Kelly, J. (2023). 'Life is right, the architect is wrong': Public participation and architectural criticism, 1962-73. In *No more giants* (pp. 185-209). Manchester: Manchester University Press. doi: 10.7765/9781526143761.00013.

[13] Kos, H., & Kharambura, S. (2017). Reflections on a new historical and architectural work: Instead of a review. *The Ethnology Notebooks*, 4, 988-994.

[14] Kosasih, I.B., & Sangaras, M.A.G. (2022). Social media affect on contemporary design for architect and client via Instagram sites. *International Journal of Research and Applied Technology*, 2(1), 178-187. doi: 10.34010/injuratech.v2i1.6916.

[15] Krasnodemska, I. (2022). The role of metropolitan Andrei Sheptytskyi in the formation of Ukrainian national identity. *Occasional Papers on Religion in Eastern Europe*, 42(9), article number 5. doi: 10.55221/2693-2148.2395.

[16] Kubik, J. (2024). Neo-feudalism and neo-traditionalism as responses to liberalism. *East European Politics and Societies*, 38(4), 1067-1079. doi: 10.1177/08883254241295463.

[17] Lekhniuk, R. (2019). Ukrainian Christian social movement in Galicia at the end of the XIX – the first quarter of the XX centuries: Ideology and political practices. *Res Gestae*, 8, 84-113. doi: 10.24917/24504475.8.4.

[18] Lin, Y., & Geertman, S. (2019). Can social media play a role in urban planning? A literature review. In S. Geertman, Q. Zhan, A. Allan & C. Pettit (Eds.), *Computational urban planning and management for smart cities* (pp. 69-84). Cham: Springer. doi: 10.1007/978-3-030-19424-6_5.

[19] Lindsay, G., Sawyer, M., & Alaily-Mattar, N. (2025). Architecture in the age of social media: Introduction to the special issue. *Archnet-IJAR: International Journal of Architectural Research*, 19(2), 311-317. doi: 10.1108/ARCH-03-2025-0114.

[20] Linko, M.E. (2020). The Guggenheim Museum Helsinki plan as a media debate. *Museum & Society*, 18(4), 425-440. doi: 10.29311/mas.v18i4.3171.

[21] Lizzio-Wilson, M., Thomas, E.F., Louis, W.R., Amiot, C.E., Bury, S.M., Molenberghs, P., Decety, J., & Crane, M.F. (2022). Do the means affect the ends? Radical tactics influence motivation and action tendencies via the perceived legitimacy and efficacy of those actions. *European Journal of Social Psychology*, 52(4), 695-717. doi: 10.1002/ejsp.2847.

[22] Luck, R. (2018). Participatory design in architectural practice: Changing practices in future making in uncertain times. *Design Studies*, 59, 139-157. doi: 10.1016/j.destud.2018.10.003.

[23] Lviv Architects Forum. (n.d.). *Facebook*. Retrieved from https://www.facebook.com/groups/299391490154544.

[24] O'Regan, T. (2013). Reception and exposure in architecture, film and television. *Architectural Theory Review*, 18(3), 272-278. doi: 10.1080/13264826.2014.875611.

[25] Petryshyn, H., Lukasschuk, H., Tupis, S., & Kryvoruchko, O. (2016). Change in dendrological composition of plantations in the park on the St. George Square in Lviv in terms of urban development intensification. *The Scientific Bulletin of UNFU*, 26.8, 224-231.

[26] Posatskyy, B. (2015). Genesis and problems of spatial development of Lviv (at the turn of the 20th-21st century). *Experience and Prospects of Urban Development in Ukraine*, 28, 142-158.

[27] Save Historical Lviv. (n.d.). *Facebook*. Retrieved from https://www.facebook.com/groups/457798087953863.

[28] Tempestini, M. (2025). Criticism goes social: Exploring public architectural criticism through architecture awards. *Archnet-IJAR: International Journal of Architectural Research*, 19(2), 411-433. doi: 10.1108/ARCH-04-2024-0165.

[29] Thietart, R.-A., & Malaurent, J. (2024). How do social media contribute to the emergence of "extreme" events? The rise of Tour Paris 13: The "Sistine Chapel" of street art. *Academy of Management Discoveries*, 10(4), 543-567. doi: 10.5465/amd.2022.0229.

[30] Topdağı Yazıcı, B., Irapoğlu, N., & Güleçoğlu, H.N. (2025). From restoration to social media: Exploring the nexus of architecture, social media and information sharing behaviours. *Open House International*, 50(1), 40-64. [doi: 10.1108/OHI-12-2023-0284](https://doi.org/10.1108/OHI-12-2023-0284).

[31] Treffers, F. (2023). People, participation and processes in rebuilding Ukraine at a crossroads. In A. Rubbo, J. Du, M.R. Thomsen & M. Tamke (Eds.), *Design for resilient communities* (pp. 177-189). Cham: Springer. [doi: 10.1007/978-3-031-36640-6_13](https://doi.org/10.1007/978-3-031-36640-6_13).

[32] Vlasenko, Y., & Ryan, B.D. (2022). Decommunization by design: Analyzing the post-independence transformation of Soviet-era architectural urbanism in Kyiv, Ukraine. *Journal of Urban History*, 50(2), 247-288. [doi: 10.1177/009614422210798](https://doi.org/10.1177/009614422210798).

[33] Wanderlust Welsh. (n.d.). *Bratislava city guide – 13 things to see and do*. Retrieved from https://wanderlustwelsh.com/things-to-do-bratislava/.

[34] Znak, A., & Znak, I. (2023). Classical order interpretation in Lviv of the independence era in view of the world and national practices. *AIP Conference Proceedings*, 2490(1), article number 020016. [doi: 10.1063/5.0122939](https://doi.org/10.1063/5.0122939).

Роман Франків

Кандидат архітектури
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0003-1100-0930

Богдан Черкес

Доктор архітектури, професор
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0001-6809-956X

Архітектура в контексті соціокультурної поляризації: на прикладі міста Львів (1991-2025)

Анотація. Актуальність дослідження полягала у вивченні сучасного архітектурного врядування міста Львів, що потребувало розвиненої медіакомпоненти та налагодженого діалогу між групами з протилежними культурними й естетичними поглядами. Метою дослідження було визначення залежності стилістики міської архітектури від модерації громадської думки та запобігання антагоністичним і ворожим наративам у професійному й публічному середовищі. У статті розглянуто взаємозв'язок між соціокультурною поляризацією та стилістичною еволюцією міської архітектури Львова у 1991-2025 роках. На прикладі Львова показано, що відсутність ефективного посередництва між традиціоналістськими та ліберальними позиціями в архітектурному дискурсі призводила до конфліктів цінностей і зниження якості проєктних рішень. На основі аналізу медійних і професійних матеріалів було виокремлено дві основні фази архітектурного розвитку: постмодернізм (1991-2010), що характеризувався відкиданням радянського модернізму та романтизацією історичних форм, і неомодернізм (2011-2025), у межах якого модернізм переосмислювався як символ європейської ідентичності. Різка критика неомодерністських проєктів з боку громадськості стала соціальним явищем, що впливало на архітектурні рішення. Прикладом цього був конфлікт навколо реконструкції площі Святого Юра, який завершився компромісним рішенням і започаткував тенденцію до «нейтральних» та прозаїчних форм. Практична цінність статті полягає у демонстрації того, як налагодження взаєморозуміння між прихильниками різних архітектурних підходів може підвищити якість проєктних рішень, уникнути надмірного спрощення та зберегти архітектуру як носій міської ідентичності

Ключові слова: прозаїчна архітектура; спрощення; неомодернізм; традиціоналізм; модерація проєктування; естетичний конфлікт; міська ідентичність

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 728.2-027.37
DOI: 10.56318/as/1.2026.18

ISSN: 2411-801X
e-ISSN: 2786-7374

Maria Blinova
Doctor of Architecture, Professor
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Chornoglazivska Str., Kharkiv, Ukraine
https://orcid.org/0000-0003-0936-0494

Andrii Soloviov*
PhD Student
O.M. Beketov National University of Urban Economy in Kharkiv
61002, 17 Chornoglazivska Str., Kharkiv, Ukraine
https://orcid.org/0009-0004-2289-8445

Post-conflict housing in Ukraine: The Baugruppen model as a catalyst for sustainable urban regeneration

Abstract. The aim of the study was to analyse the possibilities of applying the Baugruppen model in Ukraine as a tool for affordable housing and post-war reconstruction, combining legal, institutional, and spatial dimensions. Comparative analysis of legal and policy contexts between the two countries identified gaps in Ukraine's regulatory environment, such as insufficient municipal authority, lack of financial incentives, and absence of intermediary organisations. This study explored the potential application of the Baugruppen (community-led development) model for addressing modern housing challenges in Ukraine. The paper examined the historical trajectory of cooperative housing in Germany and Ukraine, highlighting how Germany's supportive legal frameworks and institutional mechanisms had fostered Baugruppen initiatives. Using the Vauban district in Freiburg, Germany, as a case study, the research demonstrated how participatory design, ecological principles, and collaborative governance contributed to the success of Baugruppen projects. The findings underlined the need for Ukraine to reform its housing policies, incorporating lessons from Germany's Baugruppen model, and highlighted the possibilities for cooperation between municipalities, local communities, and international partners to create conditions for Baugruppen projects. It was determined that these changes should encompass a reorientation of land-allocation policies, the introduction of concept-based tendering mechanisms, and the establishment of new development frameworks, in which end users were directly involved in decision-making processes and exert a substantially greater influence over project outcomes. If such institutional gaps were addressed, the model could help Ukraine rebuild destroyed housing, provide homes for displaced people, and support sustainable urban development in line with national and international reforms

Keywords: sustainable urban development; affordable housing; building cooperative; post-conflict reconstruction; participatory design

INTRODUCTION

Ukraine's modern housing crisis cannot be explained solely by wartime destruction. Although the large-scale damage caused since 2022 had intensified the situation, many structural weaknesses of the housing sector predated the invasion. V. Teremetskyi *et al.* (2024) noted that the national housing system continued to operate within

Suggested Citation:
Blinova, M., & Soloviov, A. (2026). Post-conflict housing in Ukraine: The Baugruppen model as a catalyst for sustainable urban regeneration. *Architectural Studies*, 12(1), 18-28. doi: 10.56318/as/1.2026.18.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 18-28
Received: 04.11.2025 Revised: 03.02.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

a regulatory framework largely inherited from the late Soviet period. The 1983 Housing Code formally remained in force despite profound socio-economic transformation and Ukraine's ongoing European integration trajectory. T. Hudima *et al.* (2025) suggested that meaningful reform cannot be limited to legislative amendments; it required a reconsideration of governance principles, including transparency, social targeting, and sustainability-oriented regulation aligned with EU standards. The urgency of this institutional reconsideration had been amplified by the scale of wartime destruction. According to the latest Ukraine recovery and reconstruction needs assessment by the A. Himmelfarb (2025), housing constituted one of the most heavily affected sectors, with estimated damages reaching USD 57.6 billion and millions of square meters of residential space destroyed or rendered uninhabitable. Yet reconstruction was not merely a technical task of rebuilding housing stock. It also raised fundamental questions about how housing was financed, governed, and delivered.

In this context, the debate increasingly shifted from quantity to mechanisms. Reproducing pre-war delivery models, whether state-driven or market-led, risks perpetuating earlier systemic limitations, including affordability gaps and weak community integration. Governance-based alternatives, particularly those that incorporated participatory planning and collective ownership structures, offered a different trajectory. Such approaches resonated with broader European discussions on sustainable urban development and aligned with the objectives of Sustainable Development Goal, which called for inclusive, safe, resilient, and sustainable cities (Blinova & Rodyk, 2024). While the Baugruppen model had not yet been the subject of targeted research within the Ukrainian academic context, there was already a growing body of literature on participatory urban planning and collaborative governance that could serve as a foundation for its adaptation. K. Mezentsev *et al.* (2020) analysed public space planning in Kyiv through the lens of citizen participation, while N. Antonenko (2022) examined the integration of participatory practices in post-Soviet urban redevelopment in Southern Ukraine. D. Pasyuta *et al.* (2023) offered practical tools for embedding stakeholder engagement into the planning process. Although these works were not focus directly on cooperative housing delivery, it established an important theoretical and practical foundation for considering community-led development frameworks.

I. Hamiduddin & N. Gallent (2016) emphasised that community-led and cooperative housing frameworks, widely discussed in European planning literature, offered one such direction. It repositioned future residents from passive beneficiaries to active participants in spatial and financial decision-making, thereby linking affordability, long-term stewardship, and environmental performance. P.A.C. Pfatteicher *et al.* (2024) analysed the German experience of housing cooperatives over the long term, arguing that their resilience to political and economic shocks was grounded in self-help logics, cooperative principles, and robust auditing with member-controlled surpluses. The authors traced five historical phases – from 19th century origins and legal consolidation to reunification-era harmonisation – showing how policy, legislation, and macroeconomic cycles shaped cooperative governance and operating models. Researchers concluded that transferability depended on enabling regulation that protected cooperative purpose and supported long-term stewardship rather than short-term market extraction. G.J. Coates (2013) conceptualised Freiburg's Vauban as a district-scale operationalisation of sustainable urbanism, in which architectural performance, mobility systems and participatory governance were treated as mutually reinforcing. Vauban integrated compact mixed-use planning with local services, light-rail accessibility, extensive cycling/walking networks and car-sharing, thereby reducing private car dependence. A key architectural contribution was the Baugruppen-led, resident-architect co-design process, which produced socially cohesive yet typologically diverse housing and shared outdoor spaces. The R-50 cohousing precedent study performed by ArchDaily (2013) documented a Baugruppe-led, architect-initiated project at Ritterstraße 50 in Berlin-Kreuzberg and explained its delivery model – site acquisition through a bidding process, collective financing, and an intensive co-design workflow. It reported key parameters (19 flats, ~2,130 m^2 total living space, ~80-132 m^2 unit sizes, and an average cost of about EUR 2,150/m^2) and highlighted shared and semi-public spaces as social infrastructure. Baugruppen/cohousing models can support sustainable urban outcomes, while cautioning that such projects tended to over-represent middle-class households and may exclude lower-income groups without explicit policy instruments.

Although housing reform in Ukraine and cooperative housing models in Europe had each been studied in considerable depth, they were rarely examined in relation to one another. Ukrainian scholarship tended to concentrate on legislative changes, social housing provision, or participatory planning as separate themes. At the same time, research on Baugruppen and collaborative housing had largely evolved within relatively stable institutional settings, with limited attention to post-conflict environments. This left open the question of how such governance-based housing frameworks might function under the specific legal, urban and socio-economic conditions currently shaping Ukraine's reconstruction process. Therefore, the research goal was to substantiate Baugruppen (community-led development) as a governance-ready instrument for post-conflict housing delivery in Ukraine by comparing German and Ukrainian cooperative-housing trajectories and regulatory frameworks, and by operationalising conditions from the Vauban case across affordability, environmental performance, governance, and participation.

MATERIALS AND METHODS

This study employed a qualitative, sustainability-oriented research methodology to assess the potential of a community-led development (Baugruppen) approach for delivering affordable, inclusive, and environmentally responsible housing in Ukraine. The research was organised in three stages: first – analysis of the historical context of cooperative housing in Germany and Ukraine; second – review of legal frameworks and policy documents; third – a case study of the Vauban district in Freiburg. This structure allowed both theoretical comparison and practical evaluation for Ukraine's recovery. The first stage examined the historical trajectory of cooperative, group-built and social housing in Germany and Ukraine, with attention to how cooperative traditions had supported long-term resilience, social cohesion, and resource efficiency in the built environment. This stage situated the Baugruppen model within a broader sustainable development context, drawing lessons from both countries' socio-economic and environmental histories. The city of Lviv and the social housing project on Mykolaychuk Street, the concept of social housing on Hlynyanskyi Trakt Street, Hansen Village in Tarasivka, Kyiv region, the city of Bila Tserkva, and a housing complex for internally displaced persons from Mariupol were selected as examples for the study. These cities experimented with pilot projects for affordable housing, but it was also determined that they lacked the targeted measures and competitive land allocation processes observed in Germany, such as conceptual bidding (Konzeptverfahren). These projects were chosen as the most recent affordable housing cases implemented in Ukraine after the full-scale invasion began. Competitive land allocation methods, such as concept-based bidding, were absent, and state-backed financial tools similar to those provided by Germany's KfW Bank were not yet available. The second stage involved a systematic review of relevant literature, policy documents, and legal frameworks, applying a structured content analysis to identify enabling conditions for community-led housing. The review compared German instruments such as Building Code (BauGB) (1960), Act on Cooperative Societies (2024). Also, it was analysed municipal regulations with The Housing Code of Ukraine No. 5464-X (1983), Law of Ukraine No. 1087-IV (2003), The Civil Code of Ukraine No. 435-IV (2003), and Draft Law of Ukraine No. 4586-IX (2025). Special focus was placed on how each system addressed sustainable land allocation, climate-responsive design standards, financing for low-carbon housing, and mechanisms for multi-stakeholder collaboration between local governments, communities, and intermediary organisations. This comparative analysis highlighted, where Ukrainian policy could be adapted to embed cooperative housing within a sustainability-oriented planning framework.

The third stage applied a case study methodology to the Vauban district in Freiburg, Germany. This district was selected to assess the relevance of Baugruppen practices for Ukraine for three main reasons: 1) Vauban demonstrated the integration of ecological and climate-responsive principles, including high standards of energy efficiency, the use of renewable energy, and the implementation of green infrastructure, which directly corresponded to sustainability goals for the reconstruction and regeneration of Ukrainian cities; 2) Vauban highlighted the potential of cooperative housing development to lower construction costs, while meeting the needs of diverse social groups, from middle-income households to residents with limited resources. This experience was particularly relevant for Ukraine, where there was an urgent need to provide socially inclusive housing solutions for internally displaced persons, veterans, and other vulnerable populations; 3) Vauban established innovative mechanisms for collaboration among municipal authorities, developers, and citizen groups, offering a model for participatory governance and cross-sector partnerships in urban planning that could inform sustainable housing strategies in Ukraine (Hamiduddin & Gallent, 2016). The case study was used to assess the transferability of Baugruppen practices to Ukraine, particularly for post-war reconstruction, integration of internally displaced persons, and achievement of Sustainable Development Goals (n.d.) on inclusive, safe, resilient, and sustainable cities. Findings from each stage were compared using qualitative content analysis, focusing on four themes: affordability, environmental performance, governance, and participation. These themes were then juxtaposed with Ukraine's legislative, socio-economic, and ecological realities to identify critical success factors and formulate policy recommendations.

RESULTS AND DISCUSSION

Legal framework and institutional mechanisms for building cooperative housing (Baugruppe)

According to data presented by UkrInform (2024) approximately 50 million square meters of residential housing stock have been destroyed or damaged due to Russian military aggression. This massive destruction, coupled with the aging of existing buildings and an outdated Soviet-era social policy, had created a critical housing deficit (Fig. 1). As of 2025, over 600,000 Ukrainians remained on the national housing register, a figure that does not fully account for the 4.9 million officially registered internally displaced persons (IDPs), 26% of whom required immediate social protection. The infographic underscored the demographic diversity of those affected by the crisis. Moreover, with every third citizen having a low-income level, there was an urgent need to transition from inefficient privatisation models to modern instruments like social rental housing and "rent-to-own" schemes. Creating these conditions was essential not only for the integration of IDPs but also for the potential return of 6.6 million refugees from abroad, whose homecoming depended on the availability of stable and resilient housing solutions.

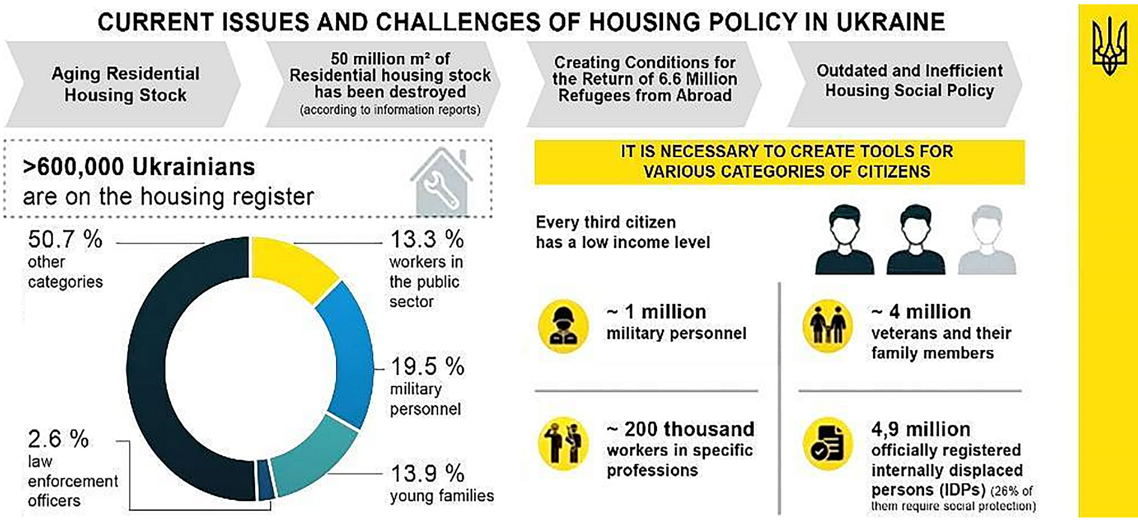


Figure 1. Modern issues and challenges of housing policy in Ukraine

Source: UkrInform (2024)

The situation was further complicated by the Soviet-inherited Housing Code, which was designed for a fully state-owned housing stock and a centralised policy framework. As it was demonstrated by Ye. Vlasenko (2017), following mass privatisation in the early 1990s, leaving less than 4% of the housing stock under state or municipal ownership, the legal framework became largely obsolete. During the transitional period, the state of social and affordable housing deteriorated sharply, while the cooperative housing tradition, which had provided non-commercial, community-oriented housing solutions, was almost entirely lost. In the 1980s, cooperative construction reached a peak, allowing individuals and legal entities to pool resources for building or renovating homes for their own use. Ye. Vlasenko (2015) noted that with the shift toward market relations, this approach was abandoned, and the housing sector became predominantly profit-driven, with limited provision even of basic economy-class housing at prices accessible to the majority of citizens. In modern context of post-war recovery needs, the demand for socially inclusive, affordable, and environmentally sustainable housing had become unprecedented. As mentioned during the discussion on the theme of the housing crisis in Ukraine with the support of the International Renaissance Foundation (2025), citizens have submitted over 850,000 applications via the Diia system, covering more than 60 million m^2 of damaged housing, versus the pre-war annual commissioning of only 9-10 million m^2. While some progress had been achieved in the social housing sector through government initiatives and international support, the challenge of creating affordable housing that was also resource-efficient, climate-adaptive, and socially cohesive remained unresolved.

To explore the potential for implementing cooperative housing models such as Baugruppen in Ukraine, it was necessary to examine the legislative and institutional mechanisms in Germany that had both enabled the adoption of this model and embedded it within a wider sustainable development agenda. The legal and institutional framework supporting Baugruppen was grounded in a combination of historical legislation, cooperative law, urban planning policies, and innovative institutional mechanisms that collectively addressed housing affordability, while advancing participatory, socially inclusive, and environmentally responsible urban development. The foundation for cooperative housing in Germany lain in the Act on Cooperative Societies (2024), first enacted in 1867 and subsequently reformed, particularly in 1889 and 2006. This law secured limited liability for cooperative members, ensured democratic governance principles, and promoted the equitable distribution of benefits. P.A.C. Pfatteicher *et al.* (2024) had described that amendments in 2006, 2009, and 2017 modernised its provisions by integrating digitalisation, simplifying administrative procedures, and enabling virtual participation, thereby strengthening inclusivity and accessibility. In parallel, Germany's municipal land use and zoning laws, particularly the Building Code (BauGB) (1960), provided a legislative basis for prioritising cooperative housing within sustainable urban regeneration strategies. This document allowed local governments to designate land for non-speculative and community-oriented housing projects, often at reduced prices, thus directly linking land policy to social equity and low-carbon urban development objectives. I. Hamiduddin & N. Gallent (2016) demonstrated that cities such as Berlin and Hamburg had implemented these principles through structured land allocation competitions and targeted financial incentives. While H. Haas (2020) highlighted that the 1990 Tax Reform Act ended the formal non-profit status of housing cooperatives, it retained tax benefits for those meeting conditions related to member-based revenue generation. This shift prompted cooperatives to adjust business models, but many maintained their commitments to affordability, participatory decision-making, and resource-efficient building practices.

Germany's experience showed that success in Baugruppen development was underpinned by institutional mechanisms that connected legal frameworks with practical implementation. R.C. Bartholomäi (2004) specified that at federal and state levels, instruments such as low-interest loans, targeted grants, and tax incentives reduced financial barriers for members, while promoting environmental performance and long-term community resilience. Given the high cost and scarcity of urban land, municipal policies like fixed-price tendering and concept-based bidding (Konzeptverfahren) were vital. These methods allocated public land based not only on financial bids but also on a project's social and ecological value to the local community. As concluded by S. Schwarz & I. Sabatier-Schwarz (2017), Baugruppen often exceled in these evaluations due to their integration of affordability, inclusive governance, and sustainable design. In several municipalities, portions of residential development land were reserved for Baugruppen, reflecting political commitment to community-led and climate-conscious housing. D. Scheller (2019) noted that cities such as Hamburg, Freiburg, and Tübingen allocated around 40% of municipal land sales for such projects. Long-term lease arrangements of up to 100 years at low interest rates further support financial feasibility, while allowing municipalities to retain ownership and influence over urban sustainability outcomes. R.C. Bartholomäi (2004) pointed out that participatory urban planning practices were systematically embedded into Baugruppen processes, enabling future residents to collaborate with architects, planners, and municipal authorities to achieve socially cohesive and environmentally efficient neighbourhoods. Intermediary organisations, including the Forum Gemeinschaftliches Wohnen e.V. (Reimer & Peters, 2025) and regional cooperative associations, provided critical expertise in legal compliance, financing, and architectural planning, while also disseminating best practices in sustainable construction. Building cooperatives and community-led housing projects were also becoming a significant part of the UK's property landscape. T. Archer & C. Harrington's (2021) report provided a sector-wide, funding-focused appraisal of the community-led housing (CLH) pipeline in England and the institutional conditions required to deliver it. Authors interpreted England's CLH pipeline as an SDG-aligned delivery system that linked affordable homes with place-based outcomes – placemaking, community wealth-building, and local empowerment. They contended that CLH's architectural and urban value should be evidenced through energy efficiency and climate action contributions, design-led wellbeing gains, including shared spaces, adaptable layouts, and resident stewardship, and by linking self-help housing models to local skills, jobs, and training pathways. The report recommended embedding CLH-supportive policies in spatial plans and strengthening impact measurement to justify targeted, long-term investment.

In contrast, the Ukrainian legislative and institutional environment for cooperative housing remained underdeveloped. The Civil Code of Ukraine No. 435-IV (2003) and the Law of Ukraine No. 1087-IV (2003) provided a general basis for cooperative formation but were not tailored to the specific requirements of housing cooperatives, including long-term affordability, participatory governance, and integration of ecological design principles. P. Fedoriv & N. Lomonosova (2019) noted that repeated attempts to revise the Housing Code between 2010 and 2021 were unsuccessful, but the Russian-Ukrainian war, which started in 2022, and the resulting displacement crisis renewed urgency for reform. Consultations among government ministries, local authorities, and international partners had led to the Draft Law of Ukraine No. 4586-IX (2025), which outlined a systemic approach to housing strategy, included cooperative forms, and had the potential to embed sustainability criteria into housing policy. In 2020, Ukraine lacked the kind of institutional support ecosystem found in Germany. Municipalities in Ukraine played a limited role in supporting cooperative housing. K. Höller (2024) pointed out that the Law of Ukraine "On Local Self-Government in Ukraine" granted local authorities the power to allocate municipal land and implement housing programmes, but cooperative housing was rarely a priority in these policies. As stated in the Resolution of the Cabinet of Ministers of Ukraine No. 695 (2020), the lack of affordable housing had become one of the main socio-economical issue since the beginning of the full-scale invasion. O. Avramova *et al.* (2023) noted that existing housing programmes focused primarily on individual ownership or social housing provision, without fully addressing cooperative models. The State Fund for Support of Youth Housing Construction (n.d.) could potentially be expanded to include cooperative housing, with eligibility tied to sustainability performance and community participation standards. Additionally, international financial institutions and development partners could play a role in providing blended finance for Baugruppen-style projects that meet social inclusion and environmental quality benchmarks.

By aligning future legislative reforms and institutional mechanisms with principles of sustainable development, Ukraine can create a policy framework that promoted cooperative housing as a driver of affordable, inclusive, and low-carbon urban regeneration. Drawing on the German experience, embedding Baugruppen within Ukraine's housing strategy can support the achievement of the Sustainable Development Goals (n.d.), particularly Goal 11 on inclusive, safe, resilient, and sustainable cities, while also accelerating post-conflict recovery. Such cooperative approaches as Baugruppen, in which future residents form a "building group" that directly participated in the design and management of housing to meet long-term needs, reducing reliance on speculative developers helped to address three key policy challenges (Hamiduddin & Gallent, 2016): 1) improving housing affordability through cost savings of 20-25% by eliminating developer margins; 2) strengthening social cohesion by fostering interaction and shared responsibility among residents; 3) enabling design diversity and environmental performance improvements through direct collaboration between residents, architects, and contractors. Given Ukraine's urgent housing needs, the Baugruppen model offered a pathway to reconstruction that combined affordability, community integration, and low-carbon urban development. This relevance was reinforced by the inclusion of cooperative practices in the Draft Law of Ukraine No. 4586-IX (2025), which prioritised such approaches for both new construction and the restoration of damaged housing. Within the framework of sustainable urban development, the concept of community extended beyond a purely sociological category and acquired a distinct spatial and governance-related dimension. Research on the notion of the "closed community" emphasised that it should not be understood solely as a form of physical isolation, but rather as a specific mode of organising social life that shaped patterns of spatial use, levels of resident participation, and degrees of collective responsibility. From this perspective, cooperative housing models, including Baugruppen, can be interpreted as controlled yet socially permeable communities, capable of integrating security, social cohesion, and the core principles of sustainable development.

Although no scholarly works had focused specifically on investigating community-led development (Baugruppen) practices in the architectural design of affordable housing in the Ukrainian context, international studies demonstrated the model's capacity to integrate affordability, sustainability, and inclusivity. For example, A. Sharam (2020) explored cooperative housing in Australia as a pathway to greater community inclusiveness and environmental responsibility, while M.G. Lloyd *et al.* (2015) examined the mainstreaming of self-development in the UK and the Netherlands to address housing shortages through citizen-led initiatives. S. Bresson & S. Denèfle (2015) investigated the diversity of self-managed co-housing in France, highlighting how cooperative frameworks can be adapted to different socio-economic and regulatory environments. Evidence of the Baugruppe model's international adaptation included the handbook, prepared by M. Kopeć *et al.* (2015) in conjunction with the Prague exhibition "Baugruppe ist super! Contemporary housing – inspiration from Berlin". The volume systematised key terminology, articulated prospective advantages for members, and offered a cost model demonstrating financial efficiency. These works collectively underlined the adaptability of Baugruppen principles across diverse national contexts.

Features of the sustainable urban district of Vauban in Freiburg, Germany

The Vauban redevelopment was undertaken between 1993 and 2006 on a 38-hectare site formerly occupied by military barracks. G.J. Coates (2013) noted that after the French military's departure in 1992, the area experienced a period of informal occupation before the Freiburg City Council acquired the land and initiated a redevelopment process centred on ecological sustainability and social integration. The non-profit "Forum Vauban" was mandated to lead a comprehensive public participation process, ensuring that residents and stakeholders shaped the district's vision in line with the principles of the Local Agenda 21 (United Nations Sustainable Development, 1992) and the emerging discourse on sustainable urban regeneration. Land allocation policies strongly favoured community-led housing groups. Over 40 Baugruppen were awarded plots through competitive processes prioritising families, seniors, and residents. Many of these projects incorporated passive house standards, with more than 200 dwellings built to ultra-low energy specifications, including Germany's first multi-family passive house (Fig. 2).

Figure 2. The Vauban sustainable urban district project in Freiburg, Germany – aerial view

Note: photo by A. Schwarzkopf. The bottom right part of the image depicts Solar Settlement – 59-home Plus Energy housing community, designed by R. Disch

Source: based on G.J. Coates (2013)

S. Fastenrath & B. Braun (2018) and Rolf Disch solar architektur (n.d.) mentioned that the district also integrated landmark sustainability projects such as the Solar Settlement and the "Sun Ship" commercial building, developed by Solar Settlement Ltd. and financed partly through four Freiburg Solar Funds, pioneering ethical-ecological investment vehicles (Fig. 3). Constructed primarily from timber and ecological materials, these buildings featured extensive photovoltaic systems with a total capacity of approximately 445 kWp, generating about 420,000 kWh of renewable energy annually. Urban mobility strategies reinforced environmental goals: the district was designed as a car-free zone, supported by underground parking, car-sharing schemes, and extensive pedestrian and cycling networks, thereby reducing transport-related emissions and fostering active lifestyles. Institutional support was critical.

Figure 3. The Vauban sustainable urban district project in Freiburg, Germany. Residential houses at Solar Settlement

Note: photo by C. Andrewglaser

Source: based on G.J. Coates (2013)

G.J. Coates (2013) and S. Fastenrath & B. Braun (2018) highlighted that the Freiburg municipality established dedicated bodies such as the Vauban Project Group and the Freiburg Local Authority Vauban Committee were created to coordinate planning, infrastructure provision, and stakeholder engagement. As noted by A. Staub (2025), coperative housing organisations, notably the Genova Co-operative, took responsibility for designing and managing shared facilities, ensuring that communal spaces strengthened social cohesion. Public-private-community partnerships facilitated job creation, supported local businesses, and encouraged socio-economic diversity, enabling the inclusion of low-income households, internally displaced persons, and vulnerable groups. The Vauban case demonstrated that a cooperative, sustainability-driven redevelopment model can achieve multiple objectives: delivering affordable housing, fostering inclusive communities, reducing ecological footprints, and enhancing urban resilience. These outcomes were enabled by transparent land allocation, targeted financial instruments, strong municipal leadership, and embedded participatory processes. For Ukraine, adapting these strategies could support war-damaged housing reconstruction, enable climate-smart neighbourhoods, and advance the national commitment to the Sustainable Development Goals (n.d.), while reinforcing local governance and citizen participation.

Examples of social housing in Ukraine

After the beginning of Russia's full-scale invasion in 2022, the topic of housing for IDPs had become one of the main socio-economic issues. Ukrainian social-housing initiatives demonstrated a predominantly provider-led delivery – logic municipal, state-business, or philanthropic – in which participation was typically mediated through institutional design choices (competitions, "needs-based" programming, partnership governance) rather than through resident co-production of projects. In Lviv, the pilot municipal scheme on Mykolaychuka Street was developed via an architectural competition and was financed with external support. As stated by D. Krutko (2025), it targeted IDPs and war-affected residents, embeded universal design through fully barrier-free apartments, and was planned as municipal housing owned by the city community, while indicating limited evidence of resident co-governance beyond beneficiary targeting. The Big City – Lab (2025) concept and the related case-study for Hlynyanskyi Trakt in Lviv, as it was mentioned in the project description, focused on a 15-minute access, integration with social infrastructure (school), green spaces, and a mixed-tenure model with a substantial social-housing share – yet participation was framed primarily as transparency, shared responsibility and community integration within an institutional management model, not as formalised resident decision-making across the project cycle.

Hansen Village in Tarasivka (Kyiv region) exemplified philanthropic provision of rent-free housing with extensive communal amenities (including shelters, sports and education); however, available documentation at the Village webpage does not specify participatory governance mechanisms for residents beyond service provision (Hansen Ukrainian Mission, 2025). Finally, the "My Home. Ukraine" pilot in Bila Tserkva for Mariupol IDPs, as mentioned at Metinvest (2025), operationalised a multi-actor partnership and a social-rental affordability rule (rent capped at 30% of household income), with the housing retained as property of the Mariupol community, while again leaving participation largely at the level of institutional representation rather than resident co-management. Across considered Ukrainian cases, the strongest convergence with the Vauban logic was visible in social inclusion and welfare outcomes, while the weakest alignment concerns participatory urban governance, transparent land allocation for resident-led groups, and the institutional ecosystem (intermediaries, legal/financial advisory) that enabled Baugruppen-type delivery. Thus, the projects mostly treated residents as beneficiaries/tenants, not as co-producers of development.

To align the reviewed Ukrainian cases with Baugruppen principles, projects should institutionalise resident co-governance by establishing councils with formal decision rights over layouts, shared spaces, rules of use and post-occupancy management, supported by documented consultation and feedback cycles. Municipalities should introduce concept-based land allocation through competitions for cooperative/collective groups (including tenant-to-cooperative pathways), scoring social inclusion, affordability, stewardship and low-carbon design rather than price. Social rental schemes should be complemented by stewardship instruments: enforceable long-term affordability and anti-speculation covenants, mixed-income quotas and mechanisms for tenant participation (e.g., gradual cooperative membership or shared equity). Environmental alignment required NZEB/passive-house procurement standards (Bureau 69 architects, 2023) with subsidies and technical support, plus legal-financial routes for resident-owned renewables (PV/heat pumps) and revolving or green finance. Car-light planning and dedicated cooperative-housing offices were essential enabling infrastructures. To support a structured analysis of the Vauban case study and to assess the relevance of its sustainability principles for the Ukrainian context, Table 1 was developed as an analytical framework. Table 1 systematised the key ecological, social, and governance mechanisms identified in the Vauban district and related them to their potential modes of adaptation in Ukraine, taking into account differences in legislative frameworks, institutional capacity, and post-war recovery priorities. Thus, it was synthesised the key sustainability mechanisms demonstrated in the Vauban district, including participatory urban governance, transparent land allocation, high energy efficiency standards, integration of renewable energy, sustainable mobility strategies, social inclusion policies, and dedicated institutional support structures, and outlined their potential applicability within the Ukrainian context. While these mechanisms indicated a feasible framework for adapting the Vauban concept to post-war housing reconstruction and sustainable urban regeneration in Ukraine, their practical implementation required further empirical investigation, contextual adjustment to national legislative and institutional conditions, and in-depth interdisciplinary research to assess their long-term social, environmental, and governance impacts. Beyond the German context, collaborative and community-led housing models had been extensively examined across Europe, particularly in the United Kingdom and the Netherlands. Studies of community land trusts and self-help housing initiatives in the UK demonstrated how collective ownership structures and locally embedded governance mechanisms can address affordability challenges, while fostering long-term stewardship of housing assets (Moore & Mullins, 2013). At a broader theoretical level, R. Lang *et al.* (2020), in systematic review of collaborative housing research between 1990 and 2017, identified governance transformation as a central analytical theme. Researcher's findings suggested that collaborative housing should be understood not merely as a spatial or architectural typology, but as a reconfiguration of relationships between residents, public authorities, and market actors. The authors emphasised that the durability and scalability of such initiatives depended on supportive legal frameworks, municipal facilitation, and intermediary structures – factors that directly resonated with the institutional conditions examined in this study.

Table 1. Vauban sustainability mechanisms and their adaptation potential for Ukraine

Sustainability mechanism	Vauban example	Adaptation potential for Ukraine
Participatory urban governance	Mandatory community consultation led by "Forum Vauban"; collaborative decision-making integrated into planning and design	Establish local participatory planning bodies with decision-making authority; integrate civil society and IDPs in post-war housing design processes
Transparent land allocation	Competitive concept-based bidding prioritising social, environmental, and affordability criteria	Introduce municipal-level concept competitions for cooperative housing plots, with criteria rewarding low-carbon design and social inclusion
Energy efficiency standards	Over 200 passive houses; first German multi-family passive house; bioclimatic design principles	Incorporate passive house or NZEB standards into cooperative housing legislation; incentivise with subsidies or tax benefits
Renewable energy integration	Solar Settlement and "Sun Ship" generating ~420,000 kWh/year; funded via ethical-ecological investment funds	Promote community-owned renewable energy projects; enable green bonds and cooperative investment funds for solar and heat-pump integration in housing
Sustainable mobility	Car-free district design; underground parking; car-sharing schemes; pedestrian- and cycling-friendly infrastructure	Prioritise pedestrian- and cycle-friendly layouts in new developments; integrate car-sharing hubs; limit on-street parking in cooperative housing projects
Social inclusion policies	Mixed-income residents, senior housing, and low-income inclusion; cooperative management of shared spaces	Ensure quota systems for vulnerable groups (IDPs, veterans, low-income households); support cooperative governance training for residents
Institutional support structures	Dedicated municipal units (Vauban Project Group, Local Authority Vauban Committee) coordinating cross-sector collaboration	Establish municipal or regional cooperative housing offices to provide technical, legal, and financial advisory support

Source: developed by the authors

CONCLUSIONS

This research demonstrated that implementing a Baugruppen (community-led) approach to affordable housing in Ukraine was both timely and feasible, particularly in the context of post-war recovery and long-term urban sustainability. The analysis confirmed, that while Ukraine once had a strong tradition of cooperative housing, subsequent Soviet centralisation and post-independence market liberalisation significantly weakened this tradition. Modern legislative reforms revealed an opportunity to revive cooperative practices and adapted them to modern sustainability-oriented priorities. Germany's experience showed that a robust legal framework, municipal support, and intermediary organisations were crucial for the success of Baugruppen projects. Mechanisms such as land allocation competitions, long-term leases, low-interest loans, and dedicated advisory structures provided a fertile ground for participatory and environmentally responsible housing development. The Vauban Sustainable Urban district illustrated how principles of resource efficiency, ecological construction, inclusive governance, and low-carbon mobility can be integrated into community-led housing.

For Ukraine, adapting these lessons required strengthening municipal authority, developing financial instruments for cooperative groups, and tailoring cooperative legislation to safeguard affordability, inclusiveness, and resilience. In parallel, the establishment of intermediary support bodies could consolidate expertise and provide technical guidance, bridging gaps between policy and practice. The Baugruppen model could simultaneously respond to Ukraine's urgent housing needs and set a direction for future urban development. Its principles combined affordability, ecological standards, and social inclusion, which were essential for building resilient communities after the war. Study provided a foundation for future research on the spatial morphology of community-led neighbourhoods, the integration of cooperative typologies within existing urban grids, and the impact of Baugruppen-based development on density, mobility, and environmental performance in reconstructed districts.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Act on Cooperative Societies. (2024, October). Retrieved from https://www.gesetze-im-internet.de/geng/.
[2] Antonenko, N. (2022). From research to participation: An attempt to reset the post-Soviet Southern cities of Ukraine. *Periodica Polytechnica Architecture*, 53(2), 104-112. doi: 10.3311/PPar.18944.
[3] ArchDaily. (2013). *R50 – cohousing/ ifau und Jesko Fezer + Heide & von Beckerath*. Retrieved from https://www.archdaily.com/593154/r50-nil-cohousing-ifau-und-jesko-fezer-heide-and-von-beckerath.
[4] Archer, T., & Harrington, C. (2021). *Delivering the community led housing pipeline in England*. Cambridge, Liverpool: UK Cohousing Network; Confederation of Co-operative Housing and Locality.
[5] Avramova, O., Slota, V., Kulinich, O., Fedorenko, T., & Myrza, S. (2023). State housing policy of Ukraine: Status and development perspectives. *Cuestiones Políticas*, 41(76), 46-63. doi: 10.46398/cuestpol.4176.02.
[6] Bartholomäi, R.C. (2004). The development of housing policy. In B. Egner, N. Georgakis, H. Heinelt & R.C. Bartholomäi (Eds.), *Housing policy in Germany: Positions. Actors. Instruments* (pp. 17-36). Darmstadt: Schader-Stiftung.
[7] Big City – Lab. (2025). *The concept of social housing in Ukraine*. Retrieved from https://bcl.com.ua/en/projects/koncepciya-socialnogo-zhitla-v-ukrayini.
[8] Blinova, M., & Rodyk, Ya. (2024). Analysis of the implementation of the Sustainable Urban Development Goal in Ukraine. *IOP Conference Series: Earth and Environmental Science*, 1376, article number 012040. doi: 10.1088/1755-1315/1376/1/012040.
[9] Bresson, S., & Denèfle, S. (2015). Diversity of self-managed co-housing initiatives in France. *Urban Research & Practice*, 8(1), 5-16. doi: 10.1080/17535069.2015.1011423.
[10] Building Code (BauGB). (1960, June). Retrieved from https://www.gesetze-im-internet.de/bbaug/BJNR003410960.html.
[11] Bureau 69 architects. (2023). *Nzeb and Passivhaus standards*. Retrieved from https://bureau69.com/nzeb-and-passivhaus-standards/.
[12] Coates, G.J. (2013). The sustainable urban district of Vauban in Freiburg, Germany. *International Journal of Design & Nature and Ecodynamics*, 8(4), 265-286. doi: 10.2495/DNE-V8-N4-265-286.
[13] Draft Law of Ukraine No. 4586-IX "On the Fundamental Principles of Housing Policy". (2025, September). Retrieved from https://itd.rada.gov.ua/billinfo/Bills/Card/55543.
[14] Fastenrath, S., & Braun, B. (2018). Sustainability transition pathways in the building sector: Energy-efficient building in Freiburg (Germany). *Applied Geography*, 90, 339-349. doi: 10.1016/j.apgeog.2016.09.004.
[15] Fedoriv, P., & Lomonosova, N. (2019). Housing policy in Ukraine: Current state and prospects for reform. *Cedos*. Retrieved from https://cedos.org.ua/wp-content/uploads/verstka.-zhitlo-i-vijna.-richnij-oglyad-eng.pdf.
[16] Haas, H. (2020). Paradigm shift in housing policy: On the position and development of the promotion of home ownership in the Federal Republic of Germany. In O. Depenheuer, E. Hertzsch & M. Voigtländer (Eds.), *Home ownership for broad sections of the population* (Vol. 18; pp. 35-49). Berlin, Heidelberg: Springer. doi: 10.1007/978-3-662-61287-3_3.
[17] Hamiduddin, I., & Gallent, N. (2016). Self-build communities: The rationale and experiences of group-build (Baugruppen) housing development in Germany. *Housing Studies*, 31(4), 365-383. doi: 10.1080/02673037.2015.1091920.
[18] Hansen Ukrainian Mission. (2025). *Hansen Village. Tarasivka, Kyiv region*. Retrieved from https://www.hum.giving/hansen-village.
[19] Himmelfarb, A. (Ed.). (2025). *Ukraine. Rapid damage and needs assessment (RDNA4). February 2022 – December 2024*. Washington, DC: World Bank Publications.
[20] Höller, K. (2024). Ukraine on the road to housing affordability: A consistent approach in difficult times. In *Economic commission for Europe, committee on urban development, housing and land management. 85th session*. Geneve: Economic Commission for Europe, Committee on Urban Development, Housing and Land Management.
[21] Hudima, T., Ustymenko, V., Soshnykov, A., & Oliukha, V. (2025). Housing reform and lawmaking in Ukraine: Between European standards and domestic challenges. *European Journal of Sustainable Development*, 14(2), 841-860. doi: 10.14207/ejsd.2025.v14n2p841.
[22] International Renaissance Foundation. (2025). *Housing crisis in Ukraine: How to provide IDPs with housing in 2025?* Retrieved from https://www.irf.ua/en/zhytlova-kryza-v-ukrayini-yak-zabezpechyty-vpo-zhytlom-u-2025-roczi/.
[23] Kopeć, M., Doudová, H., & Dušek, O. (2015). *BAUGRUPPE! Handbook*. (Translated by J. Šmrha). Prague: Prague Institute of Planning and Development.

[24] Krutko, D. (2025). Will the new social housing become “khrushchyovkas”? Oleh Drozdov on the challenges of architecture and the role of cities. *LIGA.net*. Retrieved from https://biz.liga.net/ua/all/all/interview/chy-stane-nove-sotsialne-zhytlo-khrushchovkamy-oleh-drozdov-pro-vyklyky-arkhitektury-ta-rol-mist.

[25] Lang, R., Carriou, C., & Czischke, D. (2020). Collaborative housing research (1990-2017): A systematic review and thematic analysis of the field. *Housing, Theory and Society*, 37(1), 10-39. doi: 10.1080/14036096.2018.1536077.

[26] Law of Ukraine No. 1087-IV “On Cooperation”. (2003, July). Retrieved from https://zakon.rada.gov.ua/laws/show/1087-15?lang=en#Text.

[27] Lloyd, M.G., Peel, D., & Janssen-Jansen, L.B. (2015). Self-build in the UK and Netherlands: Mainstreaming self-development to address housing shortages? *Urban, Planning and Transport Research*, 3(1), 19-31. doi: 10.1080/21650020.2014.987403.

[28] Metinvest. (2025). *My Home. Ukraine: Bila Tserkva launches housing construction for Mariupol IDPs under new government initiative*. Retrieved from https://metinvestholding.com/en/media/news/mj-dm-ukrana-u-blj-cerkv-zapuskayutj-budvnictvo-zhitla-dlya-pereselencv-z-marupolya-za-novoyu-uryadovo-ncativoyu.

[29] Mezentsev, K., Provotar, N., & Palchuk, M. (2020). Public spaces through the lens of participatory urban planning – the case of Kyiv. *Ukrainian Geographical Journal*, 2, 30-37. doi: 10.15407/ugz2020.02.030.

[30] Moore, T., & Mullins, D. (2013). Scaling-up or going viral? Comparing self-help housing and community land trust facilitation. *Voluntary Sector Review*, 4(3), 333-353. doi: 10.1332/204080513X671931.

[31] Pasyuta, D., Ludviková, D., Treffers, F., Korniyenko, G., Van Epp, T., & Zhang, J. (2023). *The public participation handbook of urban planning for Ukraine*. Kyiv: Ro3kvit Urban Coalition for Ukraine & Ukraine Rebuilding Action Group. doi: 10.36196/0726.2023.

[32] Pfatteicher, P.A.C., McCarthy, O., & Power, C. (2024). Housing co-operatives in Germany: 160 years of evolution and resilience. *Journal of Co-operative Studies*, 57(1), 39-53. doi: 10.61869/GCSP6342.

[33] Reimer, R., & Peters, A. (Eds.). (2025). *Guide to communal living plus*. Hannover: FORUM Gemeinschaftliches Wohnen e.V.

[34] Resolution of the Cabinet of Ministers of Ukraine No. 695 “On Approval of the State Strategy for Regional Development for 2021-2027”. (2020, August). Retrieved from https://zakon.rada.gov.ua/laws/show/695-2020-%D0%BF?lang=en#Text.

[35] Rolf Disch solar architektur. (n.d.). *The solar settlement*. https://www.rolfdisch.de/en/projects/the-solar-settlement/.

[36] Scheller, D. (2019). Hamburg: Housing movements and local government. In P. Hagbert, H.G. Larsen, H. Thörn & C. Wasshede (Eds.), *Contemporary co-housing in Europe: Towards sustainable cities?* (pp. 57-73). London: Routledge.

[37] Schwarz, S., & Sabatier-Schwarz, I. (2017). Self-organised urban space without profit: Four examples in Berlin. *plaNext – Next Generation Planning*, 5(1), 78-90. doi: 10.24306/plnxt.2017.05.006.

[38] Sharam, A. (2020). ‘Deliberative development’: Australia’s Baugruppen movement and the challenge of greater social inclusion. *Housing Studies*, 35(1), 107-122. doi: 10.1080/02673037.2019.1594712.

[39] State Fund for Support of Youth Housing Construction. (n.d.). Retrieved from https://www.molod-kredit.gov.ua/en/about-fund.

[40] Staub, A. (2025). Taking matters into their own hands: The Vauban Housing Community (1993-2003), Ekostaden Augustenborg (1998-2002), and Marmalade Lane Co-Housing (2006-2018). In A. Staub (Ed.), *Architecture and social sustainability* (pp. 180-196). London: Routledge. doi: 10.4324/9781003480426-12.

[41] Sustainable Development Goals. (n.d.). *Take action for the sustainable development goals*. Retrieved from https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

[42] Teremetskyi, V., Avramova, O., Maikut, Kh., Tserkovna, O., & Kramar, R. (2024). Current situation and transformation ways of housing policy in Ukraine. *Social & Legal Studios*, 7(1), 164-173. doi: 10.32518/sals1.2024.164.

[43] The Civil Code of Ukraine No. 435-IV. (2003, January). Retrieved from https://zakon.rada.gov.ua/laws/show/435-15?lang=en#Text.

[44] The Housing Code of Ukraine No. 5464-X. (1983, June). Retrieved from https://zakon.rada.gov.ua/laws/show/5464-10?lang=en#Text.

[45] UkrInform. (2024). *Updating the housing policy as a requirement of the Ukraine facility*. Retrieved from https://www.youtube.com/watch?v=3uEZh6DR1C4.

[46] United Nations Sustainable Development. (1992). Agenda 21. In *United Nations conference on environment & development*. Rio de Janerio: UN.

[47] Vlasenko, Ye. (2015). *The retreat of the state: Liberalisation of the housing market in Ukraine*. (Master’s thesis, Malmö University, Malmö, Sweden).

[48] Vlasenko, Ye. (2017). Housing privatisation in post-socialist countries: Reasons and preconditions. *Mistosite. Retrieved from* https://mistosite.org.ua/en/articles/housing-privatisation-in-post-socialist-countries-reasons-and-preconditions.

Марія Блінова

Доктор архітектури, професор
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Чорноглазівська, 17, м. Харків, Україна
https://orcid.org/0000-0003-0936-0494

Андрій Соловйов

Аспірант
Харківський національний університет міського господарства імені О. М. Бекетова
61002, вул. Чорноглазівська, 17, м. Харків, Україна
https://orcid.org/0009-0004-2289-8445

Постконфліктне житло в Україні: модель Baugruppen як каталізатор сталого відродження міст

Анотація. Метою дослідження було аналізувати можливості застосування моделі Baugruppen в Україні як інструменту для доступного житла та відновлення після війни, поєднуючи правові, інституційні та просторові виміри. Порівняльний аналіз правового та політичного контексту між двома країнами виявив прогалини в регуляторному середовищі України, такі як недостатнє повноваження місцевих органів влади, відсутність фінансових стимулів та відсутність посередницьких організацій. У цьому дослідженні розглянуто потенційне застосування моделі Baugruppen (розвиток, ініційований громадою) для вирішення сучасних проблем житлового будівництва в Україні. У статті досліджено історичний розвиток кооперативного житла в Німеччині та Україні, зокрема, як підтримуючі правові рамки та інституційні механізми Німеччини сприяли розвитку ініціатив Baugruppen. Використовуючи район Ваубан у Фрайбурзі (Німеччина) як приклад, дослідження продемонструвало, як участь у проєктуванні, екологічні принципи та спільне управління сприяли успіху проєктів Baugruppen. Результати підкреслили необхідність реформування житлової політики України, враховуючи уроки з моделі Baugruppen Німеччини, та зазначили можливості для співпраці між муніципалітетами, місцевими громадами та міжнародними партнерами для створення умов для реалізації таких проєктів. Було визначено, що ці зміни мають охоплювати переорієнтацію політики розподілу земель, впровадження механізмів конкурсного відбору на основі концепцій та створення нових рамок розвитку, в яких кінцеві користувачі братимуть активну участь у прийнятті рішень і матимуть значно більший вплив на результати проєктів. Якщо такі інституційні прогалини будуть усунені, модель може допомогти Україні відновити зруйноване житло, забезпечити житлом переміщених осіб та підтримати сталий розвиток міст у рамках національних та міжнародних реформ

Ключові слова: сталий розвиток міст; доступне житло; будівельна кооперація; відновлення після конфлікту; участь у проєктуванні

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 624.073.52
DOI: 10.56318/as/1.2026.29

ISSN: 2411-801X
e-ISSN: 2786-7374

Vasyl Petriv*
Postgraduate Student
Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies Lviv
79010, 50 Pekarska Str., Lviv, Ukraine
https://orcid.org/0009-0009-3297-1171

Load-bearing capacity and deformability of steel-concrete floors on profiled steel decking

Abstract. This article aimed to provide a regulatory and analytical justification of the effect of the degree of shear interaction on compliance with the requirements of the first and second groups of limit states for composite floors with profiled decking. The research was carried out on the basis of a regulatory and analytical approach and was implemented with the application of the current Ukrainian normative documents and codified calculation models of steel-concrete floors as composite flexural members. In the calculation models adopted, either full or partial compatibility of the strains of steel and concrete elements' deformations was adopted. The results showed that the load-bearing capacity and deformability of floors were interdependent properties formed within the framework of a unified stiffness-force mechanism of composite cross-section behaviour. It has been established that the degree of shear interaction between the steel deck and the concrete slab was an integrating parameter that simultaneously controlled the achieved design bending resistance and the effective stiffness of the floor system. With full shear interaction, the maximum realisation of the transformed geometrical and stiffness characteristics of the cross-section was achieved, which allowed fulfilling both groups of limit states simultaneously. In the case of partial composite action, a coordinated reduction in design resistance and an increase in deflections were observed, with deformability indicators showing greater sensitivity to reductions in effective stiffness than load-bearing capacity indicators. It was shown that, under identical service loads, deflections may reach permissible limit values earlier than limiting stresses were attained, thereby defining serviceability as the governing constraint in design decisions. The practical significance of the obtained results lies in the possibility of their application by design and expert organisations in the practice of regulatory assessment and design of steel-concrete floors with profiled decking

Keywords: composite action; shear interaction; serviceability; effective stiffness; deflections; limit states

INTRODUCTION

In modern building structures design practice, steel-concrete floors reinforced with a profiled steel decking were widely used. This was due to the features of their structural scheme, a rational balance between material consumption and the load-bearing capacity, as well as the ability to cover large spans with a given self-weight. Such floors were used both in civil and industrial construction as load-bearing and enclosing structural elements, and as participants in the spatial work of buildings. Within the current regulatory framework, a key task was the assessment of the load-bearing capacity and deformability of composite floors with appropriate consideration of the composite action of the steel and concrete components, as the nature of this interaction governs the formation of the stress-strain state of the element. In the study by Y. Dmytrenko (2021), it was shown that code-consistent modelling of shear interaction between steel elements and the reinforced concrete slab had a direct effect on the determination of the

Suggested Citation:
Petriv, V. (2026). Load-bearing capacity and deformability of steel-concrete floors on profiled steel decking. *Architectural Studies*, 12(1), 29-41. doi: 10.56318/as/1.2026.29.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 29-41
Received: 03.10.2025 Revised: 09.01.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

effective geometric properties of the composite cross-section and the accuracy of its load-bearing capacity assessment. Even in the framework of linear elastic calculation models, the results were dependent on the accepted hypothesis about the level of composite action. The comprehensive approach to taking into account the stage-by-stage nature of structures' behaviour was realised in the study by M. Savytskyi *et al*. (2021), which stated that the stress-strain state of the steel-reinforced concrete floors changed essentially depending on the construction stage. This finding substantiated the need for a normative distinction between design situations and for separate verifications with respect to limit states. The study also demonstrated the transition from the behaviour of steel elements acting without participation of the concrete slab to the formation of full composite action, accompanied by changes in the distribution of internal forces and deflections. In the study by A. Hasenko *et al*. (2022), the influence of effective geometric parameters of the composite cross-section on the load-bearing capacity of floors was analysed. It was shown that a reduction in the effective width of the concrete slab or a decrease in the efficiency of shear interaction was accompanied by a reduction in the flexural strength of steel-reinforced concrete systems. Within that study, the relationship between the parameters of the composite cross-section, load-bearing capacity, and deformability of floors was examined. The study by L. Storozhenko & G. Gasii (2020) systematised design aspects of the calculation of steel-concrete floors, with particular emphasised on the consideration of deflections, crack resistance, and the composite action of materials within the national regulatory framework. It was shown that rational use of composite elements enabled a reduction in material consumption, provided that checks for the first and second groups of limit states were performed correctly.

In the research by M. Hernich *et al*. (2021), steel-reinforced concrete structural systems were treated as a single composite cross-section, for which the stress-strain state and deformability were analysed with due regard to the mechanical properties of the materials and the conditions of shear interaction. Using the example of bridge superstructures, it was substantiated that such a composite scheme provided increased stiffness and load-bearing capacity, while simultaneously reducing mass, which was of particular importance for tasks related to the restoration of transport infrastructure. A publication by M. Saccone *et al*. (2025) summarised the results of experimental and theoretical investigations of composite floors, which indicated the influence of longitudinal shear behaviour on the formation of the ultimate load-bearing capacity and the serviceability deformation capacity for various concretes. It was noted that the characteristics of the "deck-slab" interaction affect the actual parameters of the composite action and the values of the calculated deflections. Similar results were obtained in the study by P. Ravichandran & S. Harini (2024), where it was shown that the design span, the geometrical parameters of the profiled deck and the thickness of the concrete layer affected the stiffness of the composite cross-section, due to the influence on the effective moment of inertia and the values of deflections. This fact necessitated their normatively consistent accounting in the design evaluation of the deformability of steel-concrete floors. In the study by L.G.F. Grossi *et al*. (2020), the behaviour of composite slabs with profiled steel decking was analysed through the mechanism of longitudinal shear at the "deck-concrete" interface as a factor determining the degree of composite action and the governing type of limit state. Experimental comparison of specimens with different shear span lengths and additional reinforcement showed that the introduction of reinforcing bars increased the realised shear load-bearing capacity and shifts slab behaviour towards a more stable and deformable response compared with unreinforced solutions. The results obtained were interpreted in terms of evaluating longitudinal shear strength as a parameter that determined the degree of involvement of the steel component in the work and the limits of applicability of structural solutions for composite floors. In the research by B.A. Izzuddin & J. Sio (2021), the floor was recognised as the main element of frame structures that provided force redistribution and structural integrity under accidental actions. The authors argued that the deformative properties of floors should be taken into account, when analysing robustness, since horizontal tie forces, which were decisive for excluding the progressive collapse of structures, were transmitted precisely through the floor slabs.

Despite the presence of scientific and applied research in the scientific and technical literature, there were various approaches to the theoretical evaluation of the load-bearing capacity and deformability of steel-concrete floors with profiled steel decking, which have not been systematised in the form of a single normatively consistent design calculation scheme. The publications differed in the methods for consistently taking into account the effect of partial shear interaction, determining the actual geometrical parameters of the composite cross-section, as well as combining the verification of the first and second groups of limit states without using empirical coefficients. In addition, there were differences in understanding the content of the relationship between the loadbearing capacity and the serviceability-related deformability in the current normative documents. This study aimed to perform a theoretical estimation of the load-bearing capacity and deformability of the steel-concrete floors reinforced with profiled steel decking, taking into account the interrelated requirements of the first and second groups of limit states and the composite action of the steel and concrete elements. To achieve the stated aim, the study performed a regulatory and analytical estimation of the load-bearing capacity of the steel-concrete floors reinforced with profiled steel decking according to the first group of limit states, taking into account the geometric parameters of the composite cross-section and the conditions of shear interaction. The influence of the degree of shear interaction between the steel and concrete on the composite action of the floor system and the effective stiffness characteristics of the cross-section was analysed. A theoretical estimation of the floor deformability according to the second group of limit states was also carried out, and an integrated normative interpretation of the relationship between the load-bearing capacity and serviceability was provided.

MATERIALS AND METHODS

The study was performed as a regulatory and analytical investigation, focused on a reproducible interpretation of design verifications for the steel-concrete floors reinforced with profiled steel decking within the framework of the limit state method. The source base consisted of current regulatory and regulatory-technical documents of Ukraine, which were applied in accordance with their functional purpose for the specification of loads and load combinations, verification of the steel and concrete components, consideration of composite action, and serviceability criteria. The permanent and variable loads, as well as the design load combinations, were established in accordance with SCN No. V.1.2-2:2006 (2006). Requirements for the steel elements of the floor system, in particular for the profiled decking as the steel component of the composite cross-section, were applied in accordance with SCN No. V.2.6-198:2014 (2022). The design properties of concrete and the principles for assessing the resistance of concrete and reinforced concrete elements were adopted in accordance with SCN No. V.2.6-98:2009 (2009). Checks for the first and second groups of limit states, including criteria for load-bearing capacity and serviceability, were interpreted in accordance with SCN No. V.1.2-6:2021 (2022). The consideration of the composite action of the steel and concrete was implemented through the code-defined concept of the degree of shear interaction between the profiled decking and the concrete slab. The general principles for the analysis and design of steel-reinforced concrete elements, together with terminological approaches, were adopted in accordance with SCN No. V.2.6-160:2010 (2010). Provisions relating to the parameters of composite action, effective geometric and stiffness characteristics of the composite cross-section, and conditions of partial shear interaction were taken from the DSTU No. B V.2.6-215:2016 (2016).

The methodology was based on a sequential analysis, harmonisation, and systematisation of regulatory requirements, followed by the structured presentation of conclusions for the first group of limit states (ultimate limit state, ULS) and the second group of limit states (serviceability limit state, SLS). At the first stage, requirements for the specification of loads and load combinations were organised, and ULS criteria were generalised in the form of a normative condition ensuring loadbearing capacity, while SLS criteria were formulated in terms of deformation (deflection) limits as a component of serviceability. At the second stage, provisions concerning the composite action of steel and concrete were systematised, with explicit distinction between conditions of full and partial shear interaction as prerequisites determining the effective characteristics of the composite cross-section applied in ULS/SLS verifications. At the third stage, the factors influencing compliance with the requirements of the first group of limit states were presented in a reproducible format of "parameter – normative condition – engineering interpretation of influence". Within this framework, the following parameters were identified: concrete slab thickness, geometry of the profiled decking, degree of shear interaction, composite action scheme, and level of design loading. The synthesis of the results was formulated as a normatively consistent theoretical interpretation of the relationship between load-bearing capacity and deformability, considered as interrelated characteristics of the behaviour of steel-concrete floors within building load-bearing systems.

RESULTS

Load-bearing capacity of steel-concrete floors according to the first group of limit states

Analysis of the results of the regulatory and analytical assessment of the load-bearing capacity of steel-concrete floors according to the first group of limit states showed that fulfilment of the condition $M_{Ed} \leqslant M_{Rd}$, derived from the normative criterion for ensuring load-bearing capacity under the first group of limit states in accordance with SCN No. V.1.2-6:2021 (2022) is governed by a set of interrelated structural and regulatory factors. This list included: the design values and combinations of external loads; geometrical parameters of the composite cross-section (the thickness of the concrete slab, the geometrical parameters of the profiled decking, and the position of the neutral axis); design parameters of the steel and concrete; conditions for the implementation of the composite action, which was the degree of shear interaction between the profiled decking and the concrete slab. All these factors together determined the relation between the design effect and the design resistance of the cross-section. In the framework of the existing normative approach, the load-bearing capacity of the floor was considered not as the sum of the resistances of the individual components of the structure, but as an integral property of the steel-concrete cross-section, formed according to the principles of the composite action. The rational choice of the above parameters made it possible to use the profiled steel decking not only as permanent formwork, but also to involve it in the process of resisting bending loads, which increased the effective resistance of the cross-section and reduces the level of stresses in the concrete component. Such behaviour of the floor corresponded to the normative concept of steel-concrete systems as single composite elements (according to SCN No. V.2.6-160:2010, 2010), in which the distribution of internal forces between the interacting materials was determined not by their nominal properties, but by their composite action in the composite cross-section. It was in these conditions that the fulfilment of the requirements of the first group of limit states was ensured, without artificially increasing the cross-sections or introducing additional structural reserves.

The results showed that the normatively admissible level of resistance of the composite crosssection was formed depending on the geometrical parameters of the floor system, in particular, the relation between the height of the profiled steel decking and the thickness of the concrete layer, and the position of the neutral axis in the flexural cross-section. In particular, the reduction of the thickness of the concrete slab or the efficiency of shear interaction between the steel decking and the concrete led to a decrease in the design resistance of the composite cross-section, which was observed in the results of verification of the conditions of the first group of limit states. Within the requirements of the SCN No. V.1.2-6:2021 (2022), it manifested itself in a decrease in the design resistance M_{Rd} and, consequently, in a narrowing of the range of permissible design solutions, even in the case of meeting the standard values of loads and impacts specified in SCN No. V.1.2-2:2006 (2006). Under these conditions, the reserve of the load-bearing capacity of the floor was limited, and full composite action was not realised, which indicated the fundamental importance of the structural compatibility of the floor components within the normative calculation model. The formation of the load-bearing capacity of steel-concrete floors was directly related to the conditions of shear interaction between the profiled steel decking and the concrete slab. In accordance with the provisions of SCN No. V.2.6-160:2010 (2010) and DSTU No. B V.2.6-215:2016 (2016), the level of shear interaction was used to classify the modes of behaviour of the steel-concrete cross-section with full or partial compatibility of deformations. A decrease in the efficiency of shear interaction led to a redistribution of the internal forces in the cross-section, an increase in the share of the bending stresses perceived by the concrete component and a decrease in the reduced design resistance of the steel part. In a normative sense, this was manifested in a decrease in M_{Rd} and, as a consequence, a further narrowing of the range of admissible design solutions within the first group of limit states. In order to systematise the effect of the main parameters on fulfilment of the criteria for the first group of limit states, the normative dependencies were systematised in the form "parameter – normative condition – and effect" (Table 1).

Table 1. Systematisation of normative parameters influencing fulfilment of the $M_{Ed} \leqslant M_{Rd}$ criterion for the first group of limit states in steel-concrete floors

Structural parameter	Normative condition (document)	Normative interpretation of influence on M_{Rd}	Conclusion for compliance with $M_{Ed} \leqslant M_{Rd}$
Concrete slab thickness	Normative requirements for the behaviour of concrete and reinforced concrete	Increasing thickness enhances the potential for the formation of the compressed zone and the integral resistance of the composite cross-section	With rational parameter ratios, the risk of M_{Ed} approaching M_{Rd} is reduced
Profiled decking geometry	Requirements for steel elements and profiles	Determines the structural capacity and effectiveness of engaging the steel component in bending	With geometrically compatible design, the range of permissible solutions is expanded; with incompatible geometry, it is limited
Degree of shear interaction	Conditions for considering full/ partial interaction	Reduced interaction lowers the effective resistance of the composite cross-section and increases sensitivity to parameter variations	Partial interaction increases the likelihood of the criterion reaching its limit
Composite action scheme	Principles of composite action	Establishes the normative framework for the integral cross-section resistance as a result of the composite action of steel and concrete	When composite principles are observed, the criterion is formulated within the integral resistance model
Level of design load	Standardisation and load combinations	Increasing M_{Ed} raises the requirements for the integral cross-section resistance	Compliance with the criterion depends on the margin of M_{Rd} relative to M_{Ed}

Note: M_{Ed} – design bending moment from normative load combinations; M_{Rd} – design resistance (load-bearing capacity) of the composite cross-section in bending; criterion $M_{Ed} \leqslant M_{Rd}$ – fulfilment of the load-bearing capacity requirement according to the first group of limit states (ULS)

Source: SCN No. V.1.2-2:2006 (2006), SCN No. V.2.698:2009 (2009), SCN No. V.2.6-160:2010 (2010), DSTU No. B V.2.6-215:2016 (2016), SCN No. V.2.6-198:2014 (2022)

As followed from Table 1, the systematisation in the form "parameter – normative condition – effect" indicated that the fulfilment of the criterion $M_{Ed} \leqslant M_{Rd}$ for the first group of limit states was determined not by the individual effect of one or another parameter, but by the normatively determined interconnection of the geometric parameters of the cross-section and the conditions for implementation of the composite action in accordance with SCN No. V.1.2-6:2021 (2022). In this aspect, the thickness of the concrete slab was related to the possibility of the formation of the compressed area and the level of involvement of the concrete component in the total resistance of the composite cross-section. An increase in the slab thickness at structurally justified ratios of the parameters was normatively perceived as an increase in M_{Rd}. The geometry of the profiled decking influenced the structural capacity and the level of involvement of the steel component in the resistance to bending moments in the composite system: at a geometrically coordinated arrangement, it was normatively perceived as an increase in the calculated resistance of the cross-section, and at a geometrically uncoordinated arrangement, it was perceived as a restriction of the composite efficiency and a reduction of the permissible design range. The degree of shear interaction was a system-forming factor that determined the mode of operation of the cross-section (full or partial) and, accordingly, adjusts the normative ideas about the compatibility of deformations and the distribution of internal forces. A decrease in the level of shear interaction was normatively perceived as a reduction in the effective resistance of the composite cross-section and an increase in the sensitivity of the verification of the first group of limit states, in accordance with DSTU No. B V.2.6-215:2016 (2016). The composite action scheme was used to understand the resistance of the cross-section as an integrated property, while the design load value (determined in accordance with the standard combinations of actions) was the upper boundary of requirements for this integrated property. Therefore, the loadbearing capacity of the steel-concrete floor in the existing standard model was understood as a result of the design action coordination, geometric model of the composite cross-section and conditions for the implementation of the composite action as a result of shear interaction between the steel and concrete.

Influence of the degree of shear interaction on composite action of the floor

The degree of shear interaction between the profiled steel decking and the concrete slab determined the type of composite action of the steel-concrete floor and influences the implementation of transformed geometric and stiffness characteristics of the cross-section. In the existing standard model, this factor was used as an engineering indicator of the strain compatibility of the steel and concrete in the composite cross-section. The general provisions for the composite action and the requirement for ensuring strain compatibility of deformations were given in the SCN No. V.2.6-160:2010 (2010). When there was full shear interaction, the steel-concrete cross-section was calculated as a single composite section, with full implementation of the transformed geometric and stiffness parameters. In this condition, the internal forces between the steel and concrete were shared within the coordinated calculation scheme without reduction of the transformed parameters. The calculation parameters of the composite crosssection and the rules for accounting for the shear interaction were determined in accordance with the DSTU No. B V.2.6-215:2016 (2016), which formalised the contribution of steel and concrete to the resistance to bending moments and shear forces within the standard model. In the case of partial shear interaction, the design values of the effective geometric characteristics of the composite cross-section were decreased, which was normatively accounted for through adjustment of the transformed geometric parameters and design resistance. In this case, in the calculation formulas, the incomplete deformation compatibility between the steel and concrete was taken into account, which imposed restrictions on the maximum allowable internal forces in the cross-section, when verified for the first group of limit states, in accordance with the SCN No. V.1.2-6:2021 (2022). Reduction of the degree of shear interaction was also accompanied by a decrease in the effective flexural stiffness of the steel-concrete element, which was manifested in an increase in the calculated values of deflections and an increase in the sensitivity of the verification results for the second group of limit states, in accordance with SCN No. V.1.2-6:2021 (2022). Therefore, the degree of shear interaction was an integral parameter that simultaneously affected the evaluation of both the load-bearing capacity and the serviceability of the steel-concrete floor in a unified normative calculation model. To clarify, the diagram of the composite action of the floor and the role of shear interaction between the steel decking and the concrete slab were presented in Figure 1. Analysis of the diagram showed that the transition from full to partial shear interaction between the profiled steel decking and the concrete slab was accompanied not only by a decrease in the realised level of the effective geometric and stiffness characteristics of the composite cross-section, but also by a qualitative change in the mechanism of its operation. In the case of full shear interaction, a steel-concrete cross-section works as a single beam with full compatibility of deformations, at the same time it realised the maximum possible transformed moment of inertia and the design moment resistance of the cross-section. Internal forces were redistributed between the steel and concrete parts of the section in accordance with their transformed stiffness characteristics, and the stress state of materials developed within the normatively acceptable limits without local overstrain. In the case of partial shear interaction between the components of the floor, there were longitudinal displacements, which disturbed the full compatibility of deformations and led to the redistribution of the bending moments. Within the framework of the normative model, the effective moment of inertia of the composite cross-section decreased, the transformed stiffness of the section was reduced, and the proportion of forces perceived by the concrete part of the section increases in comparison with the full interaction. According to the norm, this entailed a reduction in the realised moment resistance of the cross-section and an increase in its sensitivity to changes in the design parameters, primarily to the geometric parameters of the profiled decking and the characteristics of the shear connectors. In this connection, the degree of shear interaction was a determining factor that simultaneously influenced both the realisation of the load-bearing capacity of a steel-concrete floor and its deformability, which created conditions that may limit the fulfilment of the first and second groups of limit states within the current normative calculation model.

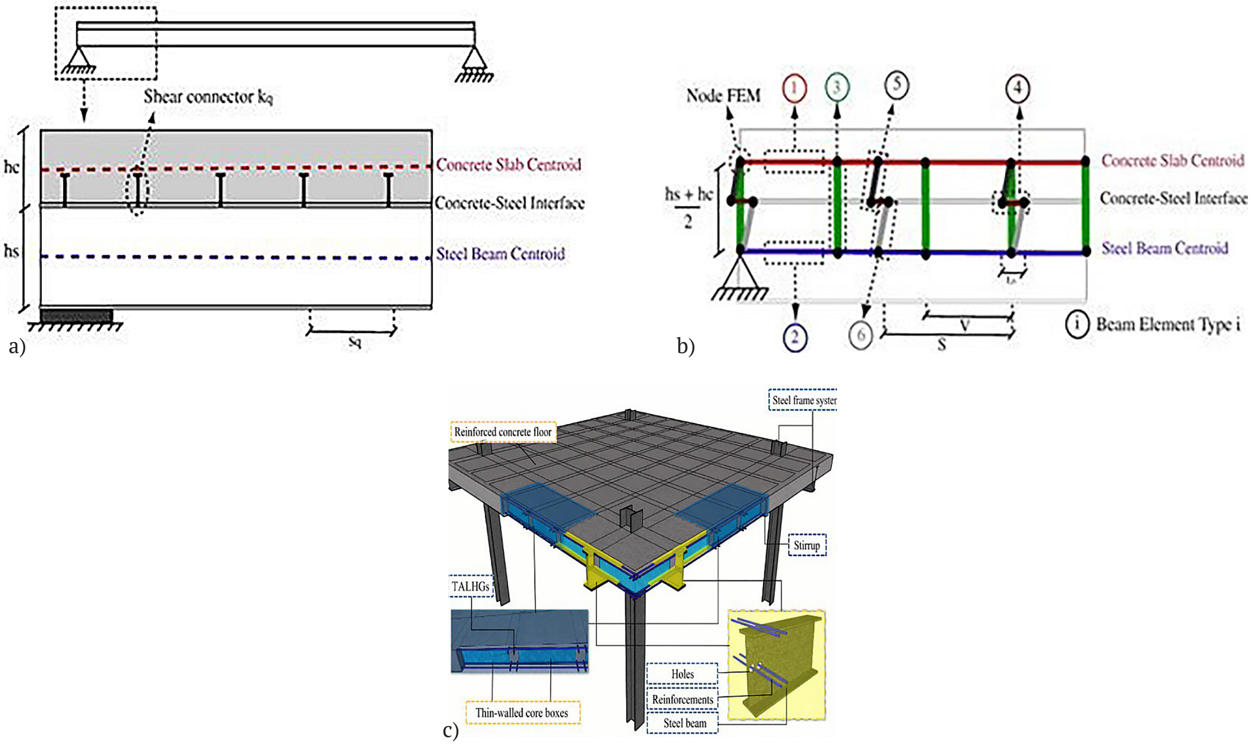


Figure 1. Schematic representation of the composite action of a steel-concrete floor, considering shear interaction between the profiled steel decking and the concrete slab

Note: a – design scheme of the steel-concrete floor showing the geometric configuration of the cross-section and the positions of the centroids of the steel and concrete components; b – generalised normative model of the composite element illustrating the mechanism of shear transfer between the profiled steel decking and the concrete slab; c – structural representation of the steel-concrete floor within the building's load-bearing system. Symbols: hs – height of the steel component of the composite cross-section; hc – thickness of the concrete slab; S – design spacing of shear connectors; V – design transverse force; k_q – shear connection stiffness; FEM – finite element numerical model; TALHGs – thin-walled steel elements/profiles participating in the composite action of the floor

Source: SCN No. V.2.6-160:2010 (2010), DSTU No. B V.2.6-215:2016 (2016)

Deformability of steel-concrete floors under the second group of limit states

The calculation under the second group of limit states was a mandatory part of a comprehensive normative estimation of the floor's performance and was carried out together with the calculation of the load-bearing capacity within a single calculation model. In the existing calculation model, the requirements for deformability were not secondary or derived; they were formalised as an independent calculation criterion, the provision of which was necessary for ensuring the serviceability of steel-concrete structures throughout their entire design life. In accordance with the requirements of the SCN No. V.1.2-6:2021 (2022), the deformability of the floors was classified as a serviceability criterion. For which the normative verification in the framework of the limit state method was obligatory. In the framework of the normative model, the design values of the steel-concrete floor deformability are determined by the effective stiffness of the composite cross-section. This, in turn, depended on the degree of participation of the profiled steel decking and the concrete slab in the composite action. The effective stiffness was determined using the transformed geometric characteristics of the cross-section and the conditions of shear interaction between its components. At full shear interaction, the effective stiffness of the cross-section was determined based on the full participation of both the steel and concrete components in resisting the bending deformations. As a result, the steel-concrete floor works as a single bending element with a high efficiency of stiffness, and the design deflections do not exceed the normative limits. In the context of the normative assessment, the results of the first and second groups of limit states were interpreted based on the comparison of the design bending moment and floor deflections. This provided a comprehensive analysis of the effect of the degree of shear interaction on both the load-bearing capacity and deformability of the composite cross-section. At the same service loads, a decrease in the effectiveness of the composite action results in an increase in the design deflections of the floor compared to the case of full material compatibility. At partial shear interaction, the increase in the deflections occurred systematically and was caused by the reduced contribution of the steel component to the resistance of bending deformations within the composite cross-section. In this case, the design deflections can attain the maximum permissible values according to the SCN No. V.1.2-6:2021 (2022). This was irrespective of the satisfaction of the requirements of the first group of limit states for the load-bearing capacity, which necessitates a separate normative verification of deformability. To standardise the effect of the degree of shear interaction on the deformability of steel-concrete floors and the satisfaction of the second group of limit states, the characteristic regulatory dependencies were systematised in Table 2.

Table 2. Effect of the degree of shear interaction on the deformability of steel-concrete floors according to regulatory documents

Performance characteristic	Full shear interaction	Partial shear interaction	Normative reference
Compatibility of deformations	Complete along the entire span	Disrupted, with relative slips present	SCN No. V.2.6-160:2010 (2010)
Effective cross-section stiffness	Fully realised	Reduced	DSTU No. B V.2.6-215:2016 (2016)
Transformed moment of inertia	Close to full composite	Reduced	Normative consideration of partial interaction
Deflection level	Minimal	Increased	SCN No. V.1.2-6:2021 (2022)
Fulfilment of SLS requirements	Ensured with a margin	May reach limit	Restriction of design solutions

Note: SLS – compliance with normative requirements for serviceability criteria, including deflection/deformation limits ($w_{max} \leqslant w_{lim}$)

Source: developed by the author

From the analysis of the data in Table 2, it followed that in the regulatory calculations, the deformational behaviour of a steel-concrete floor was directly dependent on the degree of realised shear interaction between the profiled steel decking and the concrete slab. With full shear interaction, the strains of the deformations of the cross-section were compatible along the entire span, which made it possible to model the steel-concrete floor in the form of a single composite bending element with a maximally realised effective stiffness and a transformed moment of inertia, which was close to the moment of inertia of a fully composite cross-section. With partial shear interaction, the compatibility of deformations of the strains of the steel and concrete was violated, and relative displacements in the contact zone occur. In regulatory calculations, this was taken into account by reducing the effective stiffness of the composite cross-section and decreasing the transformed moment of inertia in accordance with the DSTU No. B V.2.6-215:2016 (2016). This led to an increase in the calculated deflections and increases the sensitivity of the results of checks for the second group of limit states to the adopted assumptions about the degree of composite action. With only partial realisation of the shear interaction, the fulfilment of the serviceability requirements can be close to a limiting one, which normatively narrowed the scope of possible design solutions. The obtained results confirmed the existence of a regulatory relationship between deformability and load-bearing capacity of steel-concrete floors. A decrease in the effective stiffness of a composite cross-section in the case of partial shear interaction simultaneously affected the verification according to both the first and second groups of limit states, which was reflected in different calculated parameters, such as a decrease in the design resistance of the cross-section and an increase in the deflections. In this case, the fulfilment of the load-bearing capacity requirements without ensuring a normatively acceptable level of deformability does not give a complete idea of the behaviour of a steel-concrete floor.

Integrated analysis of the relationship between load-bearing capacity and deformability of steel-concrete floors

A combined analysis of the regulatory and analytical evaluation of a steel-concrete floor according to both the first and second groups of the limit states showed that, within the framework of the current Ukrainian normative calculation procedure, the load-bearing capacity and deformability were related characteristics of a composite cross-section, SCN No. V.1.2-6:2021 (2022). In this approach, these parameters were not considered separately, but rather defined as a part of the stiffness-force combined mechanism of the steel-concrete floor, as the requirements of first and second limit state groups were interdependent parts of the normative assessment of the structure. The degree of shear interaction between the profiled steel decking and the concrete slab was common for determining the design resistance and transformed stiffness properties of the composite cross-section. A change of this parameter was always accompanied by a corresponding change of the design bending resistance and effective stiffness of the steel-concrete element, which in turn had a direct influence on the design deflections and the nature of the deformational behaviour of the floor in service conditions. When there was full shear interaction, the steel-concrete cross-section was calculated as a single bending element, with full implementation of the transformed geometric and stiffness parameters. In this case, the internal forces were distributed between the steel and concrete components in proportion to their transformed stiffnesses; the deformations of the components remained compatible along the span; and the design deflections remained within the limits established for the second group of limit states. A partial realisation of the shear interaction reduced the efficiency of the composite action of the cross-section, which was taken into account normatively by changing its transformed stiffness characteristics. From a structural point of view, this reduction manifested itself as a decrease in the realised design resistance of the cross-section. From a stiffness point of view, this reduction led to an increase in the design deflections under the same service loads. These changes had a direct effect on the results of the second group of the limit state checks. An asymmetric sensitivity of the first and second groups of limit state criteria to a reduction of the degree of shear interaction was observed: in the case of partial composite action, the fulfilment of the load-bearing capacity requirements can still be ensured, while the design deflections more rapidly approach their maximum allowable values adopted by normative standards. In these cases, it was the results of the serviceability checks that dictated the admissibility of design and construction solutions in the regulatory framework. The integrated view of the normative dependence between the load-bearing capacity and deformability was given in Figure 2.

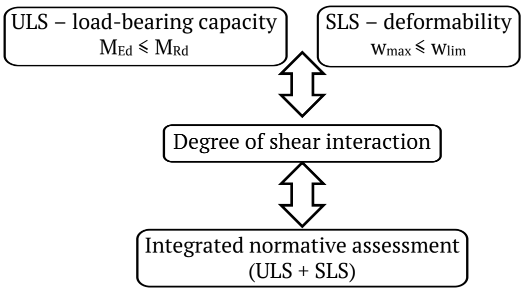


Figure 2. Integrated scheme of the normative interaction between load-bearing capacity and deformability indicators of a steel-concrete floor
Source: SCN No. V.2.6-160:2010 (2010), DSTU No. B V.2.6-215:2016 (2016), SCN No. V.1.2-6:2021 (2022)

From the scheme, it was seen that the degree of shear interaction between the profiled steel decking and the concrete slab acts as an integrating parameter that simultaneously controlled the strength and stiffness parameters of the composite cross-section of the steel-concrete floor. It directly affected the design deflections of the floor from the service loads due to changes in the effective stiffness of the cross-section, and through changes in the transformed geometric characteristics, it affected the achieved design bending resistance and load-bearing capacity of the element. A decrease in the effectiveness of the composite action causes coordinated changes in the indicators of both the first and second groups of limit states, without their individual manifestation, which reflected the integration of the normative constraints on the floor in a single design model. With partial composite action, the fulfilment of the load-bearing capacity requirements can be preserved due to the availability of some constructive reserve of the cross-section, while the design deflections more quickly approached their maximum allowable standard values, even at a slight decrease in the effective stiffness. In this case, the second group of limit state requirements determined the acceptability of design solutions in the normative model and actually limits the further application of individual structural solutions. Summarising, it can be argued that the load-bearing capacity and deformability of steel-concrete floors developed as interrelated characteristics of the composite cross-section in a unified normative evaluation system. In this system, the degree of shear interaction provided for the simultaneous fulfilment of the first and second groups of limit state requirements, ensured the consistency of the strength and deformation parameters, and limited the field of admissible design solutions in terms of the safety and serviceability of the floors.

DISCUSSION

The regulatory and analytical assessment of the load-bearing capacity and deformability of steel-concrete floors with profiled decking presented in this research demonstrated the key importance of the degree of shear interaction for the adopted normative model of the behaviour of composite cross-sections. It has been shown that the efficiency of the transfer of longitudinal shear forces between the steel decking and the concrete slab was directly related to the strength and stiffness characteristics of the floor, since the contact interaction defined the deformation compatibility of the components and, therefore, the redistribution of the internal forces in the composite cross-section. In this sense, the composite cross-section was understood as an integral system, in which the contact interaction of the components determined the realised transformed section characteristics, the position of the neutral axis and the proportion of the contribution of each component to the resistance to bending. This understanding was in agreement with the survey conclusions presented in K. Mohammed *et al*. (2017), in which steel-concrete floors were understood as a structural system, which was primarily sensitive to the actual composite action, rather than to the physico-mechanical characteristics of the individual component materials taken separately. This agreement followed from a common understanding of composite action as a stiffness-force mechanism, within which local contact effects cumulatively determined the integral performance characteristics of the floor. From the point of view of the serviceability of structures, this conclusion can be further refined as a result of long-term effects occurring in the concrete component, in particular, the specific influence of drying and shrinkage of composite slabs with profiled decking.

The mechanism of reduced efficiency of composite action and its influence on the realised resistance of the composite element was in agreement with the conclusions presented in study by N.A. Hedaoo *et al*. (2012), in which it was demonstrated by experimental and analytical comparison that a decrease in the efficiency of bonding or interaction between the components of the composite cross-section led to incomplete utilisation of the steel component, when resisting bending forces. From the design point of view, the latter effect results in a change in the effective degree of compositeness represented by the value of the design bending resistance M_{Rd} and the shift in the neutral axis of the section in the current model. The convergence of the two approaches can be explained by the same root cause: a reduction in the degree of shear connection changes the deformation compatibility of the component layers, the position of the neutral axis and the internal force distribution between the concrete and steel elements and, as a result, changes the effective strength and stiffness properties of the system. Concerning serviceability, it was crucial to keep in mind that the deformation capacity of a composite floor was not only affected by the current properties of the component materials but also dependent on time and environmental conditions. This was in line with the results by Y. Wei *et al*. (2020), who showed that the relative humidity affects the creep of concrete and, thus, the time-dependent accumulation of deformation. In the framework of SLS, this meant that for the same geometrical and loading conditions, a change in the environmental conditions results in a change in the evolution of deflection and, consequently, in the effective stiffness during the service life for the same loading conditions.

The sensitivity of deformation parameters and transformed cross-section properties to the degree of partial composite action was also in agreement with the experimental results by A. Siva *et al*. (2016), who pointed out that, when the slab was partially composite, a change in the deformation behaviour of the slab was observed before the ultimate limit state was reached, i.e., before the deformative signs of insufficient compositeness in terms of strength. In the design framework adopted herein, the latter was reflected by the fact that a reduction in the degree of shear interaction results in a reduction of the effective stiffness of the composite cross-section and, hence, in an increased rate of deflection in comparison to the change in the remaining strength capacity. The inclusion of long-term deformability in SLS verification was in line with the findings by Y. Wang *et al*. (2016) about the cumulative long-term deflection of the composite slab due to creep and shrinkage of concrete. In the context of the present regulatory and analytical formulation, this was related to the dominant role played by SLS verifications in the case of partial compositeness, even when the verifications of the first group of limit states were already fulfilled, as a result of the longterm processes in the concrete component, which reduced effective stiffness over time and increase deflections. The consideration of shear interaction was related to the geometrical features of the contact surface, namely, the profile shape of the profiled decking. Such dependence has been addressed by J.H.L.M. Mello *et al*. (2024), who concluded that the embossment geometry influences the longitudinal shear force transmission and, therefore, the verification of the longitudinal shear capacity. In the present context, this dependence meant that the geometrical features of the decking influence the achieved level of composite action and, therefore, the resulting transformed cross-section features.

The dependence on geometrical proportions and the load level was also extended to the combined response of strength and deformability. An experimental analysis carried out by S. Sirimontree *et al*. (2021) concluded that variations of the shear span-to-depth ratio influence not only the ultimate values but also the deformation capacity of composite slabs. In normative terms, this translated into a reduction of the effective flexural stiffness that was mostly accounted for by an increase in the deflection (reduction of the partial composite action degree), whereas the variation of the load-bearing capacity may be less significant for the same conditions, thus leading to a nonsimultaneous variation of the sensitivity of the ULS and SLS verifications. Analogous conclusions concerning the role of the contact surface have been reported by J. Song *et al*. (2021) based on an experimental campaign that concluded that an increase in deflection was obtained, when the stiffness of the contact surface between the steel sheets and the concrete was decreased. The contribution of contact deformation to the total deformative response of the floor was therefore concluded. Simultaneously, the parameters of the concrete component were significant with respect to the deformability of composite slabs: variations in the effective modulus of elasticity and long-term deformation parameters affected deflection magnitudes and determined the stiffness response of the system under service loads. In the case of partial composite action, the sensitivity of deflections to concrete parameters was higher due to a reduced reserve of structural stiffness.

The review provided by M.M. Rahman & G. Ranzi (2022), which systematised the behaviour of steel-concrete slabs with respect to shrinkage deformations, showed that non-uniform drying or shrinkage in the presence of steel decking changes the deformation pattern over time. In the context of the present interpretation, this confirmed the conclusion that SLS criteria were of particular relevance in the conditions of partial composite action, where the reduction in effective stiffness made the floor more sensitive to long-term deformations of the concrete component. The analytical models of longterm behaviour, used in the regulatory and analytical approach, showed that the deformability of the floor can be the factor determining the acceptability of a design solution, even when the requirements of the first group of limit states were satisfied. Similar conclusions were reported by Q. Wang *et al*. (2022), where the increase in deflections was attributed to concrete creep and the gradual loss of effective stiffness in composite slabs over time. From the methodological point of view, this raised the question of the correspondence between code-based procedures and the real in-service performance of the structure, as well as the interpretation of the results of an assessment.

In the study of L.A.M. Oliveira *et al*. (2021) devoted to the analysis of design codes in relation to the in-service performance of steel-concrete composite slabs, an approach was justified, in which SLS and ULS verifications should be considered as independent with respect to the criteria and consequences, without a direct transfer of conclusions between groups of limit states. Within the framework of the present study, this meant that, under conditions of partial composite action, deflections may increase in a disproportionate way with respect to variations in the strength reserve, and therefore, serviceability can impose constraints on a design solution independently of the results of the ULS assessment. The difference in approaches was possible regarding the evaluation of reliability and reserves: D. Gino *et al*. (2019), when applying the partial factor approach of fib Bulletin 80 to an existing object, showed the need for the explicit consideration of uncertainties and the formal reservation within the verification procedure. In the framework of the considered problem, this was manifested in the difference in sensitivity of deflections and the design bending resistance to a change in the degree of shear interaction, due to the different physical essence of stiffness and strength characteristics of the composite cross-section.

The data on the long-term behaviour of the floor were in line with the conclusions of the studies of H. Zhang *et al*. (2022), which mentioned the accumulation of deformations in composite slabs under long-term loading. In the regulatory and analytical perception, this can be explained by an increase in deflections with time at a constant service load due to a gradual decrease in the effective stiffness of the composite cross-section. At partial composite action, the effect of long-term behaviour is connected with a smaller reserve of stiffness and greater sensitivity of the total deformation reaction to the contact interaction. The decrease in stiffness of separate elements of the composite should be perceived as influencing the stress-strain state of the system as a whole, rather than as a local phenomenon. In the research of D. Baranetska *et al*. (2025), the results of calculations were presented, which characterised the systemic change in the reaction of the structure, when changing the stiffness parameters of its components. In the normative perception, this can be treated as evidence of the composite action as a unified stiffness-force mechanism, where the degree of shear interaction affected both the realised resistance and the deformability of the system. In the framework of the carried-out analysis, the revealed regularities can be commented as a complexity of the composite action in steel-concrete floors and an interdependence of force and stiffness parameters within a unified mechanism.

In the article of V. Popov *et al*. (2011), the load-bearing capacity and deformability of steel-concrete floors were considered as interconnected characteristics, which were formed as a result of the composite action of the steel and concrete components. These provisions of the normative document can be used to explain the systematic behaviour of composite floors and the relationship between the force and stiffness reactions. In the study of V. Sirobaba (2018), it was revealed that in the conditions of partial composite action, it was the deformability characteristics that determined the boundaries of the admissible design solutions of steel-concrete floors. The same picture was observed in this research, where the limiting state was the achievement of maximum deflections at earlier stages of loading than the realisation of ultimate stresses. This was due to the high sensitivity of the effective stiffness of the composite cross-section to a decrease in the degree of shear interaction between the profiled steel deck and the concrete slab. The general regulatory and analytical conclusion about the determining role of the effective stiffness and the parameters of composite action, which simultaneously controlled the load-bearing capacity and the deformational behaviour of the floors, fully agreed with the experimental and computational data, in which these same processes were directly registered by the load-deflection curve and the realised bending behaviour of the composite slabs. Bending behaviour of composite slabs with profiled steel decking was also studied by G. Zhu *et al*. (2025), where by experiment and computational simulation it was found that the parameters of the structure affected the load-deflection curve and the failure mode, and the analytical calculation based on the effective stiffness was suitable for use in design calculations to determine the deflection and load-bearing capacity of slabs. In the study of K.T. Huong *et al*. (2025), it was experimentally confirmed that the parameters of composite action between the profiled steel deck and the concrete slab determined the achieved load-bearing capacity and the deformation behaviour of the elements due to a change in the effective stiffness of the composite cross-section. Similar reductions of shear interaction efficiency were identified in the present study as a factor responsible for the premature growth of deflection, and consequently for the prevailing effect of SLS in cases, where the requirement $M_{Ed} \leqslant M_{Rd}$ was still satisfied.

The combined results of the regulatory and analytical assessment showed that the degree of shear interaction between the profiled steel decking and the concrete slab determined a unique stiffnessforce response of the steel-concrete floor, where designed bending resistance and service deformability were both simultaneously defined. These relationships appeared to be consistent with the evidence of experimental and numerical investigations on partial composite action, where the efficiency of longitudinal shear forces determined the stress distribution, the position of the neutral axis and the magnitude of the equivalent stiffness parameters of the cross-section. For partial composite action, deflections were observed to increase at a faster rate than reductions in load-bearing capacity, in line with analytical and engineering-normative perceptions of the uneven sensitivity of the first and second limit state verifications. The overall set of comparisons offered a consistent normative description of the response of steel-concrete floors, where serviceability and load-bearing capacity were not perceived as separate entities but rather as correlated outcomes of composite action, in line with contemporary trends in research and engineering practice on steel-concrete systems.

CONCLUSIONS

The regulatory and analytical assessment offered a unified description of the development of loadbearing capacity and deformability of steel-concrete floors reinforced with profiled steel decking in the context of the current design framework for the first and second groups of limit states, with a distinction between the ULS and the SLS requirements. In the normative model adopted for the study, these characteristics were not separate entities but rather were both ruled by a unified stiffness-force mechanism of the composite cross-section, where the outcomes of load-bearing capacity and serviceability verifications were correlated counterparts of the safety and performance evaluation of the structure. A degree of shear interaction between the profiled steel decking and the concrete slab guarantees an involvement of the floor's strength and stiffness properties in a combined design model, and influenced the realised design bending resistance and the effective stiffness element. The complete shear interaction realised a monolithic behaviour of a steel-concrete cross-section in a standard design model, the highest possible involvement of geometrical, stiffness properties of the transformed section, and the lowest possible deflection values. All of this guarantees the fulfilment of the requirements of the first and second groups of limit states in terms of standard admissible values of the design load combinations. The partial realisation of composite action was accompanied by the corresponding decrease of the design resistance and increase of deflection values, i.e., the effective stiffness of a cross-section is reduced under the same loading conditions. It was also observed that, under partial shear interaction, deformability indicators (deflections) reach the SLS limit values more quickly than a reduction of the load-bearing capacity reserve takes place, was also found. The obtained result predetermined an asymmetric sensitivity of ULS and SLS criteria and thus the acceptability of design solutions. The use of normatively generalised design models without verification for specific types of structural solutions and contact zone configurations was a limitation of the study. In the future, a numerical and experimental refinement of the influence of local contact zone parameters, long-term action of concrete properties (shrinkage, creep) and an optimisation of standard procedures for an account of the partial composite action in steel-concrete floors are foreseen.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Baranetska, D., Barabash, M., Bieliatynskyi, A., Pylypenko, O., & Mashkov, I. (2025). Numerical methods of calculation of stress-strain state of combined elements of sheeting. *Journal of Mechanics*, 41, 82-102. doi: 10.1093/jom/ufaf007.

[2] Dmytrenko, Y. (2021). Modeling of joint work of steel beam constructions with reinforced concrete ribbed floor slabs. *Building Constructions. Theory and Practice*, 8, 44-57. doi: 10.32347/2522-4182.8.2021.44-57.

[3] DSTU No. B V. 2.6-215:2016. (2016). *Calculation and design of steel-concrete structures with slabs on profiled decking*. Retrieved from https://surl.li/wgddzo.

[4] Gino, D., Castaldo, P., Bertagnoli, G., Giordano, L., & Mancini, G. (2019). Partial factor methods for existing structures according to fib Bulletin 80: Assessment of an existing prestressed concrete bridge. *Structural Concrete*, 21(1), 15-31. doi: 10.1002/suco.201900231.

[5] Grossi, L.G.F., Rezende Santos, C.F., & Malite, M. (2020). Longitudinal shear strength prediction for steel-concrete composite slabs with additional reinforcement bars. *Journal of Constructional Steel Research*, 166, article number 105908. doi: 10.1016/j.jcsr.2019.105908.

[6] Hasenko, A., Dariienko, V., & Butenko, A. (2022). Effect of damage to the effective width of concrete shelves on the bearing capacity of self-stressed steel reinforced concrete floor. In *Complex composite structures of buildings and structures in conditions of martial law: Collection of scientific papers of the XIV international scientific and technical conference* (pp. 18-20). Poltava: National University "Yuri Kondratyuk Poltava Polytechnic".

[7] Hedaoo, N.A., Gupta, L.M., & Ronghe, G.N. (2012). Design of composite slabs with profiled steel decking: A comparison between experimental and analytical studies. *International Journal of Advanced Structural Engineering*, 4, article number 1. doi: 10.1186/2008-6695-3-1.

[8] Hernich, M., Klutchnik, S., & Spivak, D. (2021). Composite reinforced concrete bridge girders for post-conflict reconstruction of the destroyed transport infrastructure. *Bridges and Tunnels: Theory, Research, Practice*, 19, 28-37. doi: 10.15802/bttrp2021/233872.

[9] Huong, K.T., Bui, L.V.H., & Nguyen, P.T. (2025). Experimental investigation on structural behavior of composite slabs with steel decking, fiber-reinforced concrete, and lightweight aggregate concrete layers. *Scientific Reports*, 15, article number 23786. doi: 10.1038/s41598-025-08955-7.

[10] Izzuddin, B.A., & Sio, J. (2022). Rational horizontal tying force method for practical robustness design of building structures. *Engineering Structures*, 252, article number 113676. doi: 10.1016/j.engstruct.2021.113676.

[11] Mello, J.H.L.M., Pureza, D.Q., Martins, M.P., de Sousa Cardoso, H., de Melo Lameiras, R., Veloso, L.A.C.M., de Brito, J.L.V., da Silva, J.G.S., & Alencar, G.S. (2024). Longitudinal shear strength design of composite slabs by full-scale FE modelling considering the embossments. *IBRACON Structures and Materials Journal*, 17(5), article number e17505. doi: 10.1590/S1983-41952024000500005.

[12] Mohammed, K., Abd Karim, I., & Bulu, K. (2017). Profiled deck composite slab strength verification: A review. *Arid Zone Journal of Engineering, Technology and Environment*, 13(6), 655-661.
[13] Oliveira, L.A.M., Borghi, T.M., Rodrigues, Y.O., & de Cresce El Debs, A.L.H. (2021). Assessment of design codes for the in-service behaviour of steel-concrete composite slabs. *IBRACON Structures and Materials Journal*, 14(5), article number e14501. doi: 10.1590/S1983-41952021000500001.
[14] Popov, V., Bryl, N., & Teslia, O. (2011). Modelling of reinforced concrete slabs on profiled sheeting to assess reliability and efficiency. *Modern Technology, Materials and Design in Construction*, 11(2), 10-14.
[15] Rahman, M.M., & Ranzi, G. (2022). Shrinkage-induced response of composite steel-concrete slabs: A state-of-the-art review. *Applied Sciences*, 12(1), article number 223. doi: 10.3390/app12010223.
[16] Ravichandran, P., & Harini, S. (2024). Review on behaviour of steel concrete composite slabs by varying different parameters. In *Proceedings of the international conference on advancements in materials, design and manufacturing for sustainable development*. Coimbatore: EAI. doi: 10.4108/eai.23-2-2024.2346949.
[17] Saccone, M., Stochino, F., Zucca, M., & Simoncelli, M. (2025). Longitudinal shear behaviour in recycled aggregate concrete composite slabs: A state-of-the-art review. *Journal of Building Engineering*, 113, article number 114002. doi: 10.1016/j.jobe.2025.114002.
[18] Savytskyi, M., Nikiforova, T., & Frolov, M. (2021). Stress-deformed state of steel-reinforced concrete structures of floors at the stage of establishment of structures. *Ukrainian Journal of Civil Engineering and Architecture*, 3, 101-109. doi: 10.30838/J.BPSACEA.2312.010721.101.772.
[19] SCN No. V.1.2-2:2006. (2006). *Loads and impacts. design standards*. Retrieved from https://e-construction.gov.ua/laws_detail/3199621970136139233.
[20] SCN No. V.1.2-6:2021. (2022). *Basic requirements for buildings and structures. Mechanical resistance and stability*. Retrieved from https://e-construction.gov.ua/laws_detail/3074797473579927547?doc_type=2.
[21] SCN No. V.2.6-160:2010. (2010). *Steel-reinforced concrete structures. Basic provisions*. Retrieved from https://e-construction.gov.ua/laws_detail/3200413563881522897?doc.
[22] SCN No. V.2.6-198:2014. (2022). *Steel structures. Design standards. With change № 1*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=58106.
[23] SCN No. V.2.6-98:2009. (2009). *Concrete and reinforced concrete structures. Basic provisions*. Retrieved from https://e-construction.gov.ua/laws_detail/3200410998024438840.
[24] Sirimontree, S., Thongchom, C., Keawsawasvong, S., Nuaklong, P., Jongvivatsakul, P., Dokduea, W., Bui, L.V.H., & Farsangi, E.N. (2021). Experimental study on the behavior of steel-concrete composite decks with different shear span-to-depth ratios. *Buildings*, 11(12), article number 624. doi: 10.3390/buildings11120624.
[25] Sirobaba, V. (2018). *Load-bearing capacity and deformability of reinforced concrete structures made of lightweight concrete*. (Abstact, National University "Yuri Kondratyuk Poltava Polytechnic", Poltava, Ukraine).
[26] Siva, A., Senthil, R., & Swaminathan, S. (2016). Assessment of longitudinal shear strength of composite deck slab. *International Journal of Innovation and Scientific Research*, 24(2), 277-284.
[27] Song, J., Wang, W., Su, S., Wang, B., Li, Y., & Lu, Z. (2021). Experimental investigation of the bond-slip behaviour between corrugated steel plates and concrete in CSRC structures. *Construction and Building Materials*, 299, article number 124315. doi: 10.1016/j.conbuildmat.2021.124315.
[28] Storozhenko, L., & Gasii, G. (2020). Experience and current issues of designing of steel and concrete composite structures of roof and floor systems. *Academic Journal. Industrial Machine Building, Civil Engineering*, 2(55), 15-25. doi: 10.26906/znp.2020.55.2337.
[29] Wang, Q., Yang, J., Zhang, Y., Fang, Y., & Ren, Q. (2022). Analysis and design of long-term responses of simply-supported steel-concrete composite slabs. *Journal of Building Engineering*, 53, article number 104496. doi: 10.1016/j.jobe.2022.104496.
[30] Wang, Y., Wang, Q., Geng, Y., & Ranzi, G. (2016). Long-term behaviour of simply supported composite slabs with recycled coarse aggregate. *Magazine of Concrete Research*, 68(24), 1278-1293. doi: 10.1680/jmacr.16.00090.
[31] Wei, Y., Huang, J., & Liang, S. (2020). Measurement and modeling concrete creep considering relative humidity effect. *Mechanics of Time-Dependent Materials*, 24, 161-177. doi: 10.1007/s11043-019-09414-3.
[32] Zhang, H., Zhang, H.-Y., Geng, Y., Fang, P.-Q., & Wang, Y.-Y. (2022). Design formulae for long-term responses of continuous steel-recycled aggregate concrete composite slabs. *Structures*, 45, 1477-1490. doi: 10.1016/j.istruc.2022.09.092.
[33] Zhu, G., Wang, X., Wang, W., Wang, J., & Yang, Y. (2025). Research on the flexural behavior of profiled steel sheet-hollow concrete composite floor slab. *Buildings*, 15(12), article number 2140. doi: 10.3390/buildings15122140.

Василь Петрів
Аспірант
Львівський національний університет ветеринарної медицини та біотехнологій імені Степана Ґжицького
79010, вул. Пекарська, 50, м. Львів, Україна
https://orcid.org/0009-0009-3297-1171

Несуча здатність та деформативність сталебетонних перекриттів по профільованому сталевому настилу

Анотація. Метою статті було нормативно-аналітичне обґрунтування впливу ступеня зсувної взаємодії на виконання вимог першої та другої груп граничних станів композитних перекриттів із профільованим настилом. Методологія дослідження ґрунтувалася на нормативно-аналітичному підході з використанням чинної національної нормативної бази України та нормативно визначених розрахункових моделей сталебетонних перекриттів як композитних згинальних елементів, для яких у межах нормативної розрахункової моделі приймалася повна або часткова сумісність деформацій сталевої та бетонної складових. Результати дослідження показали, що несуча здатність і деформативність перекриттів формувалися як взаємопов'язані характеристики в межах єдиного жорсткісно-силового механізму роботи композитного перерізу. Було встановлено, що ступінь зсувної взаємодії між сталевим настилом і бетонною плитою є інтегруючим параметром, який одночасно визначав реалізований розрахунковий опір згину та ефективну жорсткість перекриття. За умов повної зсувної взаємодії забезпечувалася максимальна реалізація приведених геометричних і жорсткісних характеристик перерізу та виконання вимог обох груп граничних станів. За часткової композитної роботи було зафіксовано узгоджене зниження розрахункового опору та зростання прогинів, причому деформативні показники виявляли вищу чутливість до зменшення ефективної жорсткості, ніж показники несучої здатності. Показано, що за однакових експлуатаційних навантажень прогини могли досягати гранично допустимих значень раніше, ніж реалізовувалися граничні напруження, що визначало експлуатаційну придатність як обмежувальний чинник проєктних рішень. Практична значимість отриманих результатів полягала в можливості їх використання проєктними та експертними організаціями у практиці нормативного оцінювання і проєктування сталебетонних перекриттів із профільованим настилом

Ключові слова: композитна робота; зсувна взаємодія; експлуатаційна придатність; ефективна жорсткість; прогини; граничні стани

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 728.1
DOI: 10.56318/as/1.2026.42

ISSN: 2411-801X
e-ISSN: 2786-7374

Ruslan Minchenkov*
Postgraduate Student
Odesa State Academy of Civil Engineering and Architecture
65029, 4 Didrikhson Str., Odesa, Ukraine
https://orcid.org/0000-0003-1635-8317

Architecture of a sustainable future: Smart building as a synthesis of technology and nature

Abstract. The purpose of this study was to provide a comprehensive analysis of smart building technologies and their integration into sustainable, energy-efficient, and intelligent urban environments. Smart buildings were considered as systems that combined automated solutions for heating, ventilation, air conditioning, lighting, shading, security, and engineering infrastructure management, coordinated through building management systems and implemented using Internet of Things technologies, sensors, and actuators. Such systems collected real-time data to enable predictive analytics, adaptive control, and energy optimisation. It was analysed machine learning methods, including supervised learning, unsupervised learning, reinforcement learning, fuzzy logic, and stochastic optimisation, for energy consumption forecasting, renewable energy management, intelligent control, and fault diagnostics. Occupant-centric control systems were investigated, as it accounted for human presence, preferences, and comfort, enabling dynamic adjustment of building operation modes and energy use. The integration of smart buildings with smart grids based on advanced building energy management systems was analysed, allowing participation in demand response programmes, voltage regulation, and distributed renewable energy management. The study also examined smart building-integrated photovoltaic and data-driven approaches for real-time forecasting of energy generation and consumption. Digital technologies, including building information modelling, digital twins, robotics, drones, edge computing, and cloud platforms, enhanced the efficiency of design, construction, monitoring, operation, and maintenance processes. Despite the evident advantages, challenges remained, including high implementation costs, cybersecurity risks, system interoperability issues, and the need for advanced data management infrastructure. The practical value of this study lies in applying the results in various stages of architectural practice, including the design of new buildings, the renovation and retrofitting of existing structures, and the ongoing management and optimisation of building operations

Keywords: machine learning; digital twins; occupant-centric control; energy management; smart grid; data-driven optimisation; sustainability

INTRODUCTION

Smart buildings were central to sustainable and energy-efficient urban development. This study highlighted technologies that enhanced energy efficiency, occupant comfort, and environmental sustainability. It analysed international research and projects demonstrating how sensors, automated systems, and digital tools improved building performance, maintenance, and management. M. Casini (2022) reviewed virtual reality, augmented reality, and mixed reality for smart building operation and maintenance. Extended reality, integrated with digital twins, the Internet of Things (IoT), and artificial intelligence (AI), enhanced visualisation, energy control, predictive

Suggested Citation:
Minchenkov, R. (2026). Architecture of a sustainable future: Smart building as a synthesis of technology and nature. *Architectural Studies*, 12(1), 42-54. doi: 10.56318/as/1.2026.42.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 42-54
Received: 29.09.2025 Revised: 30.12.2025 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

maintenance, and decision-making. While promising, practical guidance on device integration in the architecture, engineering, construction, and operation sector remained limited. S.F.A. Shah *et al.* (2022) emphasised that machine learning and IoT enabled real-time monitoring, automation, and data-driven energy optimisation. Integration of AI and IoT improved occupant comfort, safety, and operational management, although security challenges must be addressed.

H. Teixeira *et al.* (2025) reviewed solar-control smart glazing technologies, including electrochromic, thermochromic, photochromic, gasochromic, suspended particle, and liquid crystal glazing. Electrochromic and thermochromic glazing were the most studied and effective for energy savings and thermal and visual comfort. The review identified gaps in holistic performance assessment across climates and barriers like cost, installation complexity, and market adoption. A. Behzadi *et al.* (2026) investigated model predictive control (MPC) for optimising thermal systems. In low-temperature heating and high-temperature cooling systems integrated with ground-source heat pumps and borehole thermal energy storage, MPC reduced operational costs by 13%, increased long-term savings by 20%, and shortened payback periods compared to rule-based control, while maintaining comfort and lowering CO_2 emissions. MPC demonstrated robustness under forecast uncertainty and scalability for next-generation smart buildings. S.S. Kumaresan & P.R. Jeyaraj (2025) proposed transferable reward-shaping deep reinforcement learning for energy scheduling in IoT-connected buildings. Using an aggregator for real-time appliance data, optimal scheduled balance energy savings, peak load reduction, and user comfort. Simulations and tests achieved up to 19.2% energy savings, 6.45% peak load reduction, and a satisfaction index of 0.93, showing adaptive, data-driven energy management enhanced grid stability and operational efficiency.

Researcher L. Qiu (2025) developed a reinforcement learning-based adaptive energy management system for heating, ventilation, and air conditioning (HVAC) systems, lighting. Testing in 89 buildings showed 27% energy reduction, 32% lower peak loads, comfort maintained for 96% of occupied hours, and 24% lower energy costs. The system adapted quickly to occupant behaviour and weather conditions, demonstrating effectiveness for sustainable energy management. S. Padmanaban *et al.* (2025) described smart buildings as IoT networks enabling control of lighting, ventilation, air quality monitoring, energy and water tracking, and consumption pattern analysis. These systems improved energy efficiency, comfort, security, and productivity, positioning IoT as a key building management and automation solution. M. Almadani *et al.* (2025) presented a conformalised light gradient boosting machine combining quantile regression with conformal prediction for short-term energy demand forecasting. Tested on commercial buildings from the LEAD-1.0 dataset, the model provided point and probabilistic forecasts with 90% coverage, adapted to variable consumption patterns, and reduced forecasting errors compared to baseline methods. This approach enhanced operational efficiency, anomaly detection, and decision-making in smart building digital twins, while remaining computationally efficient and scalable.

M. Feng & H. Wu (2025) proposed a smart building BIM (Building Information Modelling) co-design model integrating IoT and blockchain. Using a hyperledger fabric federated blockchain with a revolving door compression algorithm and SDT updates, the method improved data security, reduced redundancy, and enhanced collaboration efficiency. Experiments showed faster response and higher throughput, though practical validation was still needed. By integrating digital modelling tools with real-time data, stakeholders were able to simulate demolition scenarios, optimise resource management, reduce environmental impact, and minimise technical and financial risks. This approach enhanced transparency and decision-making reliability throughout the project lifecycle. The aim of this study was to provide a comprehensive analysis of modern technologies and approaches applied in smart buildings, focusing on energy efficiency, occupant comfort, digitalisation of building management, and the integration of advanced technologies such as IoT, AI, BIM, digital twins, and predictive analytics.

MATERIALS AND METHODS

The research was conducted using a comprehensive analytical approach that combined theoretical analysis, comparative study of implemented projects, review of international reports, and systematisation of digital building management technologies. At the first stage, a review of scientific publications, international standards, and certification systems was carried out, including BREEAM (n.d.), German Sustainable Building Council (n.d.), U.S. Green Building Council (n.d.), European LEVEL(s), and SRI (European Commission, 2010). This stage made it possible to formulate evaluation criteria for energy efficiency, digital readiness, and environmental sustainability of buildings. At the second stage, the structure and operating principles of smart building systems were analysed. This included sensor networks (temperature, humidity, CO_2, occupancy sensors), actuators, HVAC systems, adaptive lighting, automated shading, and security systems. Data on occupancy levels, energy consumption, and indoor environmental parameters were considered key variables for optimisation. Building Management Systems (BMS) were examined as centralised platforms that provided monitoring, automation, and predictive maintenance. Data processing was examined from the perspective of applying Big Data analytics, Machine Learning (ML), and Reinforcement Learning for energy forecasting, fault detection, and adaptive control. BIM and digital twins were analysed as integrative platforms that combined a static building model with dynamic sensor data. Deep Learning (DL) methods were considered for video stream analysis and occupant counting in order to adjust system performance in real time. Particular attention was paid to Demand-Side Management (DSM) and predictive control strategies for load balancing and peak energy reduction. The research also considered the integration of renewable energy systems (photovoltaic modules and green roofs) and smart materials to improve overall building performance. For example, the study analysed data from the Beijing National Aquatics Centre (the "Water Cube", Beijing). In addition, a report by the ACEEE (American Council for an Energy-Efficient Economy) was examined (King & Perry, 2017). Thus, the research methodology was based on the integration of theoretical analysis, international experience review, and systematisation of technological solutions, allowing for a comprehensive assessment of the potential of smart building technologies in shaping energy-efficient and sustainable urban environments.

RESULTS AND DISCUSSION

The concept of a smart building had become central to the creation of sustainable, energy-efficient, and intelligent architectural environments. Unlike traditional buildings, smart buildings integrated automated systems that regulated heating, ventilation, air conditioning, lighting, and shading based on real-time data from sensors. This ensured optimal indoor conditions, reduced energy consumption, and improved comfort. Their operation was coordinated through BMS, which allowed centralised control, monitoring, and analysis of all building subsystems, improving efficiency and enabling predictive maintenance. The development of smart buildings had been driven by rapid advances in IoT technologies, which allowed the continuous collection of data on building performance, occupancy, and environmental conditions. Cloud computing and machine learning algorithms enabled the processing of large data sets, supporting informed decision-making and real-time system optimisation. The introduction of edge computing further enhanced responsiveness by allowing local processing of sensor data with reduced delays.

A smart building aimed to anticipate user needs and operate autonomously, adjusting temperature, lighting, shading, energy and water use without human intervention. In this context, smart buildings contributed to improving quality of life and reducing environmental impact, while increasing cost efficiency. Smart buildings were evaluated according to a number of frameworks that emphasised energy efficiency, automation, sustainability, and intelligent system integration. International systems such as BREEAM (n.d.), German Sustainable Building Council (n.d.), and the U.S. Green Building Council (n.d.), European LEVEL(s) framework (a European framework for assessing the sustainability of buildings) provided guidelines for designing and assessing sustainable and environmentally responsible buildings. Regarding technological readiness, initiatives such as the European SRI assessed a building's digital capability, sustainability, and operational reliability, providing a standardised framework for evaluating smart building performance (European Commission, 2010).

Data analytics was crucial in smart building evaluation. By analysing data from sensors and meters, buildings can detect anomalies, predict failures, optimise energy use, and improve operational strategies. Digital twin technologies – virtual models of physical buildings updated in real time – were becoming an important tool in advanced smart building management. However, their implementation required significant investment in sensors and data infrastructure, as well as strong cybersecurity measures. Overall, smart buildings represented a shift towards adaptive, data-driven, and environmentally responsible architecture. While many evaluation frameworks exist, a key challenge remained the integration of environmental, technological, and operational indicators into a unified assessment system. Understanding what made an intelligent building fundamentally different from a conventional one was crucial, as this influenced architectural and engineering decisions. In many commercial interpretations, a smart building was reduced to remotely operated systems controlled by users, offering automation but no independent decision-making or adaptation. A more advanced perspective defines such a building as a system capable of monitoring indoor and outdoor conditions, identifying user behaviour patterns, learning from accumulated data, and initiating responses without direct human input. In this case, the building acted as an autonomous participant in the interaction with its occupants, optimising its functioning based on real needs.

Research and experimental projects developed by leading universities – such as the Smart Living Lab at EPFL and the University of Fribourg, the SM4All smart home interoperability project involving Sapienza University of Rome, and university-based smart building testbeds for real-time IoT data collection and control – demonstrated that truly intelligent environments provided a broad spectrum of advantages, including improved user comfort, reduced resource consumption, time savings, higher safety standards, integration of expert knowledge, support of healthy indoor conditions, and assistance for elderly or disabled residents through automated monitoring and alerts. These capabilities rely on three elements working together: hardware that gathered information about the environment and building operation; software that analysed data, identified patterns, and made decisions; and communication networks that connected all components into a unified system (European Commission, 2010; Smart Living Lab, n.d.). To determine how advanced a building was, several evaluation models calculated the share of parameters and processes that the system can monitor and regulate independently. This allowed specialists to distinguish between simple automation, where the user remained the primary decision-maker, and full intelligence, where the building detected changes and responded proactively. A higher score indicated greater autonomy, adaptability, and technological sophistication (Apanaviciene *et al.*, 2020). Progress in smart building technologies had enabled the creation of integrated systems that combined information technologies with building automation to improve energy performance and reduced operational costs. Modern solutions relied on a network of sensors, actuators, communication hardware, management software, and intelligent control devices that operated together within a unified digital environment. Control units and sensing devices were distributed throughout the building and connected to a central platform capable of exchanging data in real time. Each subsystem had its own communication channels, but all operated on a shared network infrastructure, which functioned as the technological backbone of the building (Fig. 1).

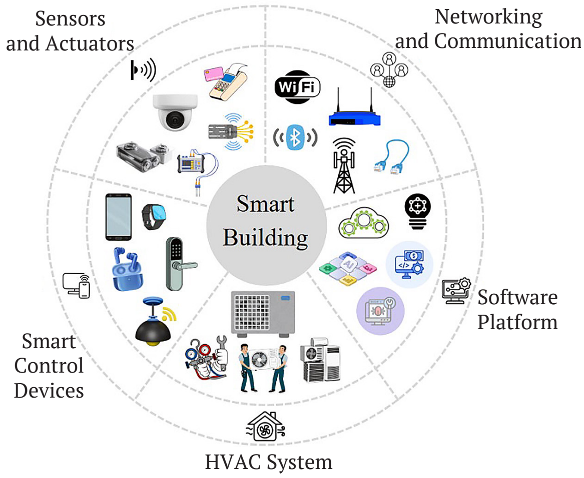


Figure 1. Integrated smart building framework
Source: based on B. Qolomany *et al*. (2019)

Among all technical installations, HVAC systems remained the most complex, as it ensured thermal comfort, air circulation, and indoor air quality, while also accounting for a major share of total energy use. Their correct operation directly influenced environmental performance and user safety. Smart buildings continuously supervised these systems and adjusted their operation automatically. The main goal was to manage lighting, security, ventilation, climate control, and other services from a single digital interface supported by computer-based decision mechanisms. The Honeywell Total Connect Remote Services platform integrated home automation functions with professional security monitoring. Through a mobile application or a dedicated control console, residents can manage lighting, shading devices, cameras, alarms, and other connected systems, while receiving instant notifications about events in the home. The solution also offered remote video access and location tracking for vehicles and assets. The system was compatible with Z-Wave equipment and must be installed by a certified Honeywell provider. It does not support Wi-Fi based smart thermostats but can operate with Honeywell cameras, sensors, and selected external products such as Lutron lighting controls and Yale electronic locks. A comparative overview of smart controllers used in modern buildings was presented in Table 1.

Table 1. Comparative analysis of smart home devices

Device	Communication Technology	Supported Platforms	Main Advantages	Main Limitations
WeMo	Wi-Fi	Android, iOS, Windows, Phone	Low-cost ecosystem; scalable via SmartThings and IFTTT; easy entry into smart automation	No dimming support; lacks colour lighting; occasional signal latency
Nest Thermostat	Wi-Fi, ZigBee, Thread	iOS, Android, Windows, macOS	Learns user behavioural patterns; adapts heating/cooling schedules automatically; strong energy-saving potential	Higher cost than many competitors; may lack manual fine-tuning preferred by some users
Lockitron	Bluetooth	iOS, Android	Keyless and proximity-based unlocking; silent operation; user-friendly installation	Wi-Fi bridge purchase required for remote access; limited device interoperability
SmartThings Hub	Wi-Fi, ZigBee, Z-Wave, Bluetooth	Android, iOS, Windows Phone	Multiprotocol support; can integrate multiple third-party devices; quiet and reliable operation	Compatibility issues may occur with non-native devices; configuration complexity for some users
Philips Hue	Wi-Fi	iOS, Android	Wide integration support; large community; deep customisation via scenes, scheduling, and smart automation	Higher product cost; some features harder to configure for beginners
BluFit Bottle	Bluetooth	iOS, Android	Easy setup; helps users monitor hydration; attractive design	Premium price compared to conventional solutions

Table 1. Continued

Device	Communication Technology	Supported Platforms	Main Advantages	Main Limitations
Canary Security System	Wi-Fi	iOS, Android	Simple installation; central smart security functions in a single unit	Expensive for its feature set; limited mainly to internal monitoring
Amazon Echo	Wi-Fi, Bluetooth	FireOS, Android, iOS	Excellent voice recognition; supports integrations across major ecosystems; universal compatibility	Intruder detection limited to indoor audio triggers; depends on constant cloud connectivity
Honeywell Smart Thermostat	Wi-Fi, Z-Wave	iOS, Android	Reliable installation; balanced functionality; integrates well with multi-device smart homes	Higher cost than similar competing thermostats

Source: based on B. Qolomany *et al.* (2019), D.D. Eneyew *et al.* (2022)

In the process of seeking solutions to complex problems, building technologists often turn to nature for inspiration. Biomimetics lain at the intersection of biology, biophysics, and materials science, requiring comprehensive knowledge in these fields. In the context of smart buildings, biomimetic principles inspired the design of adaptive and energy-efficient systems. For example, building façades can emulate the self-shading patterns of leaves to optimise natural lighting, while ventilation systems can mimic the airflow strategies observed in termite mounds to enhance indoor air circulation. Openness to new ideas and active interdisciplinary dialogue facilitated the translation of biological strategies into architectural solutions, enabling the creation of responsive, sustainable, and resilient building environments. Although the evolutionary processes in nature span millions of years, their principles can inform rapid technological innovation in smart building design. The differences in time scales, the design constraints and objectives remained similar: ensuring functionality, optimisation, and efficient scalability (Degha *et al.*, 2019). Modern evolutionary step in construction, emerging in the late 20th century (approximately 1980s-1990s) and continuing into the 21st century, involved the concept of smart materials. These materials were divided into passive materials, which sense environmental functioned as sensors, and active materials, which also acted as actuators in response to such stimuli. Intelligent materials are capable of autonomously adapting to changing environmental conditions. Examples of smart building components included windows and blinds that regulated light and temperature through technologies such as shape-memory alloys or suspended particle devices (Fig. 2).

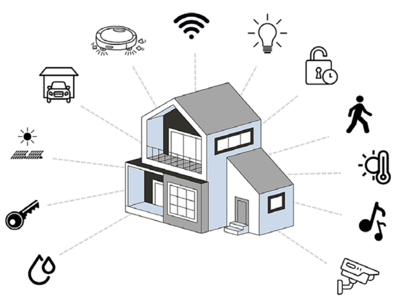


Figure 2. The concept of smart home and its advantages
Source: based on S. Vattano (2014)

Roofs can incorporate renewable energy sources, such as green roofs and photovoltaic modules, producing electricity for the building. Anti-microbial ceilings feature coatings that inhibited bacterial growth, preventing odors and stains (Dong *et al.*, 2019). Using DSM approaches in home energy management systems (HEMS), electricity consumption can be effectively regulated. To reduce user stress, the synchronisation of different household appliances was proposed, enabling a more efficient response to unexpected events. Users can reorganise their schedules to pause one appliance and reallocate the freed time slot to other devices of their choice using dynamic programming. This allowed for shorter waiting times for higher-priority devices (El-Afifi *et al.*, 2024). Urban renewal drove economic development and job creation but also produced significant amounts of construction and demolition waste (CDW), which can negatively affect the environment, public health, and urban infrastructure. Efficient management of construction and demolition waste was often hindered by insufficient data collection, limited recycling practices, and lack of integrated technologies. It was presented a smart demolition and waste management framework that combined image-based three-dimensional (3D) reconstruction and BIM. The approach enabled automated and comprehensive data collection, accurate BIM modelling of existing structures, planning of demolition sequences, assessment of safety risks, and precise calculation of CDW volumes and costs. By integrating these technologies, the framework improved efficiency, reduced environmental impact, and supported informed decision-making throughout the demolition process (Hu *et al.*, 2022).

The "appropriateness" of smart buildings refered to their value, aesthetics, adaptability, and ability to deliver useful benefits. The selection of suitable technologies was determined by how well it contribute to achieving functional, structural, technological, social, economic, and environmental objectives. Research by F.M. Abo-Elazm & S.M. Ali (2017) on the Beijing Water Cube established criteria for evaluating the appropriateness of smart buildings, highlighting the extent to which design depended on suitable technologies It was examined that the use of ethylene tetrafluoroethylene membrane façades and intelligent engineering systems enabled approximately 30% energy savings compared to conventional solutions for facilities of similar scale. Framework assessed environmental factors (such as natural and artificial lighting and ventilation), economic aspects (like the use of smart materials for longterm energy savings), functional integration of building systems, and social benefits including safety and occupant comfort (Fig. 3).

Figure 3. Beijing water cube interior
Source: based on F.M. Abo-Elazm & S.M. Ali (2017)

Local smart architecture used modern technologies to meet the needs of a specific community in a particular context, while supporting sustainable development for future generations. It relied on local resources and traditions, aimed to improve climate conditions, preserved cultural heritage, saved energy, and promoted sustainability (Abo-Elazm & Ali, 2017). The choice of constructions and the development of structural systems under the influence of technological progress shaped the characteristic features of architecture. Buildings were determined by the properties of available materials and technologies, while over time the emergence of new tools and materials contributed to the evolution of building forms and functions. Even traditional structures reflected the characteristics of their location, climate, and resources through design and materials. The period of the 19th-20th centuries was particularly revolutionary, as reinforced concrete, glass, and steel allowed the creation of lighter, more transparent constructions. Postwar advancements in materials science (after World War II, approximately 1945-1970s) further expanded the possibilities of architectural design, making it more universal and open to new materials and technologies (Frighi, 2022). For example, ACEEE (American Council for an Energy-Efficient Economy) conducted research, which analysed to identify key indicators of energy efficiency, resource savings, and the broader benefits of smart building technologies. These data were important for this study because it provided evidence-based insights into how intelligent efficiency measures can optimise building performance, reduce operational costs, and improve occupant comfort, which were central objectives of investigation (King & Perry, 2017).

Experts of the ACEEE report included utility programme administrators, smart technology manufacturers, and smart building practitioners. A combination of available data, facts, statistics, and practical observations was used to formulate conclusions and recommendations. The study focused on existing U.S. commercial buildings – including offices, retail properties, educational facilities, laboratories, healthcare institutions, and hospitality establishments. Residential buildings, new commercial construction, data centres, and warehouses were not included in the analysis. While multifamily buildings were not explicitly addressed, many energy-saving solutions from smart buildings could apply to their common areas. Commercial buildings were divided into two size categories: large (over 100,000 square feet, such as high-rise offices) and small to medium (100,000 square feet or less, such as a bank branch). Large buildings accounted for only 2% of the U.S. commercial building stock but occupied about 35% of the total floor area and were more likely to have smart building technologies installed. Small and medium buildings made up nearly 98% of the stock and typically lack such technologies, representing significant opportunities for implementation (Fig. 4).

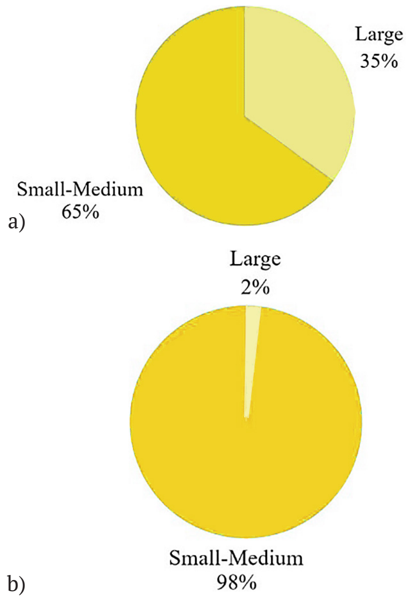


Figure 4. Data on commercial buildings in the U.S.
Note: a – number of commercial buildings; b – floor area of commercial buildings
Source: based on J. King & C. Perry (2017)

This study covered the entire U.S. commercial building stock, including roughly half of all buildings that were 35 years or older (constructed before 1980) and half of newer buildings (constructed after 1980). Building age was closely linked to construction types and installed equipment, which affected the kind of data that can be collected and the building processes that can be automated. All U.S. regions were included in the analysis. The South contained the largest share of commercial buildings (around 40% of the total), while the West and Midwest accounted for approximately 23% and 22%, respectively, and the Northeast made up the remaining 15%. These regional differences were significant, as each region had distinct weather patterns, income levels, building stock characteristics, and available utility programmes (Fig. 5).

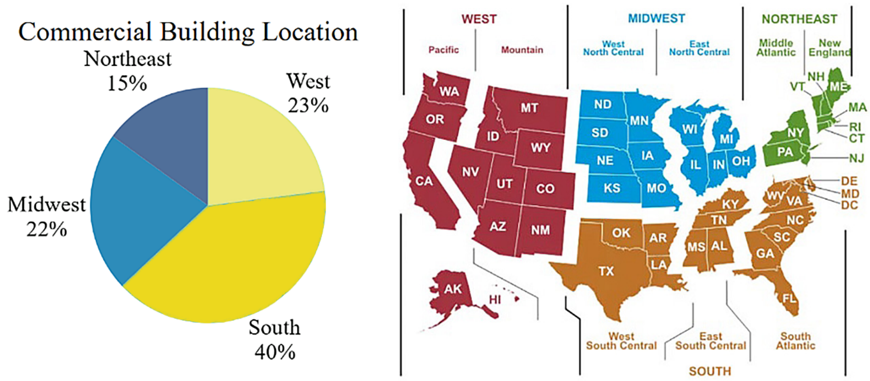


Figure 5. U.S. commercial building regional locations
Source: based on J. King & C. Perry (2017), H. Ghayvat *et al.* (2015)

These regional distributions indicated that the majority of U.S. commercial buildings were concentrated in the South and West, which correlated with higher potential energy demand due to climate conditions. So, this supported the importance of context-specific smart building strategies, as the adoption of IoT, predictive control, and energy-efficient systems must consider regional variations in occupancy, climate, and energy use. Consequently, the findings highlighted that the benefits of smart building technologies – such as energy optimisation, occupant comfort, and integration of renewable sources – may vary depending on geographic location and building characteristics. The IoT system enabled the interaction of a network of devices for collecting, exchanging, and transmitting data. In smart buildings, IoT devices automate control, reduced energy consumption, and enhanced building management efficiency. Data transmission security was ensured through the use of Constrained Application Protocol (CoAP) and datagram transport layer security protocols, which simultaneously protected information and save device energy. The application of the CoAP non-continuous awake mode further reduces energy consumption compared to other schemes. Key advantages included the integration of different building systems through IoT, protection of transmitted data with reduced energy consumption, and scalability with compatibility across various applications (John *et al.*, 2005). Smart homes for ambient-assisted living monitor resident behaviour using sensor data. Deviations from normal patterns, either unexpected or predefined as anomalies, trigger alerts for occupants. Behavioural models were generated using time-based deviation analysis, as reliable forecasting requires multiple events. The wellness prediction model had two levels: 1) lower level: raw sensor data from appliances and movement were sent to a local server via the home gateway, recording, which sensors were active; 2) upper level: software analysed data to determine optimal daily activities, using real-time intelligent recognition and classification based on sensor order and timing (Hurtado *et al.*, 2015).

The IoT enabled a network of physical objects equipped with sensors, processing units, and communication capabilities to detect events, exchange data, and interact with the environment autonomously. IoT systems supported real-time data collection and automated control, replacing traditional monitoring systems across industries. IoT generated large volumes of data, requiring connectivity, power, processing, and storage to convert it into useful information. Ensuring reliable data and network security was critical, and distributed signal processing can verify data integrity. Blockchain technology added a decentralised, transparent, and secure ledger for recording transactions and interactions. Integrating IoT with blockchain created a robust, verifiable system for managing data from connected smart devices, enabling autonomous decision-making without human intervention (Lokshina *et al.*, 2019). BIM-IoTDI (Building Information Modelling – Internet of Things Digital Infrastructure) was a layered architecture for smart-building digital twins, connecting static BIM models with dynamic IoT sensor data. Environmental data were collected by sensors and sent to storage, with static information represented as a knowledge graph and sensor data maintained in time-series databases.

The architecture provided service-oriented data access and integrated queries across static and dynamic sources. A query mediator, including components for dispatching, mapping, transforming, and postprocessing data, converted raw sensor readings into a structured format. This enabled real-time analysis, reasoning, and decision-making for smart-building digital twins (King & Perry, 2017). Big Building Data offerred various tools for building users, owners, architects, and engineering consultants. Primarily, these included data monitoring tools, which provided access to real-time metrics, historical data, and pre-calculated values. Monitoring was also useful for architects and engineers, as it allowed them to assess building and occupant behaviour. This enabled post-occupancy evaluation, energy optimisation, and improvement of user comfort. Architects can use these insights to create best practice guides and enhance their experience for future projects.

Building owners were interested in anomaly detection and predictive maintenance. By analysing historical data, standard patterns of building and occupant behaviour can be identified. Deviations from these patterns were automatically detected and can trigger alerts, such as maintenance notifications. The system can also record anomalies, their causes, and the applied solutions to suggest optimal resolutions if similar issues arise in the future. These services were currently under development (Kumar *et al.*, 2021). Energy waste in buildings often results from user behaviour. Passive approaches, like providing feedback on appliance usage, raise awareness, while active methods, such as automatically switching off standby devices, directly reduced consumption. However, existing methods often overlook user comfort and fail to handle complex contexts effectively. A context-aware system that combined passive and active strategies can optimise energy savings, while maintaining comfort. Real-time monitoring and context-awareness allowed smart buildings to adapt energy-saving measures to specific situations, potentially reducing consumption by up to 40% (Linder *et al.*, 2017).

Sensors link environmental conditions to building systems, enabling better management of energy and occupant well-being. Functional sensing systems linked environmental variables, such as temperature, to building control systems like HVAC. Z. Liu *et al.* (2023) examined sensor types, their applications, and their impact on occupant comfort and energy efficiency, and discussed how sensor data can be analysed to inform building management. The intelligent system used a deep learning model pretrained on ImageNet and retrained on a custom Room Human Counting (RHC) dataset to count occupants in real time from CCTV (Closed-Circuit Television) video streams. To handle large data volumes, Big Data technologies and deep learning libraries compatible with Apache Spark, such as TensorFlow or Caffe, are used. The predicted human count was then applied to adjust building appliances through the control system (Fig. 6).

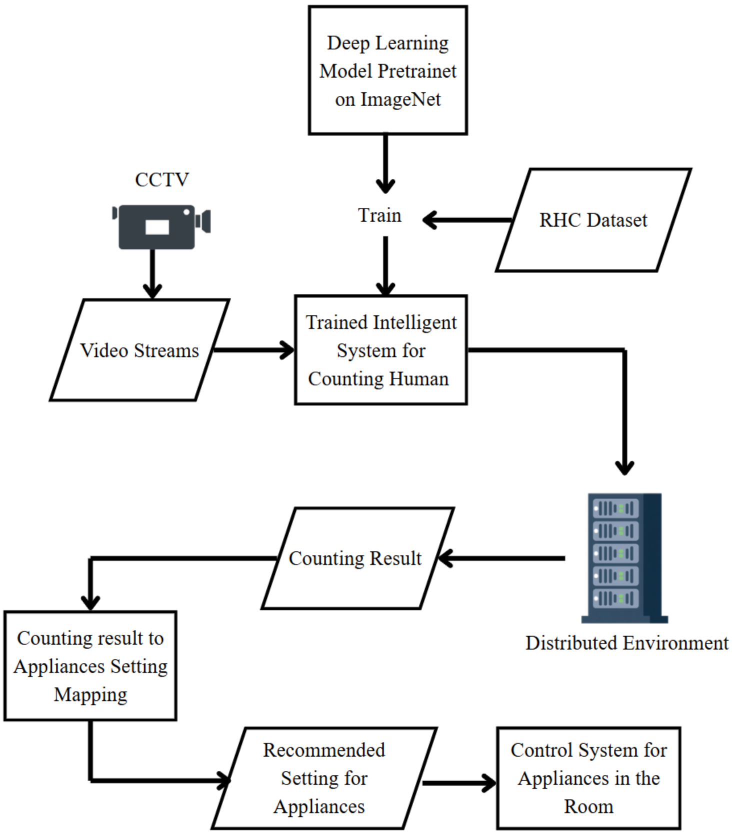


Figure 6. The proposed transfer learning scheme in the intelligent human counting system for smart building management

Source: based on B. Pardamean *et al.* (2019)

The intelligent system can be further enhanced by integrating data-driven approaches used in smart building-integrated photovoltaic (SBIPV) systems. For data-driven SBIPV, four key characteristics are identified (Fig. 7). Data sensing involved the collection of both supply-side information, such as weather conditions and roof angles, and demand-side information, including daily energy usage and prices. Collected data were then processed and analysed to identify occupant behaviour patterns and production characteristics, taking into account factors like shading effects and variable energy consumption profiles. The analysed data were subsequently used for data-driven prediction, which allowed forecasting of future trends in energy generation and consumption.

Finally, data-driven optimisation enabled efficient interaction between energy supply and demand, supporting policy guidance, the design of distributed energy systems, and peer-to-peer (P2P) energy trading.

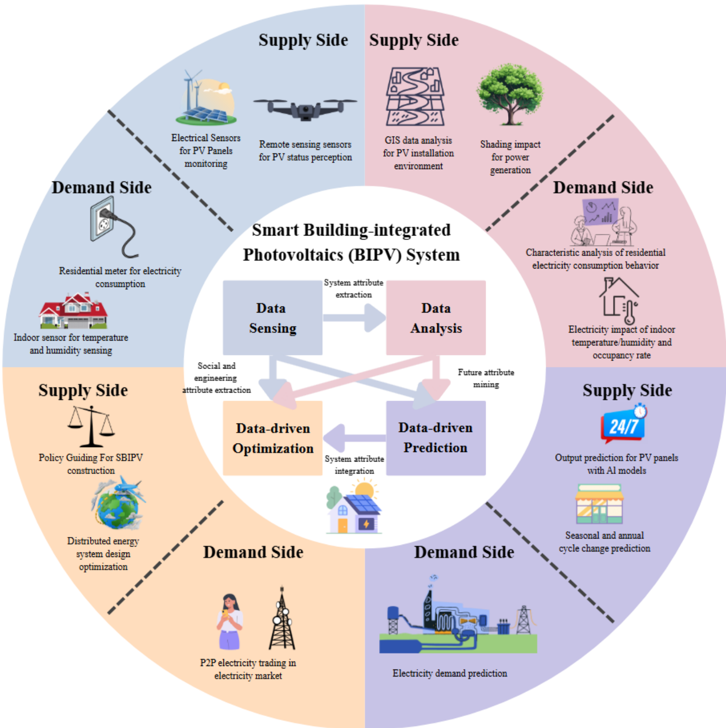


Figure 7. Structure diagram of data-driven SBIPV systems
Source: based on Z. Liu *et al.* (2023)

This integration allowed the intelligent system not only to adjust appliances based on occupant count but also to optimise energy usage dynamically based on real-time and predictive data (Qolomany *et al.*, 2019). Machine learning algorithms (supervised, unsupervised, reinforcement learning, and optimisation) were used for energy consumption forecasting, renewable energy management, intelligent control, and fault diagnostics. Special attention is given to Occupant-Centric Control (OCC) systems, which considered human presence, needs, and comfort to optimise building energy systems. The study highlighted the importance of digitalisation, automation, data collection, and analysis to enhance building efficiency and sustainability (Vattano, 2014). Future power systems required decentralised, customer-centred structures, where buildings actively supported the smart grid (SG). Buildings, responsible for a large share of urban energy use, can provide flexibility through Demand Response programmes, if integrated with advanced Building Energy Management Systems (BEMS). This study proposes a Multi-Agent System-based SG-BEMS framework, using Particle Swarm Optimisation to maximise both energy efficiency and occupant comfort. Lower-level agents process local building data, reducing complexity for higher-level agents and enabling dynamic adaptation of building systems to grid needs, such as voltage control, without compromising comfort. Simulations on a low-voltage feeder demonstrated the system's effectiveness in leveraging building flexibility to support the smart grid.

Thus, modern smart construction technologies provided integrated management of buildings and construction sites, aimed at enhancing efficiency, safety, and user comfort. H. Zhuang *et al.* (2020) noted that the use of sensors, IoT, robotics, drones, BIM, digital twins, and intelligent algorithms enabled the optimisation of workflows, increased productivity, and the promotion of sustainable development. J.L. Hernández *et al.* (2024) reviewed European buildings, noting low energy efficiency and the need for renovation. The authors discussed smart technologies like IoT, Artificial Intelligence (AI), Big Data, BIM, and Building Digital Twins, emphasising user-centred approaches and Smart Readiness Indicator (SRI). This informed research on energy optimisation, autonomous systems, and user-focused smart building design. G. Pinto *et al.* (2022) analysed transfer learning in smart buildings for energy optimisation, occupancy detection, building dynamics, and system control. The study highlighted deep learning, data-driven models, and integration of IoT, smart meters, and AI, supporting predictive control and scalable energy management. M.M.N. Shahrabani & R. Apanaviciene (2025) proposes ML to evaluate smart building integration in smart cities. Using data from 147 buildings and six algorithms (e.g., Support Vector Regression, Random Forest), reseacrhers predicted integration levels and assessed impacts on sustainability, efficiency, and resilience, guiding technology adoption strategies. S. Adhikari *et al.* (2025) reviewed BEMS, outlining components, monitoring, and control methods. Scientists showed how IoT, Renewable Energy Sources, and smart technologies enhanced energy efficiency, occupant comfort, and sustainability. G. Wang *et al.* (2024) reviewed smart building envelopes, which autonomously adapted to environmental changes, while providing insulation, protection, and structural support. The study covered types, optimisation methods, and technologies like smart windows, dynamic insulation, and Phase Change Materials, supporting energy efficiency and indoor comfort. E. Rescorla & N. Modadugu (2012) reviewed Datagram Transport Layer Security version 1.2, highlighting its role in providing secure communication over unreliable datagram-based protocols like UDP, while maintaining confidentiality, integrity, and authentication. Researchers emphasised its applicability in real-time communication systems, sensor networks, and IoT environments, offering security guarantees similar to TLS without needing a reliable transport layer. Z. Shelby *et al.* (2014) examined the CoAP, noting its efficiency in enabling machine-to-machine communication in IoT environments. Scientists emphasised CoAP's small message sizes, use of UDP, and support for asynchronous exchanges and multicast communication, making it ideal for sensor networks, smart homes, and smart buildings. Thus, the analysis of contemporary research demonstrated that smart buildings evolved from isolated automation solutions toward fully integrated, adaptive, and data-driven systems. The combination of IoT infrastructure, digital twins, ML algorithms, and intelligent materials enabled the creation of buildings capable of autonomous decision-making and continuous performance optimisation. The results confirmed that effective smart building implementation required not only technological integration but also a comprehensive evaluation framework that balanced energy efficiency, user comfort, sustainability, and operational resilience.

CONCLUSIONS

Smart buildings represented a transformative paradigm in architecture, combining automated systems, real-time data analysis, and intelligent control to create energy-efficient, sustainable, and occupant-friendly environments. The analysis of experimental projects demonstrated that intelligent environments enhanced user comfort, reduced resource consumption, and improved operational efficiency. Data from analysed projects showed how the integration of IoT devices, machine learning algorithms, and building management systems enabled buildings to operate autonomously, anticipate occupant needs, and optimise energy use. Case studies of smart building-integrated photovoltaic systems highlight how predictive analytics and context-aware energy management allow dynamic adaptation to real-time conditions, reducing energy waste and integrating renewable energy sources efficiently. The Beijing National Aquatics Centre ("Water Cube") demonstrated that the use of ethylene tetrafluoroethylene membranes and intelligent engineering systems enabled energy savings of approximately 30% compared to traditional constructions of similar scale. Also, it was analysed that that the adoption of intelligent management systems can reduce building energy consumption by 10-30%, depending on building type and level of digital integration. The use of digital twins, building management systems, robotics, drones, and advanced sensors in construction and facility management improved planning, monitoring, maintenance, and operational optimisation, contributing to safety, productivity, and environmental sustainability. Overall, smart buildings not only improve occupant comfort and resource efficiency but also support the development of sustainable and intelligent cities, providing a scalable and replicable model for modern urban environments. Their adoption, combined with ongoing technological innovation, was essential for advancing energy-efficient architecture and sustainable urban planning. Future research should prioritise the development of unified evaluation frameworks that combine environmental, technological, and operational indicators to enhance adaptability, resilience, and long-term sustainability.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abo-Elazm, F.M., & Ali, S.M. (2017). The concept of "local smart architecture": An approach to appropriate local sustainable buildings. *International Journal of Cultural Heritage*, 2, 1-12.

[2] Adhikari, S., Nguyen, T.D., & Silverman, E. (2025). A review of smart building energy management systems (BEMS) to enhance building sustainability. In W. Collins, A.J. Perrenoud & J. Posillico (Eds.), *Proceedings of Associated Schools of Construction 61st annual international conference* (Vol. 6; pp. 342-351). Zurich: Easy Chair. doi: 10.29007/sgfr.

[3] Almadani, M., Atalla, S., Himeur, Y., Gawanmeh, A., Alkhazaleh, H., & Mansoor, W. (2025). Uncertainty-aware gradient boosting for smart building energy forecasting. In *8th international conference on signal processing and information security (ICSPIS)* (pp. 1-5). Dubai: IEEE. doi: 10.1109/ICSPIS67605.2025.11318368.

[4] Apanaviciene, R., Vanagas, A., & Fokaides, P.A. (2020). Smart Building Integration into a Smart City (SBISC): Development of a new evaluation framework. *Energies*, 13(9), article number 2190. doi: 10.3390/en13092190.

[5] Behzadi, A., Goudarzi, N., Ploskic, A., Thorin, E., & Sadrizadeh, S. (2026). Advancing an already high-performance smart building with model predictive control: Multi-layer optimization under forecast uncertainty in a real building case. *Applied Energy*, 402, article number 126999. doi: 10.1016/j.apenergy.2025.126999.
[6] BREEAM. (n.d.). Retrieved from https://www.breeam.com.
[7] Casini, M. (2022). Extended reality for smart building operation and maintenance: A review. *Energies*, 15(10), article number 3785. doi: 10.3390/en15103785.
[8] Degha, H.E., Laallam, F.Z., & Said, B. (2019). Intelligent context-awareness system for energy efficiency in smart building based on ontology. *Sustainable Computing: Informatics and Systems*, 21, 212-233. doi: 10.1016/j.suscom.2019.01.013.
[9] Dong, B., Prakash, V., Feng, F., & O'Neill, Z. (2019). A review of smart building sensing system for better indoor environment control. *Energy and Buildings*, 199, 29-46. doi: 10.1016/j.enbuild.2019.06.025.
[10] El-Afifi, M.I., Sedhom, B.E., Eladl, A.A., Elgamal, M., & Siano, P. (2024). Demand side management strategy for smart building using multi-objective hybrid optimization technique. *Results in Engineering*, 22, article number 102265. doi: 10.1016/j.rineng.2024.102265.
[11] Eneyew, D.D., Capretz, M.A.M., & Bitsuamlak, G.T. (2022). Toward smart-building digital twins: BIM and IoT data integration. *IEEE Access*, 10, 130487-130506. doi: 10.1109/ACCESS.2022.3229370.
[12] European Commission. (2010). *Smart hoMes for All (SM4All)*. Retrieved from https://cordis.europa.eu/project/id/611560.
[13] Feng, M., & Wu, H. (2025). Construction of a BIM smart building collaborative design model combining the Internet of Things. *Nonlinear Engineering*, 14(1), article number 20240063. doi: 10.1515/nleng-2024-0063.
[14] Frighi, V. (2022). *Smart architecture – a sustainable approach for transparent building components design*. Cham: Springer. doi: 10.1007/978-3-030-77606-0.
[15] German Sustainable Building Council. (n.d.). Retrieved from https://www.dgnb.de.
[16] Ghayvat, H., Mukhopadhyay, S., Gui, X., & Suryadevara, N. (2015). WSN- and IOT-based smart homes and their extension to smart buildings. *Sensors*, 15(5), 10350-10379. doi: 10.3390/s150510350.
[17] Hernández, J.L., de Miguel, I., Vélez, F., & Vasallo, A. (2024). Challenges and opportunities in European smart buildings energy management: A critical review. *Renewable and Sustainable Energy Reviews*, 199, article number 114472. doi: 10.1016/j.rser.2024.114472.
[18] Hu, X., Zhou, Y., Vanhullebusch, S., Mestdagh, R., Cui, Z., & Li, J. (2022). Smart building demolition and waste management frame with image-to-BIM. *Journal of Building Engineering*, 49, article number 104058. doi: 10.1016/j.jobe.2022.104058.
[19] Hurtado, L.A., Nguyen, P.H., & Kling, W.L. (2015). Smart grid and smart building inter-operation using agent-based particle swarm optimization. *Sustainable Energy, Grids and Networks*, 2, 32-40. doi: 10.1016/j.segan.2015.03.003.
[20] John, G., Clements-Croome, D., & Jeronimidis, G. (2005). Sustainable building solutions: A review of lessons from the natural world. *Building and Environment*, 40(3), 319-328. doi: 10.1016/j.buildenv.2004.05.011.
[21] King, J., & Perry, C. (2017). Smart buildings: Using smart technology to save energy in existing buildings. *American Council for an Energy-Efficient Economy*. *Report A1701*. Retrieved from https://www.aceee.org/research-report/a1701.
[22] Kumar, A., Sharma, S., Goyal, N., Singh, A., Cheng, X., & Singh, P. (2021). Secure and energy-efficient smart building architecture with emerging technology IoT. *Computer Communications*, 176, 207-217. doi: 10.1016/j.comcom.2021.06.003.
[23] Kumaresan, S.S., & Jeyaraj, P.R. (2025). Smart building transferable energy scheduling employing reward shaping deep reinforcement learning with demand side energy management. *Journal of Building Engineering*, 104, article number 112316. doi: 10.1016/j.jobe.2025.112316.
[24] Linder, L., Vionnet, D., Bacher, J.-P., & Hennebert, J. (2017). Big Building Data – a Big Data platform for smart buildings. *Energy Procedia*, 122, 589-594. doi: 10.1016/j.egypro.2017.07.354.
[25] Liu, Z., Guo, Z., Chen, Q., Song, C., Shang, W., Yuan, M., & Zhang, H. (2023). A review of data-driven smart building-integrated photovoltaic systems: Challenges and objectives. *Energy*, 263, article number 126082. doi: 10.1016/j.energy.2022.126082.
[26] Lokshina, L.V., Greguš, M., & Thomas, W.L. (2019). Application of integrated building information modeling, IoT and Blockchain technologies in system design of a smart building. *Procedia Computer Science*, 160, 497-502. doi: 10.1016/j.procs.2019.11.058.
[27] Padmanaban, S., Azimi Nasab, M., Hatami, M., Zand, M., Dashtaki, M.A., & Azimi Nasab, M. (2025). Internet of Things in smart building management system. In O.V.G. Swathika & K. Karthikeyan (Eds.), *Resilient community microgrids*. Hoboken: John Wiley & Sons. doi: 10.1002/9781394272549.ch15.
[28] Pardamean, B., Muljo, H.H., Cenggoro, T.W., Chandra, D.J., & Rahutomo, R. (2019). Using transfer learning for smart building management system. *Journal of Big Data*, 6, article number 110. doi: 10.1186/s40537-019-0272-6.

[29] Pinto, G., Wang, Z., Roy, A., Hong, T., & Capozzoli, A. (2022). Transfer learning for smart buildings: A critical review of algorithms, applications, and future perspectives. *Advances in Applied Energy*, 5, article number 100084. doi: 10.1016/j.adapen.2022.100084.
[30] Qiu, L. (2025). Reinforcement learning approaches for intelligent control of smart building energy systems with real-time adaptation to occupant behavior and weather conditions. *Journal of Computing and Electronic Information Management*, 18(2), 32-37. doi: 10.54097/hr81cg02.
[31] Qolomany, B., Al-Fuqaha, A., Gupta, A., Benhaddou, D., Alwajidi, S., Qadir, J., & Fong, A.C. (2019). Leveraging Machine Learning and Big Data for smart buildings: A comprehensive survey. *IEEE Access*, 7, 90316-90356. doi: 10.1109/ACCESS.2019.2926642.
[32] Rescorla, E., & Modadugu, N. (2012). Datagram Transport Layer Security Version 1.2. *Internet Engineering Task Force (IETF)*. Retrieved from https://www.rfc-editor.org/rfc/pdfrfc/rfc6347.txt.pdf.
[33] Shah, S.F.A., Iqbal, M., Aziz, Z., Rana, T.A., Khalid, A., Cheah, Y.-N., & Arif, M. (2022). The role of machine learning and the Internet of Things in smart buildings for energy efficiency. *Applied Sciences*, 12(15), article number 7882. doi: 10.3390/app12157882.
[34] Shahrabani, M.M.N., & Apanaviciene, R. (2025). Evaluation of smart building integration into a smart city by applying Machine Learning techniques. *Buildings*, 15(12), article number 2031. doi: 10.3390/buildings15122031.
[35] Shelby, Z., Hartke, K., & Bormann, C. (2014). The Constrained Application Protocol (CoAP). *Internet Engineering Task Force (IETF)*. Retrieved from https://www.rfc-editor.org/rfc/pdfrfc/rfc7252.txt.pdf.
[36] Smart Living Lab. (n.d.). Retrieved from https://www.smartlivinglab.ch.
[37] Teixeira, H., Moret, A.R., Aelenei, D., & Gomes, M.G. (2025). Literature review of solar control smart building glazing: Technologies, performance, and research insights. *Building and Environment*, 274, article number 112784. doi: 10.1016/j.buildenv.2025.112784.
[38] U.S. Green Building Council. (n.d.). Retrieved from https://www.usgbc.org/leed.
[39] Vattano, S. (2014). Smart buildings for a sustainable development. *Economics World*, 2(5), 310-324.
[40] Wang, G., Fang, J., Yan, C., Huang, D., Hu, K., & Zhou, K. (2024). Advancements in smart building envelopes: A comprehensive review. *Energy and Buildings*, 312, article number 114190. doi: 10.1016/j.enbuild.2024.114190.
[41] Zhuang, H., Zhang, J., Sivaparthipan, C.B., & Muthu, B.A. (2020). Sustainable smart city building construction methods. *Sustainability*, 12(12), article number 4947. doi: 10.3390/su12124947.

Руслан Мінченков
Аспірант
Одеська державна академія будівництва та архітектури
65029, вул. Дідріхсона, 4, м. Одеса, Україна
https://orcid.org/0000-0003-1635-8317

Архітектура сталого майбутнього: розумна будівля як синтез технології та природи

Анотація. Метою цього дослідження було провести всебічний аналіз технологій розумних будівель та їх інтеграцію в стале, енергоефективне та інтелектуальне урбаністичне середовище. Розумні будівлі розглядалися як системи, що поєднували автоматизовані рішення для опалення, вентиляції, кондиціонування повітря, освітлення, затемнення, безпеки та управління інженерною інфраструктурою, координовані через системи управління будівлею і реалізовані за допомогою технологій IoT, датчиків та актуаторів. Такі системи збирали дані в реальному часі, що дало змогу використовувати прогнозну аналітику, адаптивне управління та енергетичну оптимізацію. Проаналізовано методи машинного навчання, зокрема навчання з учителем, без учителя, підкріплення, нечітку логіку та стохастичну оптимізацію, для прогнозування енергоспоживання, управління відновлювальними джерелами енергії, інтелектуального контролю та діагностики несправностей. Досліджено системи контролю, орієнтовані на мешканців, які враховували наявність людини, її уподобання та комфорт, дозволяючи динамічно коригувати режими роботи будівлі та використання енергії. Була проаналізована інтеграція розумних будівель з розумними мережами на основі вдосконалених систем управління енергоспоживанням будівель, що дозволяли брати участь у програмах реагування на попит, регулюванні напруги та управлінні розподіленими відновлюваними джерелами енергії. Досліджено інтегровані фотоелектричні системи розумних будівель і підходи, засновані на даних, для прогнозування енергогенерації та споживання в реальному часі. Цифрові технології, такі як моделювання інформації про будівлю, цифрові двійники, робототехніка, дрони, обчислення на краю та хмарні платформи, підвищували ефективність процесів проєктування, будівництва, моніторингу, експлуатації та обслуговування. Незважаючи на переваги, залишилися проблеми, пов’язані з високими витратами на впровадження, ризики кібербезпеки, питання сумісності систем та необхідність удосконаленої інфраструктури управління даними. Практична цінність цього дослідження полягає в застосуванні результатів на різних етапах архітектурної практики, включаючи проєктування нових будівель, реконструкцію та модернізацію наявних споруд, а також постійну оптимізацію операцій та управління будівлею

Ключові слова: машинне навчання; цифрові двійники; контроль мешканців; управління енергією; розумна мережа; оптимізація даних; сталий розвиток

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 72.02
DOI: 10.56318/as/1.2026.55

ISSN: 2411-801X
e-ISSN: 2786-7374

Walid Bouhelis
Master, Lecturer
Mohamed Khider University of Biskra
07000, P.O. Box 145 RP, Biskra, Algeria
University of Batna1
05000, 19 Mai Al., Biskra Rd., Batna, Algeria
https://orcid.org/0009-0004-8532-5417

Abdelmalek Arrouf
Professor, Senior lecturer
Laboratory LEMPAU, University of Batna 1
05000, 19 Mai Al., Biskra Rd., Batna, Algeria
https://orcid.org/0000-0003-2471-3200

A systematic shape rules repertoire in architectural design: A proof-of-concept

Abstract. The aim of this study was to identify, structure, and empirically validate a systematic repertoire of elementary form-transformation rules that accurately depicted sketch-based architectural design processes and can be directly implemented in computational environments. To address the lack of a systematically organised, detailed repertoire of shape transformation operations in architectural design research, 48 shape rules were developed through literature review and refined through empirical observation of sketching sessions conducted by two experienced architects. The rules were assigned to two operational categories (Plastic, Structural), one meta-category (Figurative), and 14 rule classes. Protocol analysis confirmed that the repertoire captured the full range of observed form manipulations across 23 sketches and 267 coded transformations, with high intra-coder reliability (Cohen's Kappa: 0.85-0.87), confirming the robustness and clarity of the proposed classification. Structural rules made up 74% of the observed transformations, highlighting the predominance of configurational exploration in early-stage design, whereas Plastic and Figurative rules accounted for 15% and 11%, respectively. Statistical analyses, including principal component analysis and hierarchical cluster analysis, showed a consistent bipartite structure across both designers: structural rules formed a distinct cluster, while plastic and figurative rules grouped, with PC1 explaining 97-99% of the total variance. The practical significance of this research lies in providing a transparent and reusable transformation framework that supports the analysis of architectural sketching behaviour and facilitates the development of rule-based computational design tools

Keywords: architectural sketching; form manipulation; shape grammar; protocol analysis; design cognition

INTRODUCTION

Studies in architectural design confirmed the enduring relevance of rule-based approaches for representing and generating architectural form. Among these, shape grammars remained a foundational paradigm for modelling the iterative transformations, through which architects explored and developed design alternatives. By explicitly encoding form manipulations as rule-based operations, shape grammars provided a formal bridge between design

Suggested Citation:
Bouhelis, B., & Arrouf, A. (2026). A systematic shape rules repertoire in architectural design: A proof-of-concept. *Architectural Studies*, 12(1), 55-66. doi: 10.56318/as/1.2026.55.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 55-66
Received: 14.10.2025 Revised: 12.01.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

cognition, visual reasoning, and computational implementation. Parametric and computational implementations have demonstrated how rule-based systems can support early design exploration by systematically controlling transformations such as translation, rotation, scaling, and subdivision. For instance, A.F.P. Sondakh & A. Indraprastha (2023) proposed a parametric method combining shape grammar and generative components within a Grasshopper environment to guide spatial and functional reasoning during early-stage residential design. Similarly, X.-H. Xie *et al.* (2025) showed how parametric shape grammar rules implemented in Grasshopper environments enabled controlled, rule-driven form variation through explicit transformation operations.

Shape grammar approaches have also been applied to the analysis and generation of architectural form within specific spatial and cultural contexts. S. Çelik & Z. Şahin Çağli (2024) also applied shape grammar as an analytical and generative tool for facade design, identifying formation rules for detached houses on Ankara's Çınar Street through Boolean operations (join, intersect, differ) and transformation commands (rotate, mirror, shift, scale). Research demonstrated how extracted rules can be computationally implemented in CAD systems (AutoCAD, Showcase) to generate new facade designs for high-rise residences, while maintaining urban texture continuity. These bidirectional applications – analysing existing forms to extract rules, then applying those rules to generate new designs – exemplified the analytical and synthetic capabilities of shape grammar methodologies. It illustrated the capacity of grammars to encode complex formal logics, while remaining adaptable to contextual constraints. F.A. Linas & K. Chithra (2024) documented a wide diversity of shape grammar applications across architectural design, computational modelling, and spatial analysis. The authors also noted substantial variation in how transformation rules were defined, structured, and operationalised, limiting methodological consistency and comparability across studies. Parallel research streams have sought to expand the expressive power of grammar-based systems through bio-inspired models and hybrid computational pipelines. M. Kleiss *et al.* (2025) explored bio-inspired generative grammars for complex spatial configurations, while A. Plocharski *et al*. (2025) integrated grammar rules with machine learning techniques for façade generation. Although these approaches produced sophisticated generative outputs, it tended to embed transformation logic within complex computational workflows, making the underlying operations less explicit and more difficult to interpret or reuse.

S. Yiannoudes (2025) emphasised that, despite rapid advances in deep learning, rule-based form generation remained critical for maintaining transparency, interpretability, and designer control. Similarly, T. Berčič (2024) identified challenges in translating parametric and algorithmic innovations into standardised, interpretable transformation frameworks that aligned with architects' actual design practices, highlighting the importance of integrating shape grammars into parametric design tools to support systematic form manipulation. So, these works confirmed that rule-based transformation systems remained central to architectural design research. Also, it was revealed a persistent shortcoming: transformations were often defined at high levels of abstraction, tailored to specific domains, or embedded within opaque computational pipelines. What remained insufficiently addressed was the articulation of a fine-grained, systematically organised repertoire of elementary transformation operations that can accurately describe how architects manipulate form during design, while remaining directly implementable in computational systems. Despite advances in shape grammar methodologies and hybrid generative approaches (2023-2025), there was a lack of a systematically organised, fine-grained repertoire of shape transformation operations capable of accurately capturing designers' manipulations in a way that supported direct computational implementation. Broad categories such as "outline transformation" or "form modification" were insufficient for algorithmic mapping, whereas explicit operations – like rotation, translation, subdivision, bending, insertion, and replacement – can be directly translated into computational procedures.

MATERIALS AND METHODS

Methodology of this study involved a focused sample of two experienced architects, deliberately selected to test whether the repertoire can successfully capture the full range of transformations observed in residential design activities. The transformation repertoire was developed through a two-stage process combining theoretical synthesis and empirical observation. Stage 1- literature synthesis: a systematic review of the literature on shape grammars, sketching, and design transformation was conducted to ensure alignment with modern research trends, including bio-inspired generative grammars, parametric extensions, and hybrid computational approaches, while seminal works were referenced for historical context. Transformation operations were extracted at a fine-grained, operational level, including rotation, translation, scaling, subdivision, aggregation, and deletion. Similar operations described with varying terminology were consolidated, while operations rarely observed in sketches were excluded. Stage 2 – empirical refinement: the preliminary rule set was iteratively refined through observation of two architects performing residential design tasks. Transformations not adequately captured by literature-derived rules led to additional categories, while redundant or indistinguishable rules were merged or removed. The final repertoire comprised 48 clearly defined shape rules, organised into 14 operational classes and grouped under three higher-level categories: plastic transformations: modify external appearance or outline (size, form, or texture); structural transformations: alter spatial or topological relationships; figurative transformations: affect representational visualisation without changing design outcomes.

This hierarchical structure enabled identification of recurring patterns, while preserving operational detail for computational implementation. By grounding the repertoire simultaneously in established theory and observed design behaviour, this approach balanced formal rigor with empirical validity. The resulting transformation system was sufficiently detailed to capture nuanced sketch-based manipulations, yet structured enough to support computational implementation and comparative analysis across designers and design tasks. Having developed the repertoire through literature synthesis, its content and structure were validated through empirical observation of design activities using protocol analysis. Protocol analysis enabled systematic capture of design behaviours through recordings of verbalisations and sketching activities. The think-aloud technique, in which participants vocalised their thoughts, while designing, was adopted. The analysis comprised three steps: data collection, protocol description (segmentation and coding), and data processing (Bouhelis & Arrouf, 2024). Three architects initially participated in the study, with two selected for analysis based on protocol completeness and verbalisation clarity. Both participants (Architect 1 and Architect 2) had over 20 years of professional experience in residential design and had completed multiple residential projects. This focused sample size aligned with proof-of-concept studies in design research and with the study's objective of testing the repertoire's descriptive adequacy rather than achieving statistical generalisation.

The experiment comprised two phases totalling 55 minutes. Participants designed a house for a plot within a residential subdivision, producing freehand sketches, while thinking aloud. Two video cameras captured the activity: one recording the designer's gestures and facial expressions, the other documenting sketch production and detailed manipulations. Video recordings allowed for detailed analysis of both verbal protocols and graphical transformations performed during the design process (Bouhelis & Arrouf, 2024). Following data collection, protocols were segmented into analysis units. Each sketch was treated as a distinct segment, as graphical outputs directly revealed shape rule applications. Video recordings and verbalisations aided rule identification. Sketches were sequenced chronologically and organised into transformation tables for pairwise comparison between successive sketches. Each sketch was compared with its predecessor to identify form transformations, which were then coded using the shape rules repertoire. The protocols were coded following a test-retest coding procedure with adjudication: the same coder performed initial coding, then recoded all protocols after completion, and finally compared the two versions to establish the final codification through adjudication of discrepancies. Intra-coder reliability was assessed using two measures: percentage agreement between coding rounds (Architect 1: 95%; Architect 2: 93%), and Cohen's Kappa coefficient calculated on the independent coding rounds before adjudication (Architect 1: $k = 0.87$; Architect 2: $k = 0.85$) (Table 1).

Table 1. Intra-coder reliability measures

Measure	Architect 1	Architect 2	Interpretation
Percentage agreement	95%	93%	Excellent (>90%)
Cohen's Kappa	0.87	0.85	Almost perfect

Source: based on J.R. Landis & G.G. Koch (1977)

To validate the structural coherence of the repertoire, both Principal Component Analysis (PCA) and hierarchical cluster analysis using Ward's method with Euclidean distance were performed on the coded protocols. These statistical methods tested whether the proposed three-category classification system (Plastic, Structural, and Figurative rules) corresponded to empirically observable patterns in how architects deployed shape transformations. The study received ethical approval from the laboratory's Scientific Council LEMPAU-2023-HRP-037 (Bouhelis & Arrouf, 2023). Also, the study was conducted in accordance with the norms of The Declaration of Helsinki (2013). All participants provided written consent and were informed of their right to withdraw at any time.

RESULTS AND DISCUSSION

Analysis of the empirical data confirmed that architects' shape transformations can be systematically captured using the proposed repertoire of 48 rules, organised into a hierarchical system comprising two operational categories (Plastic and Structural), a meta-category (Figurative), and fourteen classes of operative rules. The theoretical grounding and empirical validation of each category have been presented, followed by an examination of the statistical patterns that emerged from their deployment across designers and design tasks. Plastic shape rules related to the first strategy identified by F.D.K. Ching (2007) as a "slug". This strategy was defined as transformation by "metamorphosis" or "plastic transformation" (Wetzel *et al.*, 2006). The term "plastic" pertained to the external appearance and outline of an element or a form, to the set of lines, shapes, or colours. Plastic shape rules were most commonly utilised to refine and enhance architectural forms (Prats *et al.*, 2009). For instance, bending a volume's outline or changing its proportions were plastic transformations that modified appearance, while maintaining overall organisation. This category of shape rules was decomposed into four different classes. These classes describe shape transformations that affected the visual properties of a form or an element as: conformation, size, colour, and texture. The second strategy, corresponded to what F.D.K. Ching (2007) metaphorically likened to a "lobster"

(Fig. 1). It was the process of producing forms through adjustment and combination. The term "structure" referred to the "internal constitution" and the "internal relations" within the architectural form, as well as the relationships among shapes and elements – specifically geometrical and topological relations (Borie *et al.*, 2006). These transformations were termed "structural transformations" or "transformations by composition".

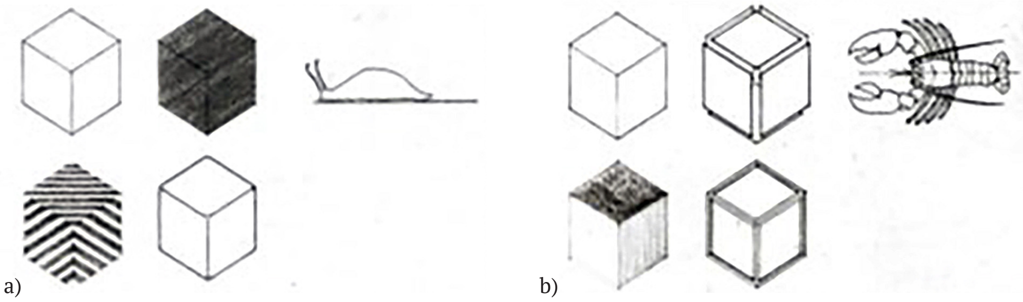


Figure 1. Examples of plastic form in architecture
Note: a - architectural form "lobster"; b – architectural form "slug"
Source: based on F.D.K. Ching (2007)

Structural transformations were primarily used to explore different spatial relationships between elements and to investigate the variety of solutions concerning the organisation, the layout, and the composition of a design. Structural shape rules were more likely to result in significant changes in shape compared to plastic transformations (Prats *et al.*, 2009). For example, adding a new volume to an existing configuration, or rotating an element, changes the overall design organisation and spatial relationships. A. Borie *et al.* (2006) noted that it included three classes of shape rules, namely: topological relations (position), geometrical relations (orientation), and constitution. The category of figurative shape rules occupied a distinct theoretical position within the repertoire, functioning as a meta-category rather than as a third equivalent category alongside plastic and structural rules. This distinction stemmed from a fundamental ontological difference: while plastic and structural rules directly transformed the architectural form itself, figurative rules operated at a representational level, transforming how the form was visualised, explored, and evaluated without modifying the design solution itself. This meta-categorical status was justified by several observations: first, figurative rules exhibited an asymmetric relationship with transformational rules. Plastic and structural transformations can be visualised through various representational modes (e.g., a structural change can be examined through plans, sections, or 3D views), but changes in representation do not produce formal transformations. Rather, it facilitated the application of transformational rules by enabling designers to select the most appropriate view for exploring or evaluating specific aspects of their design. Second, figurative rules served a mediating function between the designer and the design artifact. They do not generate new design alternatives but rather provide different perspectives on existing solutions, supporting the cognitive processes of form exploration and evaluation.

For instance, switching from a plan view to a section (a figurative transformation) does not alter the building but revealed spatial relationships that may inform subsequent structural or plastic transformations. Figurative rules were primarily utilised to enable designers exploring and visualising the shape transformations they perform. Their role was thus to test and detail visually-figured solutions generated by architects. This meta-category concerned transformations of the type of representation, the change of the rule's space or object, the change of the rule's space or floor (de Biasi, 2000), the point of view (Prats *et al.*, 2009), the direction of view, the size of the sketch, and finally its level of complexity (Rodgers *et al.*, 2000). This meta-categorical conceptualisation had methodological implications for protocol analysis. The frequency and sequencing of figurative rules can reveal designers' exploration strategies: a high rate of view changes may indicate complex spatial reasoning, while the temporal relationship between figurative and transformational rules can illuminate how designers prepared, executed, and verified their form manipulations. This hierarchical structure – with figurative rules at a meta-level supporting plastic and structural transformations at the operational level – provided a more nuanced understanding of the sketching process and offered a conceptual framework for both design process analysis and computer-aided-design tools development. Figure 2 summarised the final structure of the repertoire. The repertoire encompassed both elementary and composite transformations identified in residential architectural sketching tasks. Table 2 presented the distribution of these transformations across operational classes and higher-level manipulation categories, as observed throughout the experimental work. Notably, Plastic and Figurative transformations prevailed during later compositional stages, while Structural transformations emerged predominantly in early exploratory design phases.

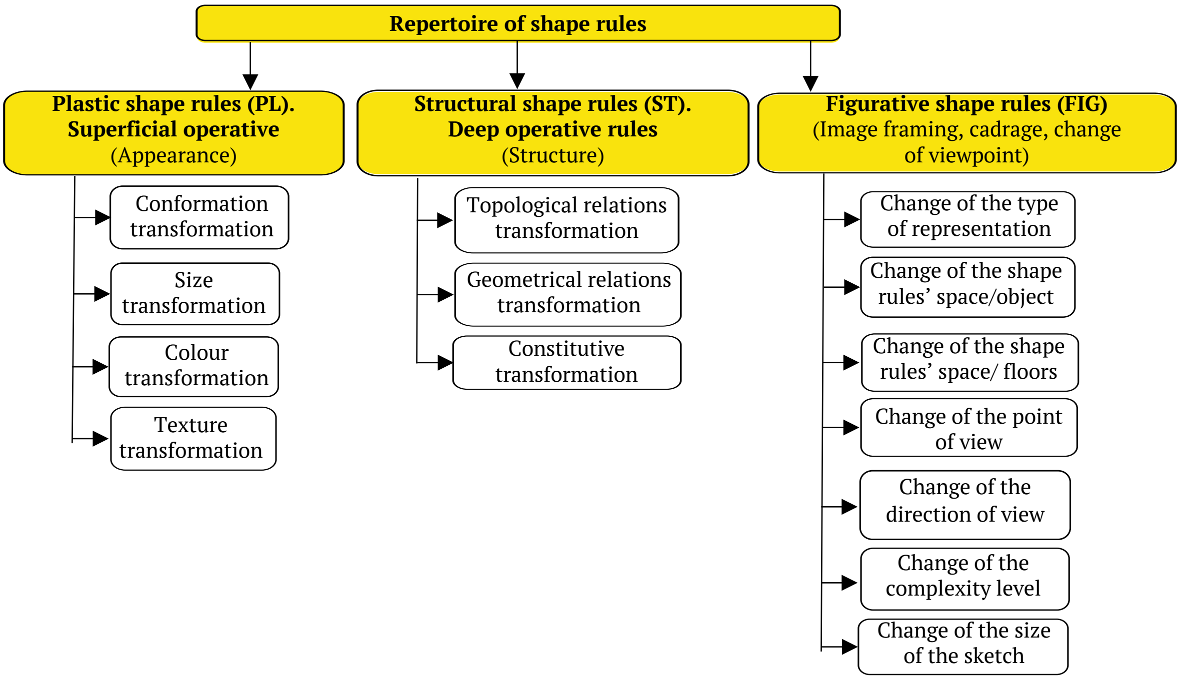
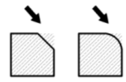
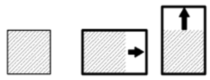
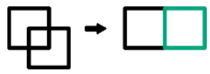
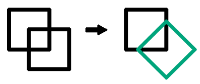
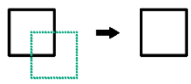


Figure 2. Global structure of the shape rules' repertoire

Source: developed by the authors

Table 2. The final constitution of the repertoire of shape rules

Categories of shape rules	Classes of shape rules	Examples	Illustrations
Plastic (PL)	Conformation transformation	Truncate, bend, push, fold, pierce, twist, pinch	
	Size transformation	Change length/width/depth	
	Colour transformation	Change colour	
	Texture transformation	Change texture	
Structural (ST)	Topological relations transformation	Change position	
	Geometrical relations transformation	Rotate, reflexion	
	Constitutive transformation	Add, delete, split, combine	
Figurative (FIG)	Change of: Type of representation Shape rules' space/object Shape rules' space/floors Point of view Direction of view Complexity level Size of the sketch	Change representation type, extend sketch, change floor	

Source: developed by the authors

Sequential analysis of sketches revealed consistent patterns in rule deployment. Across both participants, Structural rules accounted for 74% of observed transformations, Plastic rules 15%, and Figurative rules 11%, reflecting the dominance of structural reorganisation in initial residential designs. Plastic transformations were frequently combined with Structural rules, producing compound manipulations without altering the hierarchy of operations. Figurative transformations were primarily applied for clarifying design intent or adjusting visual readability. Figure 3 illustrated selected transformations from Architect 1, showing examples of Plastic (scaling), Structural (translation and aggregation), and Figurative (sketch overlay and annotation) rules applied to successive sketches. This figure demonstrated how the repertoire provided a consistent, operational framework for mapping observed design behaviours.

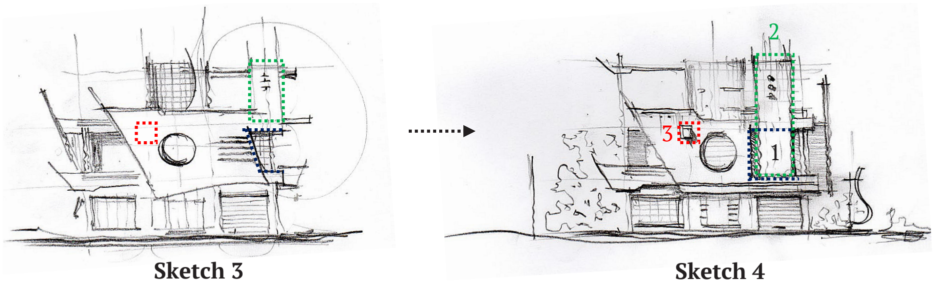


Figure 3. Example of coding process: transformations from Sketch 3 to Sketch 4 required 36 shape rules (Architect 1)
Source: developed by the authors

To validate the content of the repertoire, the identified shape rules were applied to the sketches produced by the two subjects. Two parameters were then observed: their "completeness", and their "relevance". "Completeness" meant the rules captured all the transformations performed by the architects, while "relevance" meant it was all involved. Following the coding procedure, sketches were analysed using the shape rules repertoire. The coding of the segments was recorded for each subject in an "objects/attribute" table. Table 3 represented the objects, and the categories of shape rules serve as attributes.

Table 3. An excerpt of the quantification table of the protocols of Architect 2

Segments	Categories of shape rules		
	Plastic (PL)	Structural (ST)	Figurative (FIG)
Sketch 2	0	5	0
Sketch 3	1	5	1
Sketch 4	0	1	1

Source: developed by the authors

Across both subjects, a total of 23 sketches were produced, yielding 267 coded shape transformations (Table 4). Two temporal references guided the coding: the immediately preceding sketch (chronological reference) and the sketch containing the element before modification (referential sketch). For example, if an element was added in Sketch 5, modified in Sketch 7, and deleted in Sketch 10, the referential sketch for the deletion in Sketch 10 was Sketch 5 (where the element was created), not Sketch 7 or Sketch 9. This approach ensured accurate tracking of element lifecycles throughout the design process. Structural rules were most frequent (74%, n = 198), followed by plastic rules (15%, n = 40) and figurative rules (11%, n = 29). This distribution reflected the exploratory nature of early-stage design, where organisational decisions (Structural) dominated over refinement (Plastic) and representational adjustments (Figurative). The similarity in rule distribution between subjects (Architect 1: 73% ST, 15% PL, 12% FIG; Architect 2: 79% ST, 17% PL, 4% FIG), suggested consistency in how architects deploy shape rules during early-stage design, though the small sample size (n = 2) limited generalisability.

Table 4. Descriptive statistics of the outputs of the coding process of the two Architect's

Descriptive statistics	Architect 1	Architect 2	Total
Total number of sketches	19	4	23
Total number of shape rules	219	48	267
Plastic shape rules (PL) Count percentage	n = 32 15%	n = 8 17%	n = 40 15%
Structural shape rules (ST) Count percentage	n = 160 73%	n = 38 79%	n = 198 74%

Table 4. Continued

Descriptive statistics	Architect 1	Architect 2	Total
Figurative shape rules (FIG) Count percentage	n = 27 12%	n = 2 4%	n = 29 11%
Mean of shape rules/sketch	11.53	12	11.60

Source: developed by the authors

The description and codification demonstrated that shape rules, categories, and classes within the repertoire were fully utilised to describe and codify the shape transformations executed by the participating architects. Moreover, the repertoire supported all operations performed by the subjects in this proof-of-concept. Consequently, it can be asserted that all shape rules were necessary and sufficient for a complete description of the form manipulation and generation process observed within the architectural design activity of the two participating architects. Preliminary saturation was considered to have been reached under the following conditions: 1) all observed shape transformations could be coded using the existing repertoire without requiring new rule creation; 2) the two operational categories (Plastic, Structural) and the meta-category (Figurative) consistently captured all transformation types across participants; and 3) no unclassifiable transformations emerged from the protocol analysis. While preliminary saturation was achieved within this exploratory sample, demonstrating the internal coherence and applicability of the repertoire, theoretical saturation would require validation across a larger, more diverse population of architects with varying experience levels, design styles, and task types. The current repertoire should be considered as providing coverage for the observed design activities in this proof-of-concept, establishing a foundation for future validation studies rather than claiming universal completeness at this stage. PCA was performed on the coded protocols from both architects, extracting components that explained 100% of total variance in both cases. The first principal component (PC1) accounted for 97.64% of variance for Architect 1 and 99.58% for Architect 2, indicating a highly unidimensional structure where virtually all discrimination occurs along a single dimension. Figure 4 presented biplots of the first two components (PC1: horizontal and PC2: vertical) for each architect.

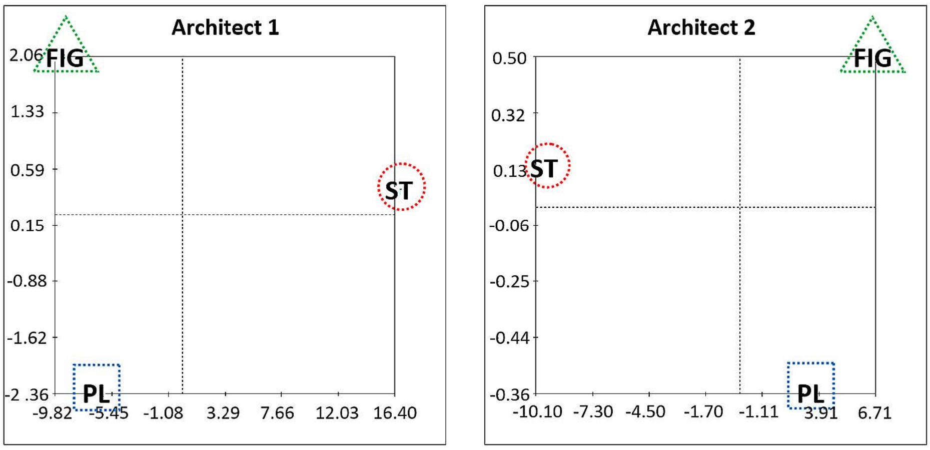


Figure 4. Factor analysis biplots

Note: green triangles – Figurative rules (FIG), red circles – Structural rules (ST), blue rectangles – Plastic rules (PL). Axes represent principal components with percentage of variance explained

Source: developed by the authors

The analysis revealed clear differentiation among the three rule categories along PC1, though with opposite orientations between subjects – a common and interpretatively neutral feature of PCA. Both architects showed a consistent bipartite structure: ST formed an isolated cluster at one extreme of PC1, while PL and FIG rules clustered together at the opposite extreme. This consistent pattern demonstrated the distinctiveness of each rule category, and the closer functional association between Plastic and Figurative rules relative to structural rules – supporting the hierarchical classification system. Figure 5 provided comparative overlays that highlighted the structural consistency across subjects. Shape rule categories (ST, PL, FIG) projected on first two components for Architect 1 (top left) and Architect 2 (top right). Bottom panels showed comparative overlays (black = reference; red/blue = subject-specific). U1 explained 97.64%/99.58% of variance; U2 explained 2.36%/0.42%.

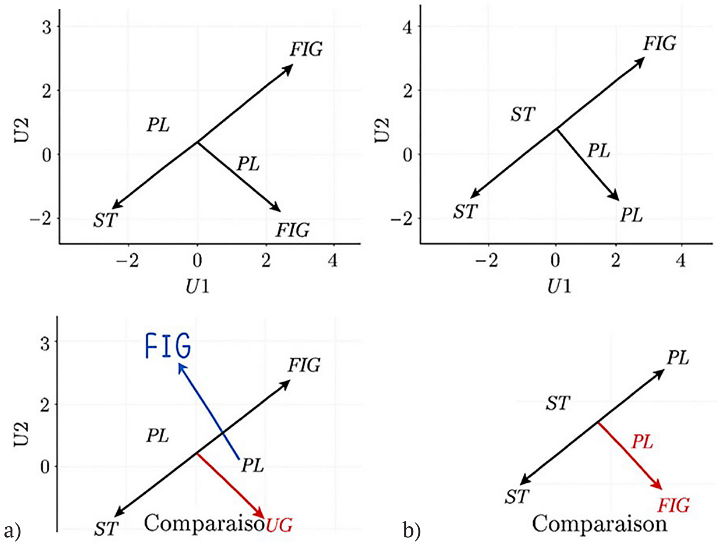


Figure 5. Principal component analysis biplots
Note: a – shape rule categories for Architect 1; b – shape rule categories for Architect 2
Source: developed by the authors

This classification was further validated by hierarchical cluster analysis using Ward's method with Euclidean distance, illustrated in the graphs in Figure 6. The dendrograms revealed a consistent bipartite structure across both architects. Structural rules (ST) formed an isolated cluster, separating at a linkage distance of approximately 23.7 for Architect 1 and 5.6 for Architect 2. In contrast, Plastic (PL) and Figurative (FIG) rules clustered together, suggesting functional similarity despite their ontological difference. This clustering pattern supported the conceptualisation of figurative rules as a meta-category that operated in parallel with plastic rules during vertical transformations (refinement and detailing), while structural rules drove lateral transformations (exploration of alternative configurations). The consistency of this pattern across both participants strengthened the validity of the three-level classification system.

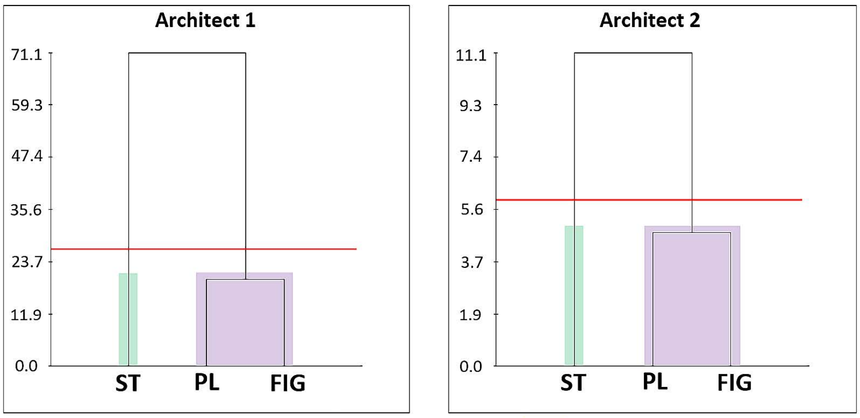


Figure 6. Hierarchical cluster analysis dendrograms for Architect 1 and Architect 2
Note: green colour – Structural rules (ST), purple colour – Plastic rules (PL) + Figurative rules (FIG). Red line indicates clustering threshold
Source: developed by the authors

Finally, the highly unidimensional structure revealed by PCA (PC1 explaining 97-99% of variance) suggested that a single underlying dimension – interpreted here as a lateral-vertical transformation continuum – captured most of the variation in rule deployment. This parsimony was significant in relation to contemporary computational design research. In machine learning-based generation, X. Zhuang *et al.* (2025) emphasised that overly complex models can reduce transparency and control. Results of this research suggested that a relatively simple operational continuum may be sufficient for capturing the dominant structure of transformation behaviour in early design, supporting the feasibility of interpretable computational tools.

Table 5. Summary of empirical patterns and theoretical interpretations

Pattern	Finding	Interpretation
Bipartite structure (PCA + cluster)	ST isolated; PL + FIG together	Two operational modes: exploration vs. refinement
Rule clustering	PL ≈ FIG despite ontological difference	Representational refinement coupled with plastic transformation
Frequency distribution	74% ST, 15% PL, 11% FIG	Early-stage design dominated by configurational exploration
Dimensionality	PC1: 97-99% variance	Lateral–vertical continuum sufficient

Source: developed by the authors

So, this study identified the shape transformations performed by architects during the form manipulation and generation phase of architectural design activity, and proposed a systematic framework capable of capturing them. To achieve this, research on grammar-based generation, performance-driven form exploration, and AI-assisted design workflows was gathered and compared, providing a contemporary basis for understanding how design rules can be formalised and operationalised during early-stage architectural design. S. Jang *et al.* (2025) highlighted that contemporary AI-based systems increasingly depended on data quality, evaluation protocols, and methodological transparency. While such systems can generate highly coherent formal outputs, they often lacked explicit interpretability in terms of step-wise transformation logic. Similarly, Y. Huang *et al.* (2025) argued that generative AI workflows reshaped design practice but still struggle to represent design reasoning as a sequence of explicit and meaningful operations. In this context, this work contributed a complementary approach: rather than replacing design operations with black-box generation, it formalised and classified the transformations themselves, preserving interpretability and aligning with human-centred computational design. The contributions of this study in relation to existing research were multifaceted. A primary contribution was the identification and definition of 48 distinct shape rules, enabling a detailed and operational description of shape manipulation and transformation actions carried out by architects in early design. Unlike many contemporary generative frameworks that focused on producing optimised outcomes or increasing output diversity, this study foregrounded fine-grained transformation semantics, providing an explicit inventory of micro-operations that can be directly mapped to computational procedures.

A.A.C. Al-Hashim & C. Alalouch (2025) demonstrated how shape grammar can support early design learning by structuring creativity through explicit rule systems. Their contribution confirmed the educational value of grammars, yet their focus remained primarily on pedagogy rather than on constructing a comprehensive and systematically classified repertoire of transformation rules. In contrast, this study contributed a more detailed operational taxonomy intended for both analytical and computational implementation. At the level of performance-driven design, L. Chen *et al.* (2025) proposed a design-grammar-based framework for high-rise office towers in early-stage design, integrating grammar generation with performance objectives. It was equally, what had been performed by S.M. Elgohary *et al.* (2023), who introduced a performative-driven form-finding framework that combined shape grammar with evolutionary genetic algorithms to generate building forms optimised for energy performance. Applied to the Sakan Masr prototype housing project in Cairo, this methodology implemented shape operations through addition and subtraction rules, while encoding environmental variables – including spatial daylight autonomy (SDA) and annual sunlight exposure (ASE) – as fitness functions. These works supported the idea that grammars can be integrated into optimisation workflows. However, such approaches often treat grammar rules as design constraints or generative heuristics rather than as an empirically grounded repertoire of transformations observed in actual designer activity. This study complemented performance-driven grammar research by supplying the missing layer of explicit transformation granularity, which can strengthen the interpretability and implementability of performance-based generative systems.

X. Zhuang *et al.* (2025) reviewed advancements and challenges in machine learning for generative architectural design, noting that modern research must balance automation with designer control and interpretability. Overall, studies confirmed that grammar-based and AI-assisted generative approaches were rapidly expanding. However, this work addressed a persistent gap: the lack of a systematically organised, fine-grained repertoire of shape transformations grounded in empirical observation of designers' operations. This contribution was particularly relevant for interpretability, pedagogy, and tool development. Beyond these conceptual contributions, the empirical analyses revealed several patterns that warrant theoretical interpretation. First, the bipartite structure observed in both PCA and cluster analysis – with structural rules forming an isolated cluster and plastic-figurative rules grouping together – suggested that early-stage architectural design was dominated by two distinct operational modes.

Results if this research indicated that early design transformations were structured and interpretable, and that computational systems may benefit from explicitly representing these two operational modes. Also, the clustering of plastic and figurative rules together, despite their ontological difference (transformative vs. representational), revealed a functional similarity in how architects deployed them during refinement. This was consistent with the observation that AI-based workflows often excel at producing refined visual outputs but struggle to distinguish representational operations from transformational ones. S. Yiannoudes (2025) highlighted that deep learning models can generate convincing architectural imagery, yet it frequently blur the distinction between "form transformation" and "representation enhancement". Empirical pattern of this study supported the need for a meta-category of figurative rules, clarifying that representational actions were not secondary but structurally integrated into early design refinement. The predominance of structural rules (74% of total transformations) in early-stage design task aligned with the configurational nature of conceptual design. This finding complemented grammar-based performance workflows such as L. Chen *et al.* (2025), where early-stage generation of tower forms was primarily concerned with organisational logic before detailed refinement. Results of this study provided empirical support for this sequencing: designers prioritise structural transformations during early exploration, while Plastic and Figurative rules became more prominent during later refinement. The repertoire directly enhanced design pedagogy. While A.A.C. Al-Hashim & C. Alalouch (2025) demonstrated that grammars can structure creativity and guide early design learning, and D. El-Mahdy (2022) showed how they can be used to improve learning through practice, repertoire of this research built on these contributions by offering a richer, more detailed inventory of transformational actions that can be explicitly taught, thereby helping students to expand their operational design vocabulary. Finally, the repertoire may also support generative morphology workflows by offering a general and systematically organised set of transformations that can be adapted to diverse morphological contexts.

CONCLUSIONS

This study addressed a fundamental gap in design research by developing a comprehensive, empirically validated repertoire for systematically categorising shape transformations in architectural design. The research successfully demonstrated the feasibility of encoding all observed form manipulations using 48 shape rules organised into two operational categories (Plastic, Structural), a meta-category (Figurative), and 14 rule classes. Empirical validation through protocol analysis of two architects' residential design tasks confirmed that the repertoire accurately captured the full range of form manipulations observed during early-stage sketching. The repertoire's structural coherence was validated through statistical analysis revealing a bipartite pattern supporting the theoretical distinction between lateral and vertical transformations. Principal Component Analysis showed PC1 explaining 97.64%/99.58% of variance across subjects, demonstrating clear differentiation among rule categories. Hierarchical cluster analysis confirmed consistent structural patterns: structural rules forming isolated clusters, while plastic and figurative rules grouped together, validating the three-category classification system. The distribution of rule use (74% Structural, 15% Plastic, 11% Figurative) reflected the exploratory nature of early-stage design and showed consistency across both subjects. The results demonstrated that architects' shape transformations can be systematically described, providing a reproducible framework for both descriptive and computational applications, with potential for three complementary domains: analysing sketching activity to uncover cognitive processes, developing pedagogical tools to enhance design education, and creating computational systems to support early-stage design exploration. Small sample size ($n = 2$ architects) limited the generalisability of findings, and while sufficient to test the viability and internal coherence of the repertoire, it cannot establish universal applicability across all architects, design contexts, or architectural styles. Beyond these limitations, the findings suggested that the repertoire can be integrated into a computational tool. Future research aims to develop a computer-assisted-design software based on the obtained repertoire to support designers and architects during the process of form generation and manipulation.

ACKNOWLEDGEMENTS

We would like to thank the three architects: Hammou Abdelhakim, Bouhadjar Abdelkader, and Bouchebaa Nasreddine, who generously shared their experiences and opened up their offices; and Laboratory LEMPAU, University Batna 1, for its institutional support.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Al-Hashim, A.A.S., & Alalouch, C. (2025). Structured creativity: Shape grammar as a pedagogical tool for early design learning. *Archnet-IJAR: International Journal of Architectural Research*, 1-21. doi: 10.1108/ARCH-07-2025-0309.

[2] Berčič, T. (2024). The gradual process of change: Integrating shape grammars in parametric tools. *Creativity Game*, 12, 46-54. doi: 10.15292/IU-CG.2024.12.046-054.

[3] Borie, A., Micheloni, P., & Pinon, P. (2006). *Form and deformation of architectural and urban objects*. Marseille: Editions Parenthèses.

[4] Bouhelis, W., & Arrouf, A. (2023). *Ethical approval – LEMPAU-2023-HRP-037*. doi: 10.5281/zenodo.18822677.

[5] Bouhelis, W., & Arrouf, A. (2024). *Excerpt of the design protocol of Architect 2 (H.A.): 10-minute video excerpt and selected sketches from a 45-minute experimental design session*. doi: 10.5281/zenodo.18841255.

[6] Çelik, T., & Şahin Çağli, Z. (2024). Productive facade studies with rule-based design: Ankara Çınar Street sampling. *Tasarım + Kuram*, 20, 76-88. doi: 10.59215/tasarimkuram.dtj431.

[7] Chen, L., Zhang, Y., & Zheng, Y. (2025). A performance-based generative design framework based on a design grammar for high-rise office towers during early design stage. *Frontiers of Architectural Research*, 14(1), 145-171. doi: 10.1016/j.foar.2024.07.001.

[8] Ching, F.D.K. (2007). *Architecture. Form, space & order* (3rd ed.). Hoboken: John Wiley & Sons, Inc.

[9] De Biasi, P-M. (2000). For a genetic approach to architecture. *Genesis*, 14, 13-65.

[10] Elgohary, S.M., Abdin, A.R., & Mohamed, R.M. (2023). Performative driven form finding in the early design stage. *Journal of Engineering and Applied Science*, 70, article number 73. doi: 10.1186/s44147-023-00225-5.

[11] El-Mahdy, D. (2022). Learning by doing: Integrating shape grammar as a visual coding tool in architectural curricula. *Nexus Network Journal*, 24, 701-716. doi: 10.1007/s00004-022-00608-w.

[12] Huang, Y., Zhang, Z., Su, P., Li, T., Zhang, Y., He, X., & Li, H. (2025). Performance-driven generative design in buildings: A systematic review. *Buildings*, 15(24), article number 4556. doi: 10.3390/buildings15244556.

[13] Jang, S., Roh, H., & Lee, G. (2025). Generative AI in architectural design: Application, data, and evaluation methods. *Automation in Construction*, 174, article number 106174. doi: 10.1016/j.autcon.2025.106174.

[14] Kleiss, M., Mokhtarimousavi, S., Dai, S., & Alani, M. (2025). Bio-generative design morphology with Radiolaria: An application of a nature-based generative shape grammar for geometrical design of space frames. In *SIGraDi 2024* (pp. 2479-2490). Barcelona: UIC Barcelona International University of Catalonia. doi: 10.48550/arXiv.2508.08572.

[15] Landis, J.R., & Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159-174. doi: 10.2307/2529310.

[16] Linas, F.A., & Chithra, K. (2024). A comprehensive literature review and bibliometric analysis on shape grammar theory and applications in architecture. *International Journal of Architectural Computing*, 24(1), 7-34. doi: 10.1177/14780771241281809.

[17] Plocharski, A., Swidzinski, J., & Musialski, P. (2025). Pro-DG: Procedural diffusion guidance for architectural facade generation. *arXiv*. doi: 10.48550/arXiv.2504.01571.

[18] Prats, M., Lim, S., Jowers, I., Garner, S.W., & Chase, S. (2009). Transforming shape in design: Observations from studies of sketching. *Design Studies*, 30(5), 503-520. doi: 10.1016/j.destud.2009.04.002.

[19] Rodgers, P.A., Green, G., & McGowan, A. (2000). Using concept sketches to track design progress. *Design Studies*, 21(5), 451-464. doi: 10.1016/S0142-694X(00)00018-1.

[20] Sondakh, A.F.P., & Indraprastha, A. (2023). Spatial configuration by rules: An experimental parametric shape rules by shape grammar method. *ARTEKS: Jurnal Teknik Arsitektur*, 8(2), 205-218. doi: 10.30822/arteks.v8i2.1626.

[21] The Declaration of Helsinki. (2013). Retrieved from https://www.wma.net/what-we-do/medical-ethics/ declaration-of-helsinki/

[22] Wetzel, J.-P., Bignon, J-C., & Belblidia, S. (2006). Use of morphological operators to assist architectural design in early stage. In *Joint international conference on computing and decision making in civil and building engineering* (pp. 3511-3518). Montréal, Canada.

[23] Xie, X.-H., Guo, S., Yan, H., Xu, Y., Zhu, H., Hong, P., & Chen, Y. (2025). Parametric landscape facilities aesthetic design method based on SOR model and Hybrid Kansei engineering: A case of landscape corridors. *Buildings*, 15(17), article number 3065. doi: 10.3390/buildings15173065.

[24] Yiannoudes, S. (2025). Shaping architecture with generative Artificial Intelligence: Deep learning models in architectural design workflow. *Architecture*, 5(4), article number 94. doi: 10.3390/architecture5040094.

[25] Zhuang, X., Zhu, P., Yang, A., & Caldas, L. (2025). Machine learning for generative architectural design: Advancements, opportunities, and challenges. *Automation in Construction*, 174, article number 106129. doi: 10.1016/j.autcon.2025.106129.

Валід Бухеліс
Магістр, викладач
Університет Мохамеда Хідера в Біскрі
07000, P.O. Box 145 RP, м. Біскра, Алжир
Лабораторія LEMPAU, Університет Батни 1
05000, 19 Mai Al., Biskra Rd., м. Батна, Алжир
https://orcid.org/0009-0004-8532-5417

Абдельмалек Арруф
Професор, старший викладач
Лабораторія LEMPAU, Університет Батни 1
05000, 19 Mai Al., Biskra Rd., м. Батна, Алжир
https://orcid.org/0000-0003-2471-3200

Систематичний репертуар правил трансформації форм у архітектурному дизайні: концептуальне доведення

Анотація. Метою цього дослідження було виявлення, структуризація та емпірична перевірка систематичного репертуару елементарних правил трансформації форм, що точно відображають процеси архітектурного дизайну на основі ескізів та можуть бути безпосередньо впроваджені в обчислювальні середовища. Для вирішення проблеми відсутності систематизованого та детального репертуару операцій трансформації форм у дослідженнях архітектурного дизайну було розроблено 48 правил трансформації форм через огляд літератури та уточнено за допомогою емпіричних спостережень за сесіями малювання, проведеними двома досвідченими архітекторами. Правила були розподілені на дві операційні категорії (пластичні, структурні), одну мета-категорію (фігуративні) та 14 класів правил. Протокольний аналіз підтвердив, що репертуар охоплював увесь спектр спостережуваних маніпуляцій з формами через 23 ескізи та 267 закодованих трансформацій, з високою внутрішньою узгодженістю кодерів (Каппа Когена: 0.85-0.87), що підтвердило надійність та чіткість запропонованої класифікації. Структурні правила становили 74 % спостережуваних трансформацій, підкреслюючи домінування конфігураційного дослідження на ранніх етапах проєктування, тоді як пластичні та фігуративні правила складали 15 % і 11 % відповідно. Статистичні аналізи, включаючи аналіз головних компонент та ієрархічний кластерний аналіз, показали послідовну дводольну структуру у обох дизайнерів: структурні правила утворювали окремий кластер, в той час як пластичні та фігуративні правила групувалися, при цьому PC1 пояснював 97-99 % загальної дисперсії. Практичне значення цього дослідження полягає в наданні прозорої та багаторазової платформи трансформацій, який підтримує аналіз поведінки при архітектурному малюванні та сприяє розвитку засобів обчислювального проєктування на основі правил

Ключові слова: архітектурне малювання; маніпуляція формами; граматика форм; протокольний аналіз; пізнання в дизайні

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 711+658.2
DOI: 10.56318/as/1.2026.67

ISSN: 2411-801X
e-ISSN: 2786-7374

Ehab Mahmoud Okba
Doctor of Architecture and Environmental Design, Professor
Fayoum University
PO Box 63514, Al-Mashtal Str., Fayoum, Egypt
https://orcid.org/0000-0002-7665-1649

Mohga Emam Embaby
Doctor of Architecture and Urban Design, Professor
Fayoum University
PO Box 63514, Al-Mashtal Str., Fayoum, Egypt
https://orcid.org/0000-0001-5520-1967

Bahaaeldin Mostafa Saad[*]
Master of Architecture, Assistant Lecturer
Fayoum University
PO Box 63514, Al-Mashtal Str., Fayoum, Egypt
https://orcid.org/0000-0001-8496-2984

Importance-priority matrix analysis for evaluating smart mobility indicators in Egypt's New Administrative Capital

Abstract. The rapid development of Greenfield Smart Cities necessitated a strategic approach to prioritising mobility technology to ensure operational efficiency and sustainability. The aim of the study was to develop a prioritisation hierarchy for evaluating smart mobility indicators in the context of urbanism, using an importance-priority matrix analysis for Egypt's New Administrative Capital. By integrating the four symbiotic pillars (infrastructure, digital transformation, service delivery, and governance), the research transitioned from theoretical description to a data-driven execution hierarchy. Methodology employed importance-priority matrix analysis, supported by the Friedman test and Kendall's coefficient of 0.759. Analysis based on thresholds of 4.0985 for importance and 18.00 for priority revealed a bifurcated trajectory for smart mobility management. Results identified 12 Quick Wins in Quadrant 1, led by Electronic Parking Space Reservation (Mean = 4.9574) and Reduction of Traffic Accident Rate (Mean Rank = 5.52), offering high-impact solutions essential for building early public trust. The matrix uncovered a strategic readiness gap in 10 foundational systems in Quadrant 2, designated as Strategic Investment. Indicators such as Real-Time Data-Driven Intelligent Transportation Systems (Mean = 4.8085) and Traffic Data Aggregation faced low execution priority (Mean Ranks > 18.00) due to fragmented institutional mandates and slow planning procedures. 7 indicators in Quadrant 4 related to sustainable behaviour (avoid/shift goals), exemplified by Expansion of Cycling Network Infrastructure (Mean= 2.4468), recorded the lowest importance and priority scores. It was concluded that a successful transition to an integrated mobility ecosystem required a fundamental paradigm shift from a technology-centric model to a governance-first strategy. The developed framework served as a standardised, transferable decision-support tool enabling policymakers to align technological investment with governance readiness. This research contributed to bridging the

Suggested Citation:
Okba, E.M., Embaby, M.E., & Saad, B.M. (2026). Importance-priority matrix analysis for evaluating smart mobility indicators in Egypt's New Administrative Capital. *Architectural Studies*, 12(1), 67-79. doi: 10.56318/as/1.2026.67.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 67-79
Received: 06.10.2025 Revised: 02.01.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

gap between technological deployment and sustainable urban planning through transit-oriented development and smart governance frameworks, ensuring that smart mobility transitions were both resilient and sustainable

Keywords: urban modernisation; intelligent transportation systems; statistical ranking; institutional fragmentation; data-driven governance

INTRODUCTION

The period from 2015 to 2025 had witnessed a radical shift in global urban planning, moving towards integrating technology to achieve city efficiency and resilience. This evolution was particularly evident in rapidly expanding urban cities, where traffic congestion had emerged as a complex structural challenge that exceeded road capacity. D. Beckers & L. Mora (2025) argued that the primary challenge in Smart City Development (SCD) was not technological, but a governance gap rooted in conceptual and process ambiguity. The authors emphasised that SCD must be viewed as a socio-technical transition requiring shared sensemaking among stakeholders to align technological innovation with urban goals. This perspective underscored that fragmented governance and the lack of citywide coordination often led to failure in orchestrating SCD projects. Digital transformation, supported by the Internet of Things (IoT) and Artificial Intelligence (AI), provided a promising path for predictive mobility. M. Islam (2025) demonstrated through a meta-analysis that AI-enabled adaptive control systems can reduce vehicle delays by up to 36%, thereby lowering fuel consumption and greenhouse gas emissions. However, the author emphasised that the efficacy of these algorithms was fundamentally linked to institutional readiness, noting that technical sophistication alone cannot overcome fragmented governance.

J.M. Ngossaha *et al.* (2024) argued that implementing such high-cost infrastructure was often unfeasible for developing nations due to limited capital and fragmented digital utilities. To bridge this gap, researchers proposed a cost-effective architecture for Vehicular Ad-hoc Networks (VANETs) utilising existing motorcycle taxis as mobile roadside units (mRSUs). Scientist's case study in Douala demonstrated that this adaptive approach, which integrated real-time data management and blockchain-based security, had significant potential to improve mobility systems and avoid congestion, achieving a 10% reduction in CO_2 emissions and a 15% decrease in traffic waiting times. E.M. Gideon & F. Chepleting (2026) employed a systematic review grounded in the Resource-Based View (RBV) to argue that technical efficacy in smart transportation was strictly contingent upon institutional capacity and cross-sectoral coordination. Notably, the study identified institutional fragility and policy inconsistency as primary inhibitors to mobility transitions in the Global South. Within this context, scientists highlighted a critical gap in Egypt's New Administrative Capital (NAC); while the city adopts the 15-minute city model and high-tech urban design, a disconnect persists between planning and lived environmental efficiency. This gap reinforced the urgent need for a governance-driven approach to prioritise strategic (Intelligent Transportation Systems) ITS interventions, ensuring that digital competencies align with institutional assets to deliver public value rather than remaining mere technical artifacts. Researchers H.B. Faheem *et al.* (2024) confirmed that structural imbalances in the Greater Cairo Metropolitan Area, exacerbated by rapid urban sprawl, require a transition toward advanced technological interventions. The authors argued that, while traditional road expansions often proved inadequate by attracting more traffic, ITS can potentially reduce CO_2 emissions by up to 80% and achieve fuel savings of 45% on urban roads. Since transport was a major source of urban emissions, the national transition was being guided by the Avoid-Shift-Improve (ASI) framework to ensure resilience. This direction, as detailed by R.A. Fathy (2025), involved the deployment of ITS across 6,000 km of core highways using international standards like ISO 14813 to ensure interoperability between field sensors and central control centres, effectively mitigating congestion and enhancing road safety.

E. Metwally *et al.* (2023) identified that despite this advanced physical foundation, there was a lack of real-time digital interfaces for traffic congestion information and environmental monitoring. According to S. Tarek & T.I. Nasreldin (2023), Egypt was rapidly transitioning toward an intermediate phase of smart mobility, which demanded the integration of smart solutions into ongoing network upgrades. However, scientists identified a significant discrepancy between expert ratings and actual performance, where high-priority attributes, such as reaching destinations efficiently and on time, remained under-addressed. D.K. Das (2024) argued that transforming urban centres into Smart Sustainable Cities (SSC) required a symbiotic relationship between four cornerstones: infrastructure, service delivery, governance, and digital transformation. M.A. Ali (2021) highlighted the NAC's innovative governance model managed by the Administrative Capital for Urban Development (ACUD). This model employed a holistic Quadruple Helix strategy and a dual-management system via the Commander Control Centre (CCC) and City Operating Centre (COC), supported by a mandatory Smart City Code to ensure operational sustainability. So, the purpose of this study was to establish a prioritisation framework for assessing smart mobility indicators within the urban context, employing an importance-priority matrix analysis for Egypt's New Administrative Capital.

MATERIALS AND METHODS

This study adopted quantitative descriptive and analytical research design, selected to address the inherent complexity of digital transformation phenomena within new urban contexts. The research process was conducted over an eight-month period from May 2025 to December 2025, comprising three integrated phases: 1) identification and validation of mobility indicators; 2) expert survey administration; 3) statistical prioritisation and gap analysis via IPMA. The study focused on the NAC in Egypt, considered a Greenfield environment and a Living Lab, justifying the development of a standardised framework applicable to similar future smart cities. To ensure a comprehensive and scientifically grounded framework, the 35 mobility indicators were derived through a rigorous three-step selection process. In the first step (Identification), an initial pool of 58 potential indicators was established through a systematic review of ITS literature (Nosratabadi *et al.*, 2020; Islam, 2025). In addition, the guidelines on Sustainable Urban Mobility Plans (SUMPs) (Rupprecht Consult, 2019) and the technical framework for the integrated provision of "Mobility as a Service" (MaaS) (Signor *et al.*, 2019) were examined. A primary pillar for this technical selection was the Egyptian Code for the Foundations and Requirements for Planning, Management, Operation, and Sustainability of Smart Cities, issued by the HBRC (Housing and Building National Research Center, 2023), ensuring alignment with the Egyptian urban context. To ensure global competitiveness, these indicators were cross-referenced and supplemented with the CITY-keys evaluation framework (Bosch *et al.*, 2017), specifically adopting transport-related KPIs focusing on multi-modal accessibility, public transit services quality, and ICT-driven operational efficiency. Furthermore, this identification phase was enriched through a benchmarking analysis of seven leading global and regional smart city cases – Zurich, Singapore, Amsterdam, Boston, Dubai, Riyadh, and Algiers – ensuring the indicators' applicability to the NAC's Greenfield environment by integrating successful operational models ranging from adaptive management to predictive systems. These seven cities were strategically selected to provide a diverse comparative lens for the identification phase. While Amsterdam and Boston offered established frameworks for pilot scalability and predictive maintenance, Singapore, Dubai, and Riyadh provided essential benchmarks for high-level governance and centralised traffic management. Furthermore, the experiences of Zurich and Algiers offered critical lessons on regulatory interoperability and adaptive management in urban environments undergoing digital transformation. By integrating these diverse operational models, ranging from AI-driven adaptation to top-down governance, this benchmarking ensured that the initial pool of indicators was both globally competitive and applicable to the NAC's unique Greenfield environment.

In the second step of the process (Contextual Screening), the synthesised list of 58 indicators was manually screened to exclude components irrelevant to Greenfield contexts or those not applicable to the NAC's current infrastructure phase, resulting in a refined list of 42 indicators. Finally, in the third step (Validation), a panel of three academic experts reviewed this filtered list for content validity and conceptual clarity. This rigorous evaluation led to the final selection of 35 indicators categorised into seven core criteria (A1 to A7). To provide a robust theoretical foundation, these components were structured to reflect the symbiotic relationship among the four pillars of smart sustainable city development: Infrastructure, which provided the bedrock for seamless delivery; Digital Transformation, acting as the catalyst for innovation and efficiency; Service Delivery, the operational output; and Governance, which ensured strategic alignment with the evolving needs of citizens (Das, 2024). This categorisation accounted for the interplay between internal technical requirements and external strategic mandates, aligning with the dual-theoretical approach to adoption dynamics (Fatorachian & Kazemi, 2025). This approach ensured that the selected criteria encompass all smart mobility dimensions required for a Greenfield environment, ranging from institutional readiness (e.g., TMC structure) to user-centric services. To clarify the internal structure, Table 1 demonstrated the conceptual framework and the hierarchical structure of the measurement instrument, illustrating the linkage between the seven main criteria and their respective sub-indicators.

Table 1. Conceptual framework and structure of the measurement instrument

	Smart mobility management strategic framework						
Criterion	**A.1 Sustainable transportation**	**A.2 Smart mobility**	**A.3 Passenger services provision**	**A.4 Traffic management centre**	**A.5 Smart parking systems**	**A.6 Intelligent transit management systems**	**A.7 Smart land use planning**
Indicators	Avoidance of unnecessary trips	Real-time data-driven ITS	Trip Information Provision	Incident Management Systems	Automated smart parking systems	Bus control unit	Smart land use distribution
	Shift to more sustainable modes	Advanced traffic management systems	Electronic Payment Systems	Traffic Data Aggregation	Electronic Parking Space Reservation	Automatic Vehicle Location	Planning development axes supporting transport network
	Optimising operational efficiency (vehicles & infrastructure)	Advanced traveller information systems	Emergency Services Provision	Environmental Conditions Monitoring	Smart payment/ Ticketing	Transit Depot Management	Smart Planning to Pre-empt Traffic Issues

Table 1. Continued

	Smart mobility management strategic framework						
Criterion	**A.1 Sustainable transportation**	**A.2 Smart mobility**	**A.3 Passenger services provision**	**A.4 Traffic management centre**	**A.5 Smart parking systems**	**A.6 Intelligent transit management systems**	**A.7 Smart land use planning**
Indicators	Expansion of cycling network infrastructure	Operational systems for commercial vehicles	Security and Safety Measures	Reduction of Greenhouse Gas Emissions	Smart payment/ Ticketing	Bus Scheduling and On-Board Payment System	Smart Planning to Pre-empt Traffic Issues
	Ease of access to city services	Advanced public transportation system	Improved Access to Vehicle Sharing Alternatives	Reduction of Traffic Accident Rate		Driver and Fuel Monitoring System	
						Traffic Signal Priority Management	
	Ease of access to commercial and health services					Accessibility to Public Transport Modes	
						Quality Assurance for Public Transport	

Source: developed by the authors

The data collection process followed a structured procedure, where inclusion criteria targeted key stakeholders with relevant professional backgrounds or a direct link to the NAC. This targeted sample included urban planners, architects, government officials, administrative officers, real estate developers, and academics, alongside informed residents as potential users of the NAC network. To maintain data integrity, incomplete submissions and responses exhibiting inconsistent answering patterns were filtered out. The final sample (N = 47) demonstrated professional expertise and diversity, which was critical for the reliability of the IPMA matrix. As detailed in Table 2, approximately 66% of the participants possess over 15 years of work experience, while 23.4% have between 10 to 15 years. Furthermore, the sample exhibited a strategic distribution across sectors; the public sector accounted for 44.7%, reflecting its regulatory role in the NAC, while the private sector and academia represented 34.0% and 21.3%, respectively. Notably, the academic sector representation (21.3%) included residents with academic backgrounds, ensuring that the evaluation of complex ITS indicators integrated both theoretical knowledge and lived operational experience. The participants' roles included technical experts (planners, architects, and developers) at 48.9%, administrative officials at 27.7%, and academics at 12.8%, ensuring the feedback was derived from a well-informed group capable of evaluating complex ITS indicators.

Table 2. Socio-demographic and professional profile of the expert sample (N = 47)

Variable	Category	Frequency (n)	Percentage (%)
Professional role	Technical experts (planners, architects, developers)	23	48.94
	Administrative & officials	13	27.66
	Academics	6	12.77
	Potential users (residents)	5	10.64
Work sector	Public/Government sector	21	44.68
	Private sector	16	34.04
	Academic/Research	10	21.28
Work experience	Less than 10 years	5	10.64
	10-15 years	11	23.40
	Over 15 years	31	65.96

Source: developed by the authors

In compliance with the ethical principles of The Declaration of Helsinki (2013), all experts were informed of the research objectives. Their voluntary completion and submission of the survey served as free and informed consent, ensuring the protection of their privacy and the confidentiality of their personal information throughout the data collection and analysis process. The survey was conducted online via Google Forms ensuring accessibility for the diverse expert groups. The questionnaire was designed in dual-question format for each criterion: 1) measuring the importance of 35 specific ITS indicators using a five-point Likert scale (5 = Essential impact, 1 = Weak impact); 2) measuring priority by asking respondents to perform a Forced Ranking of the same indicators (1 = Highest priority) based on technical feasibility and current operational needs. Following data collection, the responses were processed using IBM SPSS Statistics v.28. Descriptive statistics, including means and standard deviations, were calculated to evaluate the importance scores of the 35 ITS indicators, while the Friedman test was employed to determine the statistical significance of priority ranks due to its robustness with non-parametric data derived from forced ranking. Additionally, Kendall's W coefficient was used to quantify the level of consensus among the 47 experts, providing a reliability index for the collective judgment. The IPMA matrix was implemented to visualise the disparity between perceived importance and execution priority, enabling the identification of strategic readiness gaps. The overall arithmetic means of both dimensions served as a neutral cut-off line for the IPMA matrix, forming the horizontal and vertical axes. The calculation of the overall arithmetic means of the importance scores, which formed the horizontal cut-off line:

$$Overall\ Mean\ (Importance) = \frac{\sum_{i=1}^{k} Meani}{N}, \quad (1)$$

where $Mean_i$ – the calculated mean importance score for the i-th indicator; k – the total number of indicators ($k = 35$) included in the analysis.

Similarly, the overall arithmetic means of the priority ranks, which forms the vertical cut-off line:

$$Overall\ Mean\ Rank\ (Priority) = \frac{\sum_{i=1}^{k} Mean\ Ranki}{N}, \quad (2)$$

where $Mean\ Rank_i$ – the calculated mean rank for the i-th indicator, derived from Friedman's test; k – the total number of indicators ($k = 35$) included in the analysis.

By utilising the IPMA matrix, this study identified the gaps between perceived importance and execution priority, allowing for an empirical interpretation of implementation challenges. This approach enabled the identification of systemic non-technical barriers by analysing indicators that recorded high importance but low execution priority, thereby translating the statistical results into a strategic executive roadmap for smart mobility management.

RESULTS AND DISCUSSION

The results of the IPMA provided an empirical foundation for prioritising smart transportation components in the NAC. By comparing expert assessments of perceived importance with chronological implementation priorities, critical strategic gaps were identified. Specifically, the findings distinguish between immediate operational Quick Wins and foundational components requiring long-term structural investment. The perceived importance of the indicators (Y-axis) was analysed in light of operational implementation priorities (X-axis) to identify strategic gaps through the IPMA matrix. To clarify the application of the IPMA methodology, the calculation for the Electronic Parking Space Reservation (EPS) indicator was provided as an example based on the specific data obtained for the NAC. The position of each indicator in the matrix was determined by its coordinates (X, Y): Importance (Vertical Axis – Y): this was the arithmetic mean of the Likert scores (1-5). For the EPS indicator, the mean importance was calculated as:

$$Mean_{EPS} = 4.9574. \quad (3)$$

Since this value was higher than the overall grand mean (Y = 4.0985), it was categorised as a high-importance indicator. Priority (Horizontal Axis – X): This was derived from the Mean Rank of the Friedman test (where a lower rank indicates higher priority). For the EPS indicator, the statistical output was:

$$Mean\ Rank_{EPS} = 9.04. \quad (4)$$

Since this rank was lower (more prioritised) than the overall grand mean rank (X = 18.00), it was categorised as a high-priority indicator. Matrix Positioning: by plotting these coordinates (9.04, 4.9574), the EPS indicator was empirically positioned in Quadrant 1 (Quick Wins). This indicated that the system was both highly valued by experts and feasible for immediate implementation. Table 3 presented the statistical results for the perceived importance of the indicators, including arithmetic means and standard deviations, with the indicators ranked in descending order based on their mean importance scores.

Table 3. Descriptive statistics of indicator importance

Rank (Importance)	Indicator	Criterion	Mean (Y)	Standard deviation (SD)
1	Electronic Parking Space Reservation	A.5 (SPS)	4.9574	0.20
2	Emergency Services Provision	A.3 (PSP)	4.9362	0.32
3	Traffic Signal Priority Management	A.6 (ITMS)	4.9362	0.32
4	Security and Safety Measures	A.3 (PSP)	4.9149	0.46
5	Traffic Data Aggregation	A.4 (TMC)	4.8511	0.55
6	Real-Time Data-Driven ITS	A.2 (SM)	4.8085	0.58
7	Incident Management Systems	A.4 (TMC)	4.8085	0.54
8	Trip Information Provision	A.3 (PSP)	4.7660	0.43
9	Quality Assurance for Public Transport	A.6 (ITMS)	4.7234	0.50
10	Advanced Traffic Management Systems	A.2 (SM)	4.5319	0.50
11	Driver and Fuel Monitoring System	A.6 (ITMS)	4.5319	0.50
12	Advanced Public Transportation System	A.2 (SM)	4.5106	0.51
13	Advanced Traveller Information Systems	A.2 (SM)	4.4681	0.50
14	Reduction of Traffic Accident Rate	A.4 (TMC)	4.4468	0.58

Table 3. Continued

Rank (Importance)	Indicator	Criterion	Mean (Y)	Standard deviation (SD)
15	Automatic Vehicle Location	A.6 (ITMS)	4.4468	0.62
16	Ease of Access to Commercial and Health Services	A.1 (ST)	4.4043	0.50
17	Optimising Operational Efficiency	A.1 (ST)	4.3617	0.49
18	Electronic Payment Systems	A.3 (PSP)	4.3191	0.47
19	Automated Smart Parking Systems	A.5 (SPS)	4.3191	0.47
20	Bus Control Unit (BCU)	A.6 (ITMS)	4.3191	0.47
21	Transit Depot Management	A.6 (ITMS)	4.3191	0.47
22	Accessibility to Public Transport Modes	A.6 (ITMS)	4.1489	0.69
23	Planning Development Axes Supporting Transport Network	A.7 (SLUP)	3.5745	0.50
24	Smart Payment/Ticketing	A.5 (SPS)	3.5319	0.50
25	Reduction of Greenhouse Gas (GHG) Emissions	A.4 (TMC)	3.4894	0.51
26	Shift to More Sustainable Modes	A.1 (ST)	3.4681	0.50
27	Environmental Conditions Monitoring	A.4 (TMC)	3.4681	0.50
28	Bus Scheduling and On-Board Payment System	A.6 (ITMS)	3.4681	0.50
29	Ease of Access to City Services	A.1 (ST)	3.4468	0.50
30	Improved Access to Vehicle Sharing Alternatives	A.3 (PSP)	3.4255	0.50
31	Smart Planning to Pre-empt Traffic Issues	A.7 (SLUP)	3.4255	0.50
32	Operational Systems for Commercial Vehicles	A.2 (SM)	3.3191	0.47
33	Avoidance of Unnecessary Trips	A.1 (ST)	3.0426	0.78
34	Smart Land Use Distribution	A.7 (SLUP)	2.5106	0.51
35	Expansion of Cycling Network Infrastructure	A.1 (ST)	2.4468	0.50
Overall mean			4.0985	

Source: developed by the authors

So, the descriptive results confirmed a high consensus on the importance of operational solutions for safety and efficiency. The indicator Electronic Parking Space Reservation tops the list with the highest mean of 4.9574, closely followed by Emergency Services Provision and Traffic Signal Priority Management with a joint mean of 4.9362. Conversely, Smart Land Use Distribution (2.5106) and Expansion of Cycling Network Infrastructure (2.4468) recorded the lowest means, indicating their strategic importance was secondary to immediate technical solutions in the experts' priorities. Furthermore, the low Standard Deviation (SD) values for the highest-importance indicators (such as 0.20 for the Electronic Parking Space Reservation indicator) suggested a strong consensus among experts regarding their strategic importance, while higher values (such as 0.78 for the Avoidance of Unnecessary Trips indicator) indicated greater variability in expert assessment. The overall mean for all indicators was 4.0985, which represented the horizontal cut-off line for the IPMA matrix. To analyse the operational implementation priority, the Friedman test was applied to the forced rankings (representing the X-axis of the IPMA matrix) to determine the chronological execution sequence. Table 4 summarised statistical reliability and consensus tests supporting the ranking significance.

Table 4. Statistical reliability and consensus tests for indicators ranking

Statistical Measure	Value
Sample size (*N*)	47
Kendall's *W*	0.759
Friedman Test Chi-square (χ^2)	1212.427
Degrees of freedom (*df*)	34
Asymptotic significance (*p*-value)	<.001

Note: statistical analysis was performed using the Friedman test to determine ranking significance, and Kendall's coefficient of concordance to measure the strength of expert agreement
Source: developed by the authors

As shown in Table 4, the results of the Friedman test indicated a highly statistically significant difference in the prioritisation of the 35 indicators ($\chi^2 = 1212.427$, $df = 34$, p-value $< .001$), confirming that the final ranking was non-random. Additionally, Kendall's coefficient of concordance ($W = 0.759$) confirmed a strong and reliable consensus among the experts regarding the priority list. Subsequently, Table 5 presented the mean ranks for the indicators, where a lower mean rank signified a higher priority for implementation.

Table 5. Final implementation priorities (Mean Ranks from Friedman's test)

Rank (Priority)	Indicator	Criterion	Mean Rank (X)
1	Reduction of Traffic Accident Rate	A.4 (TMC)	5.52
2	Ease of Access to Commercial and Health Services	A.1 (ST)	5.82
3	Trip Information Provision	A.3 (PSP)	6.10
4	Advanced Public Transportation System	A.2 (SM)	6.93
5	Planning Development Axes Supporting Transport Network	A.7 (SLUP)	7.04
6	Automated Smart Parking Systems	A.5 (SPS)	7.34
7	Traffic Signal Priority Management	A.5 (SPS)	7.97
8	Electronic Parking Space Reservation	A.5 (SPS)	9.04
9	Ease of Access to City Services	A.4 (TMC)	9.22
10	Incident Management Systems	A.6 (ITMS)	9.22
11	Driver and Fuel Monitoring System	A.6 (ITMS)	10.13
12	Smart Land Use Distribution	A.7 (SLUP)	13.06
13	Electronic Payment Systems	A.3 (PSP)	13.20
14	Advanced Traveler Information Systems	A.2 (SM)	14.32
15	Emergency Services Provision	A.3 (PSP)	14.48
16	Smart Planning to Pre-empt Traffic Issues	A.7 (SLUP)	14.55
17	Smart Payment/Ticketing	A.5 (SPS)	16.34
18	Operational Systems for Commercial Vehicles	A.2 (SM)	17.76
19	Advanced Traffic Management Systems	A.2 (SM)	20.60
20	Reduction of Greenhouse Gas (GHG) Emissions	A.4 (TMC)	20.91
21	Traffic Data Aggregation	A.4 (TMC)	21.28
22	Transit Depot Management	A.6 (ITMS)	21.96
23	Expansion of Cycling Network Infrastructure	A.1 (ST)	22.76
24	Optimising Operational Efficiency	A.1 (ST)	23.49
25	Security and Safety Measures	A.3 (PSP)	23.65
26	Automatic Vehicle Location	A.6 (ITMS)	23.84
27	Real-Time Data-Driven ITS	A.2 (SM)	26.13
28	Shift to More Sustainable Modes	A.1 (ST)	27.39
29	Bus Control Unit (BCU)	A.3 (PSP)	28.10
30	Improved Access to Vehicle Sharing Alternatives	A.6 (ITMS)	28.30
31	Environmental Conditions Monitoring	A.4 (TMC)	28.79
32	Avoidance of Unnecessary Trips	A.1 (ST)	29.54
33	Quality Assurance for Public Transport	A.6 (ITMS)	30.82
34	Accessibility to Public Transport Modes	A.6 (ITMS)	31.56
35	Bus Scheduling and On-Board Payment System	A.6 (ITMS)	32.85
Overall mean rank			18.00

Source: developed by the authors

Results showed that high implementation priorities were focused on immediate operational and safety requirements. The indicator Reduction of Traffic Accident Rate recorded the lowest mean rank (5.52), closely followed by Ease of Access to Commercial and Health Services (5.82), indicating an immediate implementation priority for these components. Conversely, the highest ranked indicators were Accessibility to Public Transport Modes (31.56) and Bus Scheduling and On-Board Payment System (32.85), placing them at the end of the implementation priority list. The overall mean rank was 18.00, which represented the vertical cut-off line in the IPMA matrix. Moving to the cross-analysis and the identification of implementation gaps via the IPMA, the importance scores (means) and priority scores (mean ranks) were integrated into a two-dimensional matrix to determine strategic intervention priorities. The cut-off lines (overall grand means) were established at 4.0985 for importance and 18.00 for priority (mean rank). These values were determined based on the overall arithmetic mean of both dimensions to ensure a balanced and neutral categorisation of the indicators. The value of 4.0985 represented the grand mean of all importance scores, distinguishing between high-importance indicators (Mean $\geqslant$ 4.0985) and low-importance indicators (Mean $<$ 4.0985). Similarly, the priority cut-off line was set at 18.00, representing the overall grand mean of the mean ranks, separating high-priority indicators (Mean Rank $\leqslant$ 18.00) from low-priority indicators (Mean Rank $>$ 18.00). Figure 1 illustrated the distribution of the 35 indicators across the four quadrants.

Figure 1. Distribution of the 35 smart mobility indicators across the IPMA matrix
Source: developed by the authors

The two-dimensional matrix maps the distribution of the 35 indicators across the four quadrants, based on their mean importance (Y-axis) against their priority mean ranks (X-axis), illustrating the strategic gap between perceived importance and execution priority. The matrix revealed that a majority of the indicators were clustered in the high-importance quadrants, highlighting a strong consensus among experts on the necessity of these components. Quadrant 1 (Quick Wins) comprised 12 indicators validated for immediate implementation due to their high importance and high priority, including Electronic Parking Space Reservation, Emergency Services Provision, and Reduction of Traffic Accident Rate, indicating these components offer the highest return on investment in the short term. Conversely, 10 vital structural components were positioned in Quadrant 2 (Strategic Investment), characterising high importance but low execution priority due to structural bottlenecks that require long-term planning, such as Traffic Data Aggregation and Real-Time Data-Driven ITS. Furthermore, Quadrant 3 (Over-Emphasis) features 6 indicators that were rated as low importance but high priority, including Smart Land Use Distribution, suggesting a need for strategy review and potential rerouting of resources. Finally, 7 indicators fall into Quadrant 4 (Low Priority), including Expansion of Cycling Network Infrastructure, indicating it can be deferred to later phases due to lower expert consensus on their immediate importance and priority. A detailed summary of the quadrants, strategic focus, and conditions was provided in Table 6.

Table 6. Definition and strategic focus of the IPMA quadrants

Quadrant	Strategic focus	Description	Conditions/Range	Execution scenario
Q1	Quick Wins (Highest Priority)	High Importance (Y High) + High Priority (X Low Rank)	Y ≥ 4.098 X ≤ 18.00	Immediate investment and direct implementation
Q2	Strategic Investment	High Importance (Y High) + Low Priority (X High Rank). Structural Challenges	Y ≥ 4.098 X > 18.00	Long-term planning and allocation of structural resources
Q3	Over-Emphasis	Low Importance (Y Low) + High Priority (X Low Rank). Strategy Review needed	Y < 4.098 X ≤ 18.00	Strategy review and rerouting of resources
Q4	Low Priority	Low Importance (Y Low) + Low Priority (X High Rank). Deferral	Y < 4.098 X > 18.00	Postponement of implementation to the next phase

Source: compiled by the authors

Thus, the analysis confirmed that implementation was primarily driven by immediate safety and accessibility needs, as reflected by the high concentration of 12 indicators in Quadrant 1 (Quick Wins). These findings validated a substantial number of highly important and high-priority indicators for immediate execution, offering the highest potential for impact on public satisfaction and system reliability. However, the identified strategic gap in Quadrant 2, where 10 vital structural indicators were consistently ranked as low priority, poses a critical challenge that necessitates systemic interventions. This disparity, encompassing vital indicators characterised by high importance but low execution priority, suggested structural barriers that prevented the immediate execution of highly valued components. The challenges presented by this quadrant will be the main focus of the discussion, as the strategic gap for these essential indicators suggests systemic execution barriers.

So, the analytical results derived from the IPMA framework provided a quantitative mapping of the smart mobility landscape for the NAC. The empirical evidence identified two primary strategic trajectories: first, a robust consensus on Quick Wins (Q1), where 12 indicators, primarily focused on emergency response and parking efficiency, demonstrated high readiness for immediate execution. Second, the identification of a significant Strategic Investment gap (Q2), where 10 foundational indicators, such as Real-Time Data-Driven ITS, exhibited high strategic importance but suffered from low execution priority. Furthermore, the analysis revealed a relatively limited Over-Emphasis (Q3) on 6 indicators, while 7 indicators related to long-term sustainability and urban planning fall into Low Priority (Q4), indicating a secondary focus on non-technical behavioural changes. Practically, these findings demonstrated that despite a high technical appetite for advanced ITS (Overall Mean = 4.0985), the operational path was constrained by structural bottlenecks, necessitating a focus on governance over procurement. These results established that the immediate roadmap for policymakers should not merely focus on technology procurement but must prioritise the institutional and data-governance frameworks required to move Strategic Investment indicators into the Quick Wins category.

Empirical finding of this research aligned with the scholarly perspective of W. van Winden & D. van den Buuse (2017), who emphasised the "low-hanging fruit" approach in early-stage smart city deployment. By analysing pilot projects in Amsterdam, the authors argued that such initiatives were crucial for achieving early public trust. This study confirmed it, as the prioritisation of Q1 indicators demonstrated a clear focus on high-impact, low-complexity solutions. However, a key distinction emerges from their findings: while the surveyed experts perceived these components as high priority Quick Wins, W. van Winden & D. van den Buuse (2017) cautioned that many such pilots fail to scale up once initial funding dries up. This comparison suggested that the NAC's prioritised indicators must be designed with a clear vision for roll-out and replication, as defined in their Amsterdam study, to ensure they do not fall into the pilot trap but instead achieve wider diffusion.

The most critical finding for policy was the pronounced strategic gap identified in Quadrant 2 (Strategic Investment), which encompassed 10 indicators characterised by high importance ($Y \geqslant 4.0985$) but low execution priority ($X > 18.00$ rank). This group included foundational components, such as Real-Time Data-Driven ITS and Traffic Data Aggregation, primarily falling under the Smart Mobility (A.2) and Traffic Management Centre (A.4) criteria. This disparity was further illuminated by the benchmarking of Dubai and Riyadh, where top-down centralised governance and integrated data platforms have proven essential in bridging the gap between infrastructure deployment and operational efficiency. As analysed by A. Badhan *et al.* (2025), Dubai's strategic deployment of AI-powered traffic management systems had demonstrated a 20% reduction in travel time during peak hours. Such models offered a strategic blueprint for the NAC, demonstrating that high-level technological integration must be supported by a robust strategic roadmap and public-private collaboration. These frameworks, alongside the analytical insights of I.R. Hegazy & A. Mahboob (2024), demonstrated that transitioning from Quick Wins to resilient systems required addressing internal organisational barriers. Their evaluation of Riyadh revealed a significant innovation-implementation divide, while the city achieved high performance in public safety through extensive surveillance, it faced persistent challenges in mobility and the digital divide among different social groups. A. Susanty *et al.* (2022) investigated ITS implementation barriers using the Interpretive Structural Modelling (ISM) method. Scientists established that the primary obstacles were not technological capacity, but rather internal organisational barriers related to the timing of procedures for writing plans and divided responsibilities.

The low execution priority of these indicators further reflected the adoption dynamics analysed by H. Fatorachian & H. Kazemi (2025). Researchers utilised institutional theory to demonstrate how external pressures, such as regulatory mandates and industry norms, often constrain the integration of highly valued technologies like AI and Big Data. This explained the disparity in the current findings: while experts recognise the strategic importance of these tools, the lack of coercive regulatory incentives in the Egyptian context stifled their immediate implementation. R. Kitchin & N. Moore-Cherry (2021) demonstrated through their empirical focus on Metropolitan Boston that governance fragmentation created interjurisdictional data incompatibilities and reduced the spatial intelligence necessary for effective ITS. These findings extended this logic to the Egyptian context, where the low priority of data-driven indicators reflected a similar adoption gap caused by path-dependent administrative structures. D. Mitieka *et al.* (2025) applied Total Interpretive Structural Modelling (TISM) to map the hierarchy of barriers in emerging cities. The authors identified legacy paradigms in conventional transport planning and fragmented institutional mandates as the foundational root-cause constraints that reinforced downstream challenges.

Moreover, World Bank (2024) study confirmed that urban transport governance in many developing nations suffered from institutional fragmentation across governance levels, leading to poor policy coordination and inefficient public spending. M. Alamoudi *et al.* (2024) pointed out in their multidimensional analysis of Jeddah that the holistic integration of smart technologies was often hindered by regulatory misalignment and the lack of comprehensive policy reform. The IPMA results reinforced this, indicating that the governance and data policy environment in the NAC were not yet mature enough to support the execution of complex data-driven systems. According to O.L. Lee *et al.* (2019), Singapore's success was built upon a "system of systems" governance framework that integrated the physical infrastructure with organisational capacity and policy regulation. Building on this institutional foundation, G. Hanxiang & L.W. Yie (2025) demonstrated how Singapore's Land Transport Authority (LTA) utilised a centralised analytics engine to achieve predictive coordination and dynamic fleet adjustments.

D. Pojani & D. Stead (2015) argued that in developing cities, technological improvements were often favoured because it was perceived as easier to implement and do not require the deep-seated institutional and behavioural changes necessary for land-use reorganisation. This focus on technology over structure reflected a deviation from the Avoid-Shift-Improve (ASI) framework, a strategic principle championed by S. Lim (2023) of the World Bank in the context of Egypt's green transport master plan. S. Lim (2023) emphasised that, while Egypt had invested heavily in Improvement through massive infrastructure, true transport decarbonisation required a resilient Shift toward public and non-motorised modes. The results indicated that the Improve Dimension (technology and efficiency) was currently prioritised in the NAC over Avoid (reducing trips) and Shift (promoting non-motorised transport), a gap also highlighted by M. Sankar *et al.* (2024) as a common struggle in developing economies seeking seamless mobility. N. Labri & A. Baziz (2022) noted that technical efficacy was strictly contingent upon institutional capacity and cross-sectoral coordination. -Researcher's results, which highlighted a low applicability index due to regulatory gaps, extended this logic to the Egyptian context, where the IPMA results identified a clear "innovation-implementation" divide. Alignment with the Algiers case study suggested that the NAC's digital ecosystem must be deeply ingrained in context-responsive government plans and the standardised framework proposed in this study to ensure long-term regulatory interoperability and effective policy implementation. Operational maturity of Zurich offered a definitive benchmark for the NAC's long-term aspirations. As evidenced by the analysis of M. Menendez & L. Ambühl (2022), Zurich's success is rooted in its "Absolute Priority" policy and technical interoperability across municipal, regional, and national transport agencies, which functioned as a unified entity. The city's transition toward network-adaptive traffic control demonstrated that achieving a "Sustainably Smart" city required shifting from fragmented digital procurement to a unified, data-driven ecosystem.

International standardisation landscape offered a definitive pathway for bridging the current strategic gap. ISO/TR 4447:2022 (2022) provided a robust framework for MaaS, emphasising the necessity of shifting toward unified service consumption via interoperable digital interfaces. Crucially, this framework explicitly defined the roles of data providers, transport operators, and regulators, providing the structural clarity needed to ensure seamless urban mobility. When framing these empirical findings against this ISO benchmark, it became evident that the NAC's evolution from a technologically smart city to a sustainably smart ecosystem required more than technical procurement; it necessitated a transition from siloed deployments to a unified governance model, where these roles were clearly integrated. Adopting the responsibilities defined within the ISO framework would provide the institutional clarity required to transition the identified Quick Wins into the foundational, data-driven systems essential for long-term urban resilience. So, the strategic roadmap for the NAC must transition from technical optimism to institutional consolidation. The main strategic conclusion was that the identified implementation gap in Quadrant 2 was a governance challenge rather than a technological failure, requiring a centralised data exchange infrastructure and regulatory reform. This integrated approach ensured that the NAC's smart mobility vision remained not only operationally viable but strategically resilient against the institutional lags identified in the Egyptian context.

CONCLUSIONS

This study developed an empirical framework for prioritising ITS within the Greenfield context of Egypt's NAC, transitioning from theoretical modelling to a practical execution hierarchy. The IPMA application moved beyond statistical classification, providing a strategic roadmap, where institutional readiness met technological ambition, based on a high-consensus expert evaluation (Overall Importance Mean = 4.0985, Overall Priority Mean Rank = 18.00). The results established two primary trajectories for smart mobility, the first prioritised operational reliability and public safety as foundational pillars, with 12 indicators identified as Quick Wins (Q1). These were led by Electronic Parking Space Reservation (Mean = 4.9574) and Emergency Services Provision (Mean = 4.9362), these high-impact solutions are essential to build early public trust. The second trajectory revealed a strategic readiness gap in 10 foundational indicators categorised as Strategic Investment (Q2), notably Traffic Data Aggregation and Real-Time Data-Driven ITS. Despite their high strategic value, their implementation was hindered by non-technical barriers and a significant innovation-implementation divide (Mean Rank > 18.00). The proposed framework's reliability is underpinned by a high level of expert consensus (Kendall's $W = 0.759$) and statistically significant priority rankings ($p < .001$), ensuring that the identified roadmap was both robust and representative of institutional reality. Study concluded that a successful transition required a shift toward a governance-first strategy to bridge the identified institutional capacity gap.

Furthermore, the findings identified a sustainability gap in Low Priority areas, where smart land use and cycling infrastructure remained at the periphery of current execution plans, indicating a preference for technical efficiency

(Improve) over behavioural shifts (Avoid/Shift). Integrating transport with TOD was therefore essential for long-term urban growth and resilience. For practitioners and urban planners, the developed IPMA framework served as a validated decision-support tool to align ITS investments with actual institutional capacity, ensuring that technological deployment addressed regional priorities. However, the study faced limitations regarding expert subjective evaluations and the dynamic nature of the NAC's regulatory environment, which may affect the long-term stability of the identified priorities. Future research should focus on developing smart governance frameworks tailored to developing contexts to enhance cross-sectoral coordination and evaluate the financial feasibility of TOD models in aligning technology with sustainable urban planning goals.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Alamoudi, M., Imam, A., Majrashi, A., Osra, O., & Hegazy, I. (2024). Integrating intelligent and sustainable transportation systems in Jeddah: A multidimensional approach for urban mobility enhancement. *International Journal of Low-Carbon Technologies*, 19, 1301-1314. doi: 10.1093/ijlct/ctae078.

[2] Ali, M.A. (2021). Smart city policy in developing countries: Case study of the New Administrative Capital in Egypt. *Journal of Public Affairs*, 22(S1), article number e2774. doi: 10.1002/pa.2774.

[3] Badhan, A., Kaur, P., Kumar, A., & Mishra, V.P. (2025). Leveraging AI and IoT for smart transportation in the UAE: Challenges, opportunities, and strategic roadmap. In *8th international conference on trends in electronics and informatics (ICOEI)* (pp. 364-369). Tirunelveli: IEEE. doi: 10.1109/ICOEI65986.2025.11013108.

[4] Beckers, D., & Mora, L. (2025). Overcoming the smart city governance challenge: An innovation management perspective. *Journal of Urban Technology*, 32(2), 85-106. doi: 10.1080/10630732.2025.2461983.

[5] Bosch, P., Jongeneel, S., Rovers, V., Neumann, H.-M., Airaksinen, M., & Huovila, A. (2017). *CITYkeys indicators for smart city projects and smart cities*. Brussels: European Commission. doi: 10.13140/RG.2.2.17148.23686.

[6] Das, D.K. (2024). Exploring the symbiotic relationship between digital transformation, infrastructure, service delivery, and governance for smart sustainable cities. *Smart Cities*, 7(2), 806-835. doi: 10.3390/smartcities7020034.

[7] Faheem, H.B., El Shorbagy, A.M., & Gabr, M.E. (2024). Impact of traffic congestion on transportation system: Challenges and remediations – a review. *Mansoura Engineering Journal*, 49(2), article number 18. doi: 10.58491/2735-4202.319.

[8] Fathy, R.A. (2024). Interoperability and interworking of intelligent transportation systems and the rise of AI. *LinkedIn*. Retrieved from https://surl.li/zkthuq.

[9] Fatorachian, H., & Kazemi, H. (2025). Leveraging technology and sustainability practices for smart mobility and green logistics: A dual-theoretical approach to adoption dynamics. *International Journal of Sustainable Engineering*, 18(1), article number 2531890. doi: 10.1080/19397038.2025.2531890.

[10] Gideon, E.M., & Chepleting, F. (2026). Integrating smart transportation systems and urban governance for sustainable mobility: A systematic review and conceptual framework. *Journal of Innovations in Business and Industry*, 4(1), 79-98. doi: 10.61552/JIBI.2026.01.008.

[11] Hanxiang, G., & Yie, L.W. (2025). Singapore's land transport authority (LTA): A case study of predictive AI and centralized coordination in urban traffic management. *Journal of Innovation and Technology*, 2025(2). doi: 10.61453/joit.v2025no12.

[12] Hegazy, I.R., & Mahboob, A. (2024). Evaluating Riyadh's smart city initiatives: Insights from the IMD Smart City Index framework. *International Journal of Low-Carbon Technologies*, 19, 2446-2460. doi: 10.1093/ijlct/ctae205.

[13] Housing and Building National Research Center. (2023). *The Egyptian Code for the Foundations and Requirements for Planning, Management, Operation, and Sustainability of Smart Cities – part 1*. Cairo: Ministry of Housing, Utilities and Urban Communities; Housing and Building National Research Center (HBRC).

[14] Islam, M. (2025). Analysis of AI-enabled adaptive traffic control systems for urban mobility optimization through intelligent road network management. *Review of Applied Science and Technology*, 4(2), 207-232. doi: 10.63125/358pgg63.

[15] ISO/TR 4447:2022. (2022). *Intelligent transport systems – mobility integration – comparison of two mainstream integrated mobility concepts*. Retrieved from https://www.iso.org/standard/79979.html.

[16] Kitchin, R., & Moore-Cherry, N. (2021). Fragmented governance, the urban data ecosystem and smart city-regions: The case of Metropolitan Boston. *Regional Studies*, 55(12), 1913-1923. doi: 10.1080/00343404.2020.1735627.

[17] Labri, N., & Baziz, A. (2022). A methodological framework for evaluating smart transport applicability in Algiers. *Communications – Scientific Letters of the University of Zilina*, 24(4), 160-171. doi: 10.26552/com.C.2022.4.A160-A171.

[18] Lee, O.L., Tay, R.I., Too, S.T., & Gorod, A. (2019). A smart city transportation system of systems governance framework: A case study of Singapore. In *14th annual conference system of systems engineering (SoSE)* (pp. 37-42). Anchorage: IEEE. doi: 10.1109/SYSOSE.2019.8753829.

[19] Lim, S. (2023). Building green, resilient, inclusive, and sustainable transport systems in Egypt. *World Bank Group*. Retrieved from https://www.wbgkggtf.org/node/3889.

[20] Menendez, M., & Ambühl, L. (2022). Implementing design and operational measures for sustainable mobility: Lessons from Zurich. *Sustainability*, 14(2), article number 625. doi: 10.3390/su14020625.

[21] Metwally, E., Samir, E., & Ayman, M. (2023). The indicators of the smartness to assess Egypt's New Administrative Capital as a smart city. *Mansoura Engineering Journal*, 48(6), article number 12. doi: 10.58491/2735-4202.3089.

[22] Mitieka, D., Luke, R., Twinomurinzi, H., & Mageto, J. (2025). Mapping the institutional and socio-political barriers to smart mobility adoption: A TISM-MICMAC approach. *Smart Cities*, 8(6), article number 182. doi: 10.3390/smartcities8060182.

[23] Ngossaha, J.M., Pidy, L.T.P., Karunathilake, T., Förster, A., & Bowong, S. (2024). Advancing urban mobility in developing countries: A mobile RSU approach for sustainable transportation. *IET Intelligent Transport Systems*, 18(12), 2502-2519. doi: 10.1049/itr2.12586.

[24] Nosratabadi, S., Mosavi, A., Keivani, R., Ardabili, S., & Aram, F. (2020). State of the art survey of deep learning and machine learning models for smart cities and urban sustainability. In A. Várkonyi-Kóczy (Ed.), *Engineering for sustainable future* (Vol. 101; pp. 228-238). Cham: Springer. doi: 10.1007/978-3-030-36841-8_22.

[25] Pojani, D., & Stead, D. (2015). Sustainable urban transport in the developing world: Beyond megacities. *Sustainability*, 7(6), 7784-7805. doi: 10.3390/su7067784.

[26] Rupprecht Consult. (Ed.). (2019). *Guidelines for developing and implementing a sustainable urban mobility plan*. (2nd ed.). Cologne: Rupprecht Consult – Forschung & Beratung GmbH.

[27] Sankar, M., Pachiyappan, S., Arjun, B.S., & Srivastava, A. (2024). Assessing the impact of smart city technologies on sustainable urban mobility in developing economies. In V. Kandpal, E.D.R. Santibanez-Gonzalez, P. Chatterjee & M.K. Nallapaneni (Eds.), *Smart cities and circular economy: The future of sustainable urban development.* Leeds: Emerald Publishing Limited. doi: 10.1108/978-1-83797-957-820241018.

[28] Signor, L., *et al*. (2019). *Mobility as a service (MAAS) and sustainable urban mobility planning*. Brussels: ERTICO – ITS Europe.

[29] Susanty, A., Putri, V.A., & Purwanggono, B. (2022). Proposed policy to manage the barrier of the implementation of intelligent transportation system. *International Journal of Intelligent Transportation Systems Research*, 20, 540-559. doi: 10.1007/s13177-022-00310-8.

[30] Tarek, S., & Nasreldin, T.I. (2023). Towards applying smart mobility solutions in Egypt: An integrative framework and a case study application. *Ain Shams Engineering Journal*, 14(7), article number 101987. doi: 10.1016/j.asej.2022.101987.

[31] The Declaration of Helsinki. (2013). Retrieved from https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/.

[32] van Winden, W., & van den Buuse, D. (2017). Smart city pilot projects: Exploring the dimensions and conditions of scaling up. *Journal of Urban Technology*, 24(4), 51-72. doi: 10.1080/10630732.2017.1348884.

[33] World Bank. (2024). *Mapping urban transport governance*. Washington, D.C.: World Bank Group.

Ехаб Махмуд Окба
Доктор архітектури та екологічного дизайну, професор
Університет Фаюм
PO Box 63514, вул. Аль-Машталь, м. Файюм, Єгипет
https://orcid.org/0000-0002-7665-1649

Мохга Емам Ембабі
Доктор архітектури та міського дизайну, професор
Університет Фаюм
PO Box 63514, вул. Аль-Машталь, м. Файюм, Єгипет
https://orcid.org/0000-0001-5520-1967

Бахаелдін Мостафа Саад
Магістр архітектури, Асистент
Університет Фаюм
PO Box 63514, вул. Аль-Машталь, м. Файюм, Єгипет
https://orcid.org/0000-0001-8496-2984

Аналіз матриці «важливість-пріоритет» для оцінювання індикаторів розумної мобільності в новій адміністративній столиці Єгипту

Анотація. Стрімкий розвиток Greenfield Smart Cities зумовив необхідність стратегічного підходу до пріоритезації мобільних технологій з метою забезпечення операційної ефективності та сталого розвитку. Метою дослідження було розроблення ієрархії пріоритетів для оцінювання індикаторів розумної мобільності в контексті урбаністики із застосуванням аналізу матриці «важливість-пріоритет» для нової адміністративної столиці Єгипту. Шляхом інтеграції чотирьох симбіотичних складових (інфраструктура, цифрова трансформація, надання послуг і врядування) дослідження перейшло від теоретичного опису до ієрархії виконання, що базувалася на даних. Методологія передбачала застосування аналізу матриці «важливість-пріоритет», підтриманого тестом Фрідмана та коефіцієнтом конкордації Кендалла (0,759). Аналіз, здійснений на основі порогових значень 4,0985 для важливості та 18,00 для пріоритету, виявив біфуркувану траєкторію управління розумною мобільністю. Результати визначили 12 «швидких перемог» (Quadrant 1), серед яких провідними стали електронне резервування паркомісць (Mean = 4,9574) та зниження рівня дорожньо-транспортних пригод (Mean Rank = 5,52), що забезпечували високоефективні рішення, необхідні для формування початкової довіри суспільства. Матриця виявила стратегічний розрив готовності у 10 базових системах (Quadrant 2), визначених як стратегічні інвестиції. Такі індикатори, як інтелектуальні транспортні системи на основі даних у реальному часі (Mean = 4,8085) та агрегування транспортних даних, мали низький пріоритет реалізації (Mean Rank > 18,00) через фрагментованість інституційних повноважень і повільні процедурні процеси планування. Сім індикаторів у Quadrant 4, пов'язаних зі сталими поведінковими практиками (цілі avoid/shift), зокрема розширення мережі велосипедної інфраструктури (Mean = 2,4468), продемонстрували найнижчі показники важливості та пріоритету. Було визначено, що успішний перехід до інтегрованої екосистеми мобільності потребує фундаментального зсуву парадигми від моделі, яка акцентована на технології, до стратегії, орієнтованої на врядування. Розроблена рамка слугувала стандартизованим і відтворюваним інструментом підтримки прийняття рішень, що дало змогу узгодити технологічні інвестиції з рівнем інституційної готовності. Дослідження сприяло подоланню розриву між впровадженням технологій та сталим міським плануванням через підходи транзитно-орієнтованого розвитку та «розумного» врядування, забезпечуючи стійкість та сталий характер трансформацій у сфері розумної мобільності

Ключові слова: урбаністична модернізація; інтелектуальні транспортні системи; статистичне ранжування; інституційна фрагментація; управління на основі даних

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 712:635.9
DOI: 10.56318/as/1.2026.80

ISSN: 2411-801X
e-ISSN: 2786-7374

Vira Moroz*
PhD in Agricultural Sciences, Associate Professor
West Ukrainian National University
46009, 11 Lvivska Str., Ternopil, Ukraine
https://orcid.org/0000-0002-1457-4641

Anatolii Vyshnevskyi
PhD in Agricultural Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0001-5381-1219

Comprehensive proposals for greening and urban regeneration in Zhytomyr based on a selection of perennial plants

Abstract. The rapid development of urban construction in Zhytomyr is leading to a reduction in green space below the standard level and an intensification of the urban heat island effect, which raises the air temperature in summer by 2-4°C. This has necessitated the implementation of environmentally sustainable solutions aimed at regulating the microclimate, enhancing the aesthetic appeal of the urban environment and ensuring the social well-being of residents. The aim of the study was to develop comprehensive proposals for landscape greening and the improvement of urban areas in Zhytomyr in a landscape style based on a range of perennial ornamental plants. This ensured biodiversity, continuous seasonal ornamental appeal and the functional zoning of urban space. Plants were classified according to height, light requirements, moisture requirements and ornamental characteristics. Based on an analysis of sunlight exposure in typical urban areas, a zoning scheme was developed: 60% sunny areas, 30% semi-shaded areas, and 10% riparian zones along water bodies. Planting density ranged from 4 plants/m^2 for large species to 9 plants/m^2 for low-growing groundcovers, ensuring that the plantings would close out within 1-2 years. The selection included frost-hardy, drought-tolerant and low-maintenance plant species – ornamental grasses (*Pennisetum, Festuca*), perennial herbaceous plants (*Echinacea, Salvia, Hemerocallis, Sedum*), evergreens (*Yucca, Lavandula*) and ornamental foliage plants (*Hosta*), none of which had invasive properties. In addition, nine types of greening compositions were proposed: borders (50-70 m in length), mixed borders (100-150 m^2), flower beds (10-20 m^2), alpine rock gardens (15-20 m^2), container plantings, greening around water features (20-30 m^2), ornamental groups with solitary elements (5-10 m^2), group plantings (10-15 m^2) and flower beds (0.5-1.0 m wide). All options ensured continuous seasonal ornamental appeal from May to October, with a greening level of 40% to 70%, which exceeded the minimum regulatory requirements, and required mulching and watering during dry periods. The practical value of this work lies in the ready-to-implement projects with detailed plant placement plans and the potential for adaptation to other cities in Ukraine with similar climatic conditions

Keywords: landscape style; composition options; landscape design; urban greening; biodiversity; seasonal ornamental value; environmental sustainability

Suggested Citation:
Moroz, V., & Vyshnevskyi, A. (2026). Comprehensive proposals for greening and urban regeneration in Zhytomyr based on a selection of perennial plants. *Architectural Studies*, 12(1), 80-92. doi: 10.56318/as/1.2026.80.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 80-92
Received: 03.11.2025 Revised: 04.02.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

INTRODUCTION

Urban greening and the improvement of urban areas are integral components in the formation of sustainable urban environments, contributing to microclimate regulation, air pollution reduction, and the support of the population's psychological well-being. Under conditions of rapid urbanisation and intensive development in Ukrainian cities, the issue of a scientifically grounded approach to greening has become particularly relevant, as the reduction of green spaces has directly affected residents' quality of life and the ecological condition of urban environments. Urban greening contributes to microclimate regulation, air purification, and the maintenance of residents' psychological well-being. A. Addas (2023) demonstrated that urban green spaces can reduce temperatures by 2-4°C, improve air quality, and decrease social isolation. F. Zhang & H. Qian (2024) emphasised that urban green spaces play a critical role in carbon sequestration, pollution filtration, and the mitigation of the urban heat island effect, making their integration into urban planning essential. T. Semeraro *et al.* (2021) highlighted the importance of green roofs and community gardens for climate regulation, water management, and biodiversity support, which positively affects stress reduction among urban residents. L. Boyko *et al.* (2022) substantiated the principles of creating dendrological compositions and the criteria for their use in urban areas, emphasising the need to combine aesthetic and functional characteristics of plantings. X. Zhou *et al.* (2025) confirmed that the application of machine learning in optimising green spaces increases their economic efficiency and social cohesion.

The selection of plant material for urban greening is a key factor in the success of plantings. A. Hardberger *et al.* (2025) highlighted challenges in promoting the use of native plants due to social and market factors, proposing policy incentives and educational measures to overcome these barriers. An important aspect is also the selection of frost-resistant and drought-tolerant species capable of withstanding climatic fluctuations while maintaining ornamental value throughout an extended growing season. A. Pancewicz & A. Kurianowicz (2024) considered urban greening as a tool for climate adaptation, emphasising the importance of a systematic approach to the formation of green spaces under conditions of intensive development and climate change. The study by S. Chen *et al.* (2021) demonstrated the positive impact of redeveloping neglected urban areas in Berlin, significantly increasing green space and improving climatic conditions, thereby confirming the effectiveness of comprehensive greening approaches in densely built environments. The planning and evaluation of urban green spaces require systematic tools and methodological approaches. M. Panwar *et al.* (2025) developed the UGSAI index to assess the quality, quantity, and accessibility of green spaces in Delhi, identifying areas with insufficient greenery and providing recommendations for their development. R. Hansen *et al.* (2023) noted a shift from fragmented approaches to integrated green space management in European cities to ensure long-term sustainability. L. Tian (2022) highlighted the importance of aesthetic aspects in landscape design for enhancing the attractiveness of green spaces, which is particularly relevant in the development of urban greening proposals. K. Min (2025) identified key research directions focused on integrating green technologies into architecture to achieve carbon neutrality, opening new perspectives for urban greening development.

In Ukraine, greening issues are associated with fragmented regulatory frameworks, rapid urban development, and insufficient monitoring of green spaces. The lack of a systematic approach to planning has led to their reduction and deterioration in quality, negatively affecting both ecological and social conditions in cities. For the city of Zhytomyr, located in a temperate continental climate with cold winters and warm summers, a scientifically grounded selection of perennial plants – taking into account frost resistance, drought tolerance, and compliance with state building regulations – is essential. A comprehensive approach to landscape greening, based on an actual selection of plant species and the principles of landscape design, makes it possible to effectively address the shortage of green spaces in the city and to ensure their long-term ornamental value and ecological stability. The aim of this study was to develop landscape-style design projects with maximum use of available resources to achieve a balance between ecological sustainability, aesthetics, and social comfort. The objectives included analysis of plant material, the application of landscape design principles, the creation of compositional options and their regulatory assessment.

MATERIALS AND METHODS

The study was based on a selection of 14 species of perennial plants (Table 1), purchased by the municipal enterprise "Zelenbud" of the Zhytomyr City Council on 15 November 2025 from the "Dekor Zviahel Sad" farm (Zhytomyr.info, 2025). The proposals for greening were based on standard urban areas in Zhytomyr (squares, courtyards, footpaths, patios, waterfronts, and slopes). The visualisation of the landscape design schemes was carried out using Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.).

Table 1. Range of plants for greening the city of Zhytomyr

Plant name	Type	Height/width	Frost hardiness	Quantity, pcs.	Appearance
Salvia nemorosa 'Caradonna'	Perennial herbaceous	40-60/30-40 cm	High	30	

Table 1. Continued

Plant name	Type	Height/width	Frost hardiness	Quantity, pcs.	Appearance
Lychnis viscaria 'Pink Rosea Plena'	Perennial herbaceous	30-35/25-30 cm	High	35	
Pennisetum alopecuroides 'Moudry'	Ornamental grass	up to 80/ up to 80 cm	High	65	
Festuca glauca 'Elijah Blue'	Ornamental grass	15-25/20-30 cm	High	65	
Sedum hybride 'Purple Emperor'	Perennial herbaceous	40-50/35-40 cm	Zone 4 (down to -34°C)	65	
Yucca filamentosa	Evergreen perennial	foliage up to 70 cm, flowering stem up to 1.5 m	Zone 4 (down to -30°C)	20	
Echinacea purpurea 'Magnus'	Perennial herbaceous	60-90/60-70 cm	High	35	
Perovskia atriplicifolia 'Blue Spire'	Perennial herbaceous	60-70/50-60 cm	High	35	
Hosta 'Halcyon'	Perennial ornamental foliage	up to 40/40-50 cm	High	40	
Hosta 'Fire and Ice'	Perennial ornamental foliage	25/40 cm	High	40	
Hosta 'Sunset Grooves'	Perennial ornamental foliage	30-40/40-50 cm	High	40	
Hemerocallis hybrida 'Stella de Oro'	Perennial herbaceous	40-50/40-50 cm	High	60	
Lavandula angustifolia 'Elisabeth'	Evergreen perennial shrub	50-60/70-80 cm	down to -30°C	60	
Pennisetum alopecuroides 'Little Bunny'	Ornamental grass	40-50/30-40 cm	High	65	

Source: Garden Industry (n.d.)

The research stages included an analysis of the purchased selection of plants for urban greening. The plants were classified according to height (low-growing <40 cm, medium-growing 40-80 cm, tall >80 cm), light requirements (sunny, semi-shaded), moisture conditions (dry, moderate, moist), and ornamental characteristics (flowering period, foliage texture, autumn colouration). For the selected plants, the most suitable approach was the landscape style, incorporating asymmetry, multi-layering, and the imitation of natural landscapes. The majority of species had a natural, "wild" appearance, did not require regular trimming, and aligned with the concept of low-maintenance planting. Site zoning included: 60% sunny areas, 30% semi-shaded areas, and 10% waterside zones near bodies of water. Based on an analysis of insolation in typical areas of Zhytomyr, several compositional variants were proposed, including borders, mixborders, flower beds, alpine rock gardens, container plantings, waterside zones, decorative groups, and flower borders. Planting density in the design ranged from 4 to 9 plants/m^2 depending on plant size (7-9 plants/m^2 for low-growing species and 4-5 plants/m^2 for taller species). The design process also took into account compliance with state building regulations SCN B.2.2-5:2011 (2012) (minimum 40% greening, shrub distance of 1-2 m from pathways, and absence of invasive species) as well as the Order of the Ministry of Construction, Architecture, and Housing and Communal Services of Ukraine No. 105 (2006). The methods used included comparative analysis, morphological classification of plants, and landscape design planning, taking into account planting density and adaptation to specific growing conditions. The study did not involve statistical data processing, as it was based on landscape design proposals.

RESULTS AND DISCUSSION

The city of Zhytomyr is located in a temperate continental climatic zone (Zone 5), characterised by cold winters (down to -30°C), warm summers, and sufficient moisture, which determines the selection of frost-resistant and low-maintenance perennial species for urban greening. The city features a developed network of public squares, inner courtyards, and waterside areas along the Teteriv River; however, intensive construction during the 2010s-2020s has significantly reduced green space below the standard level (Wolch *et al*., 2014). The perennial plants selected for analysis were characterised by a harmonious combination of colour and texture and were organically integrated into a landscape-style design, defined by asymmetrical arrangement, a multi-layered structure, and an emphasis on textural and seasonal characteristics suitable for urban greening. Their decorative flowering period extends from May to October, ensuring both functionality and aesthetic expressiveness of plantings. Species such as *Pennisetum, Festuca,* and *Echinacea* were particularly well suited to the landscape style of urban planting. During site zoning, it is important to consider light conditions and relief: approximately 60% of the area should be allocated to sunny sites for species such as *Sedum* and *Lavandula*; around 30% to partial shade for hostas and certain ornamental grasses; and about 10% for waterside greening, using moisture-loving plants such as *Hemerocallis* and *Pennisetum*. For optimal balance, planting density should range from 4 plants/m^2 for tall grasses to 9 plants/m^2 for low-growing ground cover species. This scheme ensures canopy closure within 1-2 years and complies with the requirements of SCN B.2.2-5:2011 (2012) for minimum greening levels (≥40%). Plant grouping was carried out according to height (low plants in the foreground, taller ones in the background), colour (dominance of a purple-pink palette with yellow and silvery accents), and texture (combining soft ornamental grasses with the rigid foliage of yucca).

Plant maintenance was limited to mulching, spring pruning of grasses, and watering during prolonged dry periods. The proposed greening options included: borders (50-70 m in length, up to 40 cm in height); containers (3-5 units, volume 4-10 L); mixborders (100-150 m^2); waterside zones (20-30 m^2); flower beds (3-5 units, each 10-20 m^2); alpine rock gardens (15-20 m^2); decorative compositions (5-7 units, each 5-10 m^2); group plantings (10-15 m^2); and flower borders (0.5-1.0 m wide, up to 10 m long). Borders were considered one of the basic elements of urban greening, serving to frame pathways and lawns. Their role was to establish clear boundaries, ensure compositional rhythm, and maintain a low planting profile (up to 40 cm). For border creation, a composition of low-growing plant species was proposed, ensuring dense coverage and year-round ornamental value. On sunny sites, the base consisted of *Lychnis viscaria* 'Pink Rosea Plena' (25-35 specimens), forming pink accents from May to July, combined with *Festuca glauca* 'Elijah Blue' (25-30 specimens), which created a silvery-blue textural background. The total length of the border was 50-70 m. Table 2 summarises the structure of the border layers.

Table 2. Layered structure of the border composition planting

Layer	Type	Quantity per 10 m	Height	Colour/texture
Front (ground cover)	*Festuca glauca* 'Elijah Blue'	20 units	15-25 cm	Silvery-blue foliage
Middle (flowering)	*Lychnis viscaria* 'Pink Rosea Plena'	15 units	30-35 cm	Pink double flowers
Accent (every 2 m)	*Lavandula angustifolia* 'Elizabeth'	5 units	50-60 cm	Purple fragrant flowers

Source: compiled by the authors

The border layout was designed on the principle of asymmetrical waves, repeating every 2-3 metres. A visual focal point was created by combining the pink flowers of *Lychnis viscaria* with the bluish foliage of *Festuca glauca*, producing a rhythmic effect. The planting density was 5-7 plants/m^2, which met the regulatory requirements for decorative density and ensured the plants would close out within 1-2 years. In Figure 1, showing the border in its entirety, the composition is based on a three-row planting scheme with a clearly defined hierarchy of colour and texture. Along the edges of the border, a frame was formed using *Festuca glauca* 'Elijah Blue', which created a light, textural background thanks to its dense, grey-blue clumps. The middle row features *Lavandula angustifolia* 'Elizabeth', which forms a purple strip and provides a vertical rhythm to the inflorescences. The central focal area is occupied by *Lychnis viscaria* 'Pink Rosea Plena', which stands out with its rich pink flowers and serves as the compositional focal point.

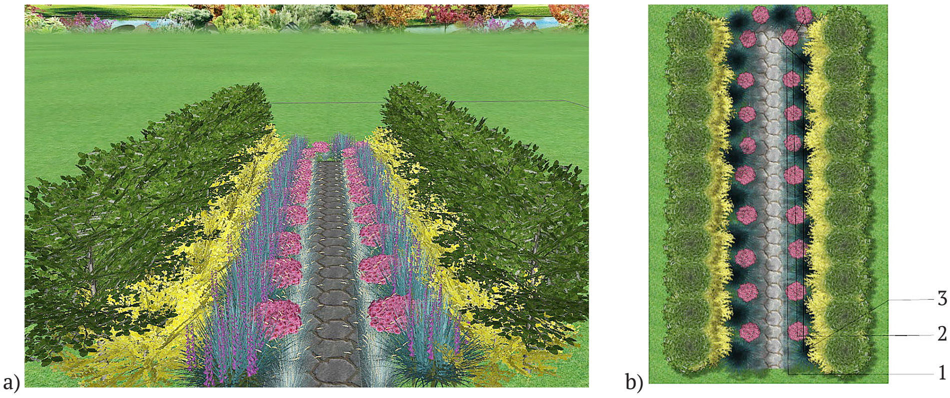


Figure 1. Border composition variant along a pedestrian pathway
Note: a – general view of the border (front view); b – plant layout (top view): 1 – *Festuca glauca* 'Elijah Blue', 2 – *Lychnis viscaria* 'Pink Rosea Plena', 3 – *Lavandula angustifolia* 'Elizabeth'
Source: compiled by the authors

For the greening of semi-shaded areas, it is advisable to plant *Hosta* 'Halcyon' (20 plants) and *Hosta* 'Fire and Ice' (20 plants), which create a striking contrast thanks to their varied foliage and provide year-round ornamental appeal. *Lavandula angustifolia* 'Elizabeth' (10 plants) can serve as an additional accent, adding a fragrant touch to the composition and characterised by abundant flowering in June-August. Containers were used for greening patios and terraces, ensuring the mobility of the compositions and a vertical structure for the plantings. O. Kosyk *et al*. (2020) confirmed the effectiveness of container planting in urban environments for paved areas and sites with complex engineering conditions, which has become typical of courtyards and pedestrian zones in Zhytomyr. *Hosta* 'Sunset Grooves', characterised by wrinkled ornamental foliage with year-round hardiness, can serve as the base element of a container planting. Complementary plants could include *Hemerocallis* 'Stella de Oro' – yellow flowers with a long flowering period (May-September), *Pennisetum alopecuroides* 'Little Bunny' with fluffy panicles flowering in September-October, and the solitary element Yucca filamentosa (an evergreen plant up to 80 cm tall) (Fig. 2). The container composition was organised in groups with height layering: low hostas were placed in the lower tier, while taller grasses occupied the upper tier. The colour scheme was maintained in a yellow-green palette with cream accents. Textural contrast was achieved by combining the smooth foliage of hostas with the fluffy inflorescences of ornamental grasses. The placement of containers was planned near benches and entrances, forming compositional focal points. The main principles of organising container plantings included mobility for seasonal rotation, textural contrast between different plant species, and the possibility of quickly replacing individual elements of the composition depending on the season. Mixborders were predominantly designed as dynamic mixed compositions with a three-layer structure, providing spatial depth and seasonal variability of the ornamental effect. The composition structure consisted of: a background layer with silvery spikes and purple inflorescences; a middle layer with vertical purple inflorescences and plants with purple foliage and decorative as well as aromatic qualities; and a foreground layer with plants featuring silvery-blue foliage and compact fluffy spikes. Table 3 presents the structured layers of the mixborder in the urban composition.

Figure 2. Variants of container compositions
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

Table 3. Layered structure of the mixborder composition

Layer	Plants	Quantity per 10 m	Height	Seasonality
Back	*Pennisetum alopecuroides* 'Moudry' + *Perovskia atriplicifolia* 'Blue Spire'	10 + 8 units	60-80 cm	August-October
Middle	*Salvia nemorosa* 'Caradonna' + *Sedum spectabile* 'Purple Emperor'	10 + 12 units	40-60 cm	June-September
Front	*Pennisetum alopecuroides* 'Little Bunny' + *Festuca glauca* 'Elijah Blue'	10 + 10 units	15-50 cm	All year round

Source: compiled by the authors

Thus, the seasonal changes in the mixed border unfolded in stages, ensuring continuous visual appeal from June to October. In June-August, the purple vertical inflorescences of *Salvia nemorosa* 'Caradonna' and the fragrant flowering of *Lavandula angustifolia* 'Elizabeth' dominated, creating a rich colour accent in the middle ground. In August-September, these were joined by the purple foliage of *Perovskia atriplicifolia* 'Blue Spire' and the blue-grey inflorescences of *Perovskia atriplicifolia* 'Blue Spire', which enriched the colour palette with cool shades. The season culminated in October, when the silvery panicles of *Pennisetum alopecuroides* 'Moudry' in the background reached their peak decorative effect, forming a striking autumnal accent. Throughout the season, *Festuca glauca* 'Elijah Blue' and *Pennisetum alopecuroides* 'Little Bunny' in the foreground provided a stable textural backdrop. The design principles included layering to create spatial depth, a colour rhythm dominated by a violet-silver palette with purple accents, as well as continuous seasonal variation in ornamental characteristics, making the mixed border one of the most distinctive types of greening for open urban spaces in Zhytomyr – parks, squares and pedestrian areas (Fig. 3).

Figure 3. Mixborder composition variant for urban areas of Zhytomyr
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

Mixborders provided spatial rhythm and seasonal variation of ornamental accents, integrating into the overall greening system of the area. Waterside landscaping (areas near ponds and streams) may cover an area of 20-30 m^2. When planning such areas, specific ecological conditions should be taken into account, including increased soil moisture and partial shade. A possible planting scheme may include a shoreline composition with *Hemerocallis* 'Stella de Oro' as the base element, providing floral accents along the water's edge from May to September. The semi-shaded zone may be composed of *Hosta* 'Halcyon' and *Hosta* 'Sunset Grooves', both of which provide foliage accents in partial shade and year-round ornamental value. Accent elements may be represented by ornamental grasses such as *Pennisetum alopecuroides* 'Moudry'. Table 4 summarises and structures the features of plant placement in the waterside zone.

Table 4. Grouping of plants in the waterside zone

Group	Species	Quantity	Placement	Colour/texture
Shoreline	*Hemerocallis* 'Stella de Oro'	10 units	Along the edge	Yellow flowers
Partial shade	*Hosta* 'Halcyon' + *Hosta* 'Sunset Grooves'	5 + 5 units	Closer to the water	Blue-green and yellow-green foliage
Accent	*Pennisetum alopecuroides* 'Moudry'	5 units	In groups	Silvery spikes

Source: compiled by the authors

This composition was designed according to the principle of asymmetrical grouping, imitating a natural shoreline. The main visual accent was the reflection of the yellow flowers of *Hemerocallis* in the water surface. The arrangement of plants ensured a balance between ornamental richness and ecological adaptability. The selected plants were characterised by tolerance to moderate moisture and the ability to maintain their decorative qualities in a waterside environment. Figure 4 shows a variant of waterside landscaping.

Figure 4. Waterside landscaping variant
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

The flower bed composition may be designed according to the principle of a concentric arrangement of plants with a dominant central layer. The centre of the composition is *Echinacea purpurea* 'Magnus' – 8 plants (vertical accent, pink flowers, flowering period July-September); the middle layer includes: *Salvia nemorosa* 'Caradonna' – 6 plants (purple vertical inflorescences, June-August); *Lychnis viscaria* 'Pink Rosea Plena' – 6 plants (pink double flowers, May-July), outer tier: *Festuca glauca* 'Elijah Blue' – 8 plants (silvery-blue foliage, ornamental throughout the year), *Lavandula angustifolia* 'Elizabeth' – 6 specimens (purple fragrant flowers, June-August). The visual focus was achieved thanks to the vertical centrepiece (*Echinacea*) and the colour rhythm of the pink and purple palette. The combination of textures – the smooth leaves of lavender, the fluffy inflorescences of sage and the greyish leaves of oatgrass – provided decorative richness. The colour scheme – pink and purple – was adapted to attract pollinators (Fig. 5).

Figure 5. Circular flower bed variant (3 m) with a concentric arrangement
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

Alternative planting arrangements may also be applied for a circular flower bed or a park flower garden, where the accent element is *Yucca filamentosa* – 1-2 specimens (vertical element). The middle layer may include *Echinacea purpurea* 'Magnus' – 5 specimens (purple flowers, summer-autumn) and *Salvia nemorosa* 'Caradonna' – 5 specimens (dark purple stems). The lower layer may consist of *Hosta* 'Halcyon' – 8 specimens (blue-green foliage, shade-tolerant) and *Sedum hybride* 'Purple Emperor' – 10 specimens (purple foliage). A border of *Festuca glauca* 'Elijah Blue' – 12 specimens creates a blue, grass-like effect. A variant of the flower bed with a concentric arrangement of plants within a single composition may also include the planting of *Lychnis viscaria* 'Pink Rosea Plena' in the central part, enhancing the pink-purple palette and ensuring dense, rhythmic flowering in the middle layer. The outer contour of the composition, formed by *Lavandula angustifolia* 'Elizabeth', creates a decorative silvery-blue textural framing layer while simultaneously emphasising the colour depth of the central part of the flower bed (Fig. 6).

a) b)

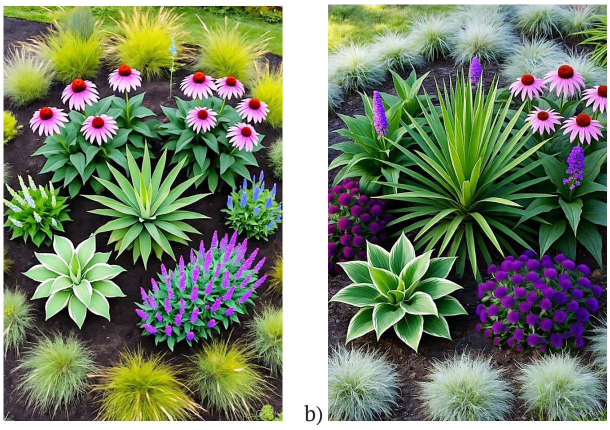


Figure 6. Variants of flower bed layout (top view)
Note: (a) flower bed variant with a concentric arrangement in a pink-purple palette; (b) flower bed variant with a vertical solitary element
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

Alpine rock gardens (rockeries) were established on sloping, sunny sites with an area of 15-20 m^2, using stone material to ensure drainage and to simulate a mountainous landscape. The composition was based on a multi-layered arrangement of plants with a pronounced textural contrast between stones, succulent-like species, and vertical accents. The structure of the composition was as follows: the lower layer (*Sedum hybride* 'Purple Emperor' – 20 specimens; August-October, *Pennisetum alopecuroides* 'Little Bunny' – 15 specimens; September-October), the middle layer (*Echinacea purpurea* 'Magnus' – 15 specimens; July-September), and the upper layer (*Yucca filamentosa* – 5 specimens; evergreen vertical accent). An aromatic component was provided by *Lavandula angustifolia* 'Elizabeth' – 10 specimens, with a flowering period from June to August (Table 5).

Table 5. Layered structure of the alpine rock garden (variant for an area of 5 m^2)

Level	Species	Quantity	Height	Texture
Upper	*Yucca filamentosa*	2 units	50-70 cm	Sword-shaped foliage
Middle	*Sedum* 'Purple Emperor' + *Echinacea* 'Magnus' + *Salvia*	8 + 6 + 8 units	30-60 cm	Purple foliage and pink flowers
Lower	*Pennisetum* 'Little Bunny' + *Lavandula* 'Elizabeth'	8 + 5 units	15-40 cm	Fluffy spikes and aromatic foliage

Source: compiled by the authors

Figure 7 shows the scheme of an alpine rock garden, where the stone substrate between layers imitates a natural mountainous landscape and ensures proper drainage. The combination of stone, succulent-like plants, and ornamental grasses creates visual depth and a naturalistic style adapted to the climatic conditions of Zhytomyr. Ornamental compositions within the landscape were formed as 5-7 compositional groups, each with an area of 5-10 m^2. These compositions functioned as focal accents within different functional zones and were based on a combination of vertical dominants, foliage plants, and grasses, ensuring rhythm, textural richness, and seasonal ornamental value. Accent groups with a vertical dominant included: *Yucca filamentosa* – 10 specimens (evergreen vertical accent); *Sedum spectabile* 'Purple Emperor' – 15 specimens (purple foliage, ornamental value from August to October); *Pennisetum alopecuroides* 'Moudry' – 25 specimens (silvery spikes, September-October). Shade compositions provided contrasting foliage and ornamental value in partial shade; thus, the following species were used: *Hosta* 'Fire and Ice' – 20 specimens, *Hosta* 'Halcyon' – 10 specimens, and *Hosta* 'Sunset Grooves' – 10 specimens. The compositions were designed in circular or triangular configurations with vertical dominants (*Yucca*) and the integration of ornamental grasses, which respond to wind movement, creating a dynamic visual rhythm.

Figure 7. Alpine rock garden scheme with a three-tier structure
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

Visual balance was achieved through the combination of foliage and grass textures, repetition of forms, and colour harmony. The colour palette was maintained in a purple-pink range with yellow accents. The compositions ensured continuous seasonal ornamental interest and required minimal maintenance (mulching and watering during dry periods). For example, in a composition with a central solitary element, the area may be 3 m^2, with a triangular structure featuring a central accent and peripheral framing. The solitary element (central feature), *Yucca filamentosa*, served as the dominant element of the composition due to its evergreen, sword-shaped foliage, establishing an architectural rhythm. The accompanying plants (middle layer) included *Sedum* 'Purple Emperor', *Pennisetum* 'Moudry', and *Lavandula angustifolia* 'Elizabeth', while the peripheral framing consisted of *Hosta* 'Fire and Ice' and *Festuca glauca* 'Elijah Blue'. Planted along the edges of the composition, they enhanced contrast through variegated foliage and provided a smooth transition to the surrounding area (Table 6).

Table 6. Structure of a decorative composition with a central solitary element

Composition layer	Species	Quantity	Placement	Decorative function
Solitary element (dominant)	*Yucca filamentosa*	1 unit	Centre	Evergreen vertical accent
Middle layer (accompanying)	*Sedum* 'Purple Emperor' + *Pennisetum* 'Moudry' + *Lavandula angustifolia* 'Elisabeth'	5 + 5 + 2 units	Around the solitaire	Textural contrast: purple foliage + silvery spikes + aromatic accent
Lower layer (framing)	*Hosta* 'Fire and Ice' + *Festuca glauca* 'Elijah Blue'	5 + 3 units	Along the periphery	Contrasting variegated foliage, transition to the adjacent area

Source: compiled by the authors

The composition shown in Figure 8 was characterised by a balanced combination of architectural form, textural contrast and seasonal variation. The evergreen *Yucca filamentosa* provided a year-round decorative base, whilst *Sedum hybride* 'Purple Emperor' and *Pennisetum alopecuroides* 'Moudry' reached their peak in August-October, creating a purple-silver autumnal accent. *Hosta* 'Fire and Ice' and *Festuca glauca* 'Elijah Blue' remained decorative throughout the growing season, enhancing the contrast and lending the composition a sense of completeness. The triangular configuration of the composition, with a vertical solitary plant at its centre, provided a consistent architectural focal point and a natural transition to adjacent landscaping elements. The colour palette featured a contrasting combination of purple-silver hues with the blue-green foliage of the hostas, maintaining aesthetic expressiveness. Such compact accent compositions are particularly effective for landscaping building entrances, key points along pedestrian routes and rest areas in the courtyards of Zhytomyr, where green space is limited but required a clear artistic solution.

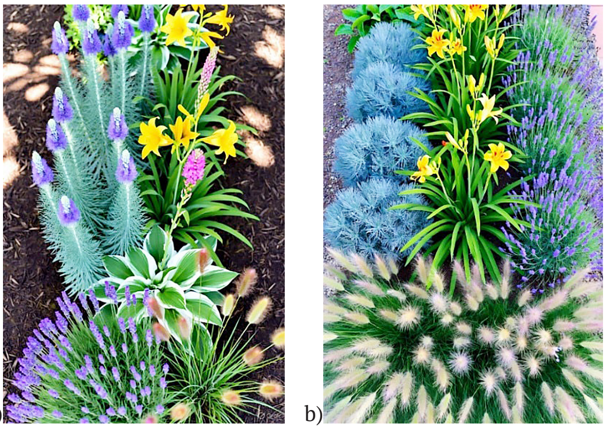
Figure 8. Scheme of a decorative composition:
triangular structure with a vertical solitary element, textural framing, and foliage complement
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

A group planting scheme for a public garden (covering an area of 10-15 m²) – suitable for parks with partial shade – combined ornamental grasses, shade-tolerant deciduous species and flowering accents (Fig. 9). Layered structure: upper layer (height 80-120 cm) *Pennisetum alopecuroides* 'Moudry' – 3 plants; *Perovskia atriplicifolia* 'Blue Spire' – 3 plants; middle layer (height 50-80 cm) *Echinacea purpurea* 'Magnus' – 6 plants, *Lychnis viscaria* 'Pink Rosea Plena' – 5 plants; lower layer (height 20-50 cm) *Hosta* 'Sunset Grooves' – 8 plants, *Sedum hybride* 'Purple Emperor' – 7 plants, *Festuca glauca* 'Elijah Blue' – 10 plants. Fragrant accent: *Lavandula angustifolia* 'Elizabeth' – 5 plants.

a) b)

Figure 9. Scheme of group planting for a public square:
a multi-layered composition with ornamental grasses, flowering accents, and shade-tolerant foliage species
Note: (a) composition variant with a warm pink-purple colour palette; (b) composition variant with a cool blue-violet colour palette
Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

The planting scheme was characterised by high resistance to pests and diseases, drought tolerance (watering required only during prolonged dry periods), minimal maintenance requirements, and provided seasonal variation in ornamental features and a natural, ecological appearance throughout the growing season. A flower border is a linear planting along a pedestrian path, 0.5-1.0 m wide and 10 m long, designed for semi-shaded areas. The composition was structured on the principle of rhythmic alternation of plants of different heights, ensuring visual dynamism, seasonal variability, and textural richness. The structure of the composition consisted of a main row (vertical accent): *Perovskia atriplicifolia* 'Blue Spire' – 4 specimens (blue-grey inflorescences, July-September); a middle row (flowering elements): *Hemerocallis hybrida* 'Stella de Oro' – 10 specimens (yellow flowers, repeat flowering May-September), *Lychnis viscaria* 'Pink Rosea Plena' – 8 specimens (pink double flowers, May-July); a lower row (foliage and aromatic elements): *Hosta* 'Fire and Ice' – 12 specimens (ornamental throughout the season), *Lavandula angustifolia* 'Elizabeth' – 10 specimens (fragrant purple flowers, June-August); and a border (ground cover element): *Pennisetum alopecuroides* 'Little Bunny' – 15 specimens (dwarf grass, ornamental September-October) (Fig. 10).



a) b)

Figure 10. Flower border design: linear composition with a multi-layered structure

Note: (a) flower border variant with a warm pink-yellow colour palette (side view); (b) flower border variant with a cool blue-yellow colour palette (top view)

Source: Realtime Landscaping Architect 2025 (Idea Spectrum) (n.d.)

The composition was designed as a rhythmic line featuring alternating layers of height, with tall plants serving to divide the space, medium-sized plants providing colour intensity, and low-growing plants creating a textural and aromatic backdrop. The design of the composition ensured the integrity of the colour palette, low maintenance requirements and ecological adaptability. The proposed comprehensive landscape greening and urban improvement schemes for Zhytomyr, based on a selection of perennial plants, demonstrated a high level of integration of ecological, aesthetic and functional aspects, in line with contemporary urban greening trends. In particular, the use of a landscape style featuring asymmetrical layout, multi-layered composition and an emphasis on seasonal ornamental value was consistent with the findings of C.O. Fernandes *et al*. (2025), who scientifically substantiated the selection of plant species as a key factor in creating sustainable and comfortable urban landscapes. The selection of frost-hardy, drought-tolerant species (*Pennisetum, Festuca, Sedum*) was consistent with the strategies of C.Y. Jim (2013) for compact cities, where the emphasis was on low-cost maintenance of plantings, and also corresponded to the principles of creating ecologically adaptive urban plantings outlined by M. Ramaiah & R. Avtar (2019). The developed design options (borders, mixborders, flower beds, alpine rock gardens, container plantings, waterside zones, decorative groups, and flower borders) ensured full utilisation of the selection of perennial plants, achieving a greening level of 40-70%, which exceeded the minimum requirements of state building regulations (SCN B.2.2-5:2011, 2012). Increased greening of urban areas helped to reduce the urban heat island effect and increase the accessibility of green spaces for the population, as confirmed by the findings of J.R. Wolch *et al*. (2014), who emphasised the importance of balanced planning of green spaces to prevent inequality in access to environmental resources. In this context, the proposed solutions enabled the effective integration of planting with amenities – footpaths, benches and riverside areas along the Teteriv River. I. Anguelovski *et al*. (2018) cautioned that the development of green spaces can lead to gentrification and the exclusion of vulnerable groups; thus, when implementing proposals for the city of Zhytomyr, it is important to ensure equal access for residents to green spaces. S. Tappert *et al.* (2018) confirmed that public involvement in the planning of urban green spaces enhances their functionality and reduces conflicts of use. The zoning of areas based on lighting and planting density (4-9 plants/m^2) took into account the ecological adaptability of species to local climatic conditions. A comprehensive assessment of the quality of green areas, using a methodology developed by W. Halecki *et al.* (2023) for urban parks, confirmed the validity of this approach for ensuring the long-term functionality of plantings. The use of a variety of perennial plants ensured biodiversity and continuous flowering from May to October, which supported pollinators and contributed to the psychological well-being of residents. Furthermore, the authors M. Ramaiah & R. Avtar (2019) emphasised that, in the context of rapid urbanisation, integrated planning of green spaces has become a prerequisite for combating pollution and climate change. Potential limitations included dependence on soil quality and climatic fluctuations in Zone 5, which required further monitoring of the plantings. Compared to approaches to the systematic management of green spaces, proposals for the city of Zhytomyr could be expanded through public engagement and the use of geographic information systems for planning, in accordance with the provisions of Law of Ukraine No. 2807-IV (2005). O. Zibtseva & V. Yukhnovskyi (2019) confirmed that the discrepancy between regulatory indicators and the actual state of greening in Ukrainian cities had become a systemic problem, the resolution of which required comprehensive, scientifically grounded approaches. Overall, the proposed approach proved effective as a comprehensive solution for improving the quality of the urban environment in Zhytomyr, ensuring compliance with regulatory requirements, ecological sustainability and the aesthetic appeal of the green spaces. The types of landscape compositions developed in the study covered all typical urban spaces and were adapted to specific conditions of light, humidity and terrain, making them suitable for implementation in other Ukrainian cities with similar climatic conditions.

CONCLUSIONS

The study developed comprehensive proposals for the landscaping and improvement of urban areas in Zhytomyr in a landscape style, based on a selection of 14 species of ornamental perennials. The selected range of frost-hardy, drought-tolerant and low-maintenance species ensured continuous decorative flowering from May to October, thereby enhancing the biodiversity of the urban environment. The proposed plantings met the regulatory requirements for minimum greening levels and required minimal maintenance – mulching and watering only during dry periods. Various types of compositions were developed for typical urban spaces in Zhytomyr – squares, courtyards, pedestrian zones and the banks of the Teteriv River: borders and flowerbeds featuring low-growing groundcover and grass species; mixed borders and ornamental groups featuring multi-layered combinations of grasses, perennial herbaceous and aromatic plants; flowerbeds with a concentric arrangement of flowering and foliage species; alpine rock gardens with succulent-like and vertical architectural elements; container plantings of mobile evergreen and flowering species; landscaping along driveways using moisture-loving and shade-tolerant plants; group plantings for partially shaded park areas featuring shade-tolerant deciduous and grass species. All options ensured colour harmony in a purple-pink palette with yellow and silvery accents, with a greening level of 40 to 70 per cent, exceeding the minimum requirements of national building regulations. The proposed solutions contributed to improving the microclimate, reducing the urban heat island effect, supporting biodiversity and pollinators, creating recreational areas, and enhancing the social well-being of residents, all with minimal maintenance costs. Future research prospects include monitoring the survival rates of the proposed plant combinations in the urban environment of Zhytomyr, expanding the range to include native species, and developing digital tools based on geographic information systems to optimise the placement of green spaces in the urban environment.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Addas, A. (2023). The importance of urban green spaces in the development of smart cities. *Frontiers in Environmental Science*, 11, article number 1206372. [doi: 10.3389/fenvs.2023.1206372](https://doi.org/10.3389/fenvs.2023.1206372).
[2] Anguelovski, I., Connolly, J., & Brand, A.L. (2018). From landscapes of utopia to the margins of the green urban life: For whom is the new green city? *City*, 22(3), 417-436. doi: 10.1080/13604813.2018.1473126.
[3] Boyko, L., Yukhymenko, Yu., & Danylchuk, N. (2022). Principles of creation of dendrocompositions and criteria for their use in urban areas. *Environmental Sciences*, 5, 180-185. doi: 10.32846/2306-9716/2022.eco.5-44.26.
[4] Chen, S., Haase, D., Xue, B., Wellmann, T., & Qureshi, S. (2021). Integrating quantity and quality to assess urban green space improvement in the compact city. *Land*, 10(12), article number 1367. doi: 10.3390/land10121367.
[5] Fernandes, C.O., Teixeira, C.P., & Veludo, M. (2025). Greening urban landscapes: A systematic literature review of planting design for resilient and livable cities. *Urban Forestry & Urban Greening*, 107, article number 128793. doi: 10.1016/j.ufug.2025.128793.
[6] Garden Industry. (n.d.). *Décor Zviahel Sad*. Retrieved from https://gardenindustry.org/ua/dekor-zvyagel-sad/.
[7] Halecki, W., Stachura, T., Fudała, W., Stec, A., & Kuboń, S. (2023). Assessment and planning of green spaces in urban parks: A review. *Sustainable Cities and Society*, 88, article number 104280. doi: 10.1016/j.scs.2022.104280.
[8] Hansen, R., *et al.* (2023). Transformative or piecemeal? Changes in green space planning and governance in eleven European cities. *European Planning Studies*, 31(12), 2401-2424. doi: 10.1080/09654313.2022.2139594.
[9] Hardberger, A., Craig, D., Simpson, C., Cox, R.D., & Perry, G. (2025). Greening up the city with native species: Challenges and solutions. *Diversity*, 17(1), article number 56. doi: 10.3390/d17010056.
[10] Jim, C.Y. (2013). Sustainable urban greening strategies for compact cities in developing and developed economies. *Urban Ecosystems*, 16, 741-761. doi: 10.1007/s11252-012-0268-x.
[11] Kosyk, O., Horupakha, V., & Humeniuk, M. (2020). Application of container plants in an urban environment. *Theory and Practice of Design*, 21, 58-65. doi: 10.18372/2415-8151.21.15061.
[12] Law of Ukraine No. 2807-IV "On the Improvement of Settlements". (2005, September). Retrieved from https://zakon.rada.gov.ua/laws/show/2807-15#Text.
[13] Min, K. (2025). Exploring research fields in green buildings and urban green spaces for carbon-neutral city development. *Buildings*, 15(9), article number 1463. doi: 10.3390/buildings15091463.

[14] Order of the Ministry of Construction, Architecture, and Housing and Communal Services of Ukraine No. 105 "On the Approval of the Rules for the Maintenance of Green Plantations in Settlements of Ukraine". (2006, April). Retrieved from https://zakon.rada.gov.ua/laws/show/z0880-06#Text.

[15] Pancewicz, A., & Kurianowicz, A. (2024). Urban greening in the process of climate change adaptation of large cities. *Energies*, 17(2), article number 377. doi: 10.3390/en17020377.

[16] Panwar, M., Mina, U., Kumar, K., & Kumar, M. (2025). Urban green space assessment index (UGSAI): A novel GIS-based measure for assessing green spaces in Delhi. *Environment and Urbanization ASIA*, 16(1), 122-142. doi: 10.1177/09754253251337350.

[17] Ramaiah, M., & Avtar, R. (2019). Urban green spaces and their need in cities of rapidly urbanizing India: A review. *Urban Science*, 3(3), article number 94. doi: 10.3390/urbansci3030094.

[18] Realtime Landscaping Architect 2025 (Idea Spectrum). (n.d.). Retrieved from https://surl.lu/pzthqo.

[19] SCN B.2.2-5:2011. (2012). *Landscaping of territories*. Retrieved from https://dbn.co.ua/load/normativy/dbn/dbn_b_2_2_5_2011/1-1-0-1033.

[20] Semeraro, T., Scarano, A., Buccolieri, R., Santino, A., & Aarrevaara, E. (2021). Planning of urban green spaces: An ecological perspective on human benefits. *Land*, 10(2), article number 105. doi: 10.3390/land10020105.

[21] Tappert, S., Klöti, T., & Drilling, M. (2018). Contested urban green spaces in the compact city: The (re-)negotiation of urban gardening in Swiss cities. *Landscape and Urban Planning*, 170, 69-78. doi: 10.1016/j.landurbplan.2017.08.016.

[22] Tian, L. (2022). Analysis of the artistic effect of garden plant landscaping in urban greening. *Computational Intelligence and Neuroscience*, article number 2430067. doi: 10.1155/2022/2430067.

[23] Wolch, J.R., Byrne, J., & Newell, J.P. (2014). Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landscape and Urban Planning*, 125, 234-244. doi: 10.1016/j.landurbplan.2014.01.017.

[24] Zhang, F., & Qian, H. (2024). A comprehensive review of the environmental benefits of urban green spaces. *Environmental Research*, 252, article number 118837. doi: 10.1016/j.envres.2024.118837.

[25] Zhou, X., Zou, X., & Xiong, W. (2025). Optimization of urban green space in Wuhan based on machine learning algorithm from the perspective of healthy city. *Frontiers in Public Health*, 13, article number 1490857. doi: 10.3389/fpubh.2025.1490857.

[26] Zhytomyr.info. (2025). *"Zelenbud" has been tasked with creating ten new green areas in Zhytomyr*. Retrieved from https://www.zhitomir.info/news_227644.html.

[27] Zibtseva, O., & Yukhnovskyi, V. (2019). Analytical evaluation of developed norms for greening of cities. *Biological Resources and Nature Management*, 11(5-6), 131-140. doi: 10.31548/bio2019.05.014.

Віра Мороз
Кандидат сільськогосподарських наук, доцент
Західноукраїнський національний університет
46009, вул. Львівська 11, м. Тернопіль, Україна
https://orcid.org/0000-0002-1457-4641

Анатолій Вишневський
Кандидат сільськогосподарських наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0001-5381-1219

Комплексні пропозиції з ландшафтного озеленення та благоустрою міських територій Житомира на основі асортименту багаторічних рослин

Анотація. Швидкий розвиток міської забудови міста Житомир призводить до скорочення площі зелених насаджень нижче нормативного рівня та посилення ефекту міського теплового острова, що підвищує температуру повітря влітку на 2-4 °С. Це зумовило необхідність впровадження екологічно стійких рішень, спрямованих на регулювання мікроклімату, підвищення естетичної привабливості міського середовища та забезпечення соціального благополуччя мешканців. Метою дослідження була розробка комплексних пропозицій з ландшафтного озеленення та благоустрою міських територій Житомира у пейзажному стилі на основі асортименту багаторічних декоративних рослин. Це забезпечило біорізноманіття, безперервність сезонної декоративності та функціональне зонування міського простору. Було здійснено класифікацію рослин за висотою, потребами в освітленні, вологості та декоративними характеристиками. На підставі аналізу інсоляції типових міських територій було розроблено схему зонування: 60 % сонячних ділянок, 30 % – напівтіньових, 10 % – прибережних зон водойм. Щільність посадки варіювалася від 4 рослин/м^2 для великих видів до 9 рослин/м^2 для низькорослих ґрунтопокривних, що забезпечувало змикання насаджень протягом 1-2 років. До асортименту увійшли морозостійкі, посухостійкі та невибагливі в догляді види рослин – декоративні злаки (*Pennisetum, Festuca*), багаторічні трав'янисті (*Echinacea, Salvia, Hemerocallis, Sedum*), вічнозелені (*Yucca, Lavandula*) та декоративно-листяні (*Hosta*), що не мали інвазивних властивостей. Також, було запропоновано дев'ять типів озеленювальних композицій: бордюри (50-70 м завдовжки), міксбордери (100-150 м^2), клумби (10-20 м^2), альпійські гірки (15-20 м^2), контейнерні насадження, озеленення при водоймах (20-30 м^2), декоративні групи з солітерними елементами (5-10 м^2), групові насадження (10-15 м^2) та рабатки (шириною 0,5-1,0 м). Усі варіанти забезпечували безперервну сезонну декоративність з травня по жовтень, рівень озеленення від 40 % до 70 %, що перевищувало мінімальні нормативні вимоги, та потребувало мульчування та поливу в посушливі періоди. Практична цінність роботи полягає у готових до впровадження проєктах із детальними схемами розміщення рослин і можливістю адаптації до інших міст України зі схожими кліматичними умовами

Ключові слова: пейзажний стиль; варіанти композицій; ландшафтний дизайн; міське озеленення; біорізноманіття; сезонна декоративність; екологічна стійкість

Architectural Studies
International Journal about Architecture

Volume 12, No. 1

UDC 72.025.5:004.8
DOI: 10.56318/as/1.2026.93

ISSN: 2411-801X
e-ISSN: 2786-7374

Oleh Nester[*]
Master, Assistant
Uzhhorod National University
88000, 3 Narodna Sq., Uzhhorod, Ukraine
https://orcid.org/0009-0003-9321-0532

Integration of artificial intelligence into the restoration of architectural monuments: Methods and prospects

Abstract. The study aimed to identify the potential of intelligent digital technologies in assessing the condition of architectural heritage sites and justifying necessary interventions. Methods of systematisation, comparative and comparative-legal analysis, and case analysis were employed. The study established that artificial intelligence in the field of architectural heritage conservation improved professional expertise, digital documentation, condition analysis, forecasting and support for restoration decisions. The effectiveness was determined by data quality, expert validation, system compatibility and algorithm transparency. At the same time, key challenges remained, including incomplete automation, the complexity of integrating digital environments, and the need for human oversight. The global regulatory and ethical framework stipulated that the application of artificial intelligence in restoration must be based on the principles of authenticity, human oversight, accountability, and the use of reliable data. The study determined that Ukrainian legislation does not yet contain specific legal regulations on the use of artificial intelligence in restoration; therefore, its application was primarily linked to documentation, standardisation of damage assessment, data preparation and the professional training of specialists. The case studies of the Dunhuang Mogao Grottoes, Mezgit Castle, St Peter's Basilica, and Lausanne Cathedral demonstrated established approaches to the use of artificial intelligence in restoration practice, as well as in the monitoring and forecasting of the condition of heritage sites. Ukrainian practices in Lviv (Historic Centre Ensemble), Odesa (Odesa Historic Centre) and Chernihiv (T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre) represented a predominantly artificial intelligence-ready environment for the future implementation of such solutions. Therefore, the opportunities for the application of artificial intelligence were linked to the transition to comprehensive integrated systems for analysis, modelling and decision support, provided that the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight were upheld. The practical significance of the possible use of results by restorers, architects, engineers and cultural heritage authorities in restoration practice, during the documentation and assessment of the condition of monuments, and in planning measures for their preservation

Keywords: heritage; digital recording; damage; digital replicas; condition monitoring

INTRODUCTION

Digitalisation of cultural heritage conservation had created a need for tools that can be used for documentation of the condition of architectural monuments and support restoration decisions. In this context, methods such as artificial intelligence (AI), computer vision, digital modelling and spatial data analysis held promise for detecting

Suggested Citation:
Nester, O. (2026). Integration of artificial intelligence into the restoration of architectural monuments: Methods and prospects. *Architectural Studies*, 12(1), 93-105. doi: 10.56318/as/1.2026.93.

Journal homepage: https://arch-studies.com.ua/en
Architectural Studies, 12(1), 93-105
Received: 05.11.2025 Revised: 02.02.2026 Accepted: 24.02.2026 Published: 26.03.2026

*Corresponding author

damage, classifying monument elements and processing data from digital surveys. Despite the high accuracy of digital technologies, their application in restoration practice was accompanied by difficulties in interpreting results, incorporating historical authenticity, material uniqueness and expert responsibility. This required a synthesis of the possibilities and limitations of integrating AI into the process of restoring architectural monuments. This topic had already been extensively explored in academic discourse. In a study by M. Mishra (2021), the various applications of machine learning for the structural monitoring of historic buildings were systematised, and it was demonstrated that algorithmic analysis improved the speed, at which technical anomalies were detected. Such approaches were most effective, when combined with data from actual surveys and remained grounded in the engineering context of the monument. V. Croce *et al.* (2023) demonstrated the potential of combining Historic/Heritage Building Information Modelling (HBIM) and AI for classifying architectural heritage in semi-automated scan-to-BIM reconstruction. This approach viewed AI not as an isolated recognition tool, but as a link in the transition from a point cloud to a structured information model suitable for further restoration decisions. M. Mishra & P.B. Lourenço (2024) summarised the state of research into AI-assisted visual inspection of cultural heritage sites as of 2024 and demonstrated that the automation of inspections enhanced the potential for early defect detection. At the same time, the study emphasised that the accuracy of such systems depended on the quality of training samples and the standardisation of damage features; consequently, the question of the reliability of interpretation remained open.

As S.W. Abusaleh (2024) established, machine learning helped to improve the effectiveness of architectural heritage conservation using predictive analysis and the optimisation of potential intervention scenarios. The author demonstrated that algorithmic analysis made it possible not only to assess the current condition of a site but also to justify the selection of the most appropriate measures, considering long-term consequences. This expanded the role of AI from the technical documentation of damage to supporting the strategic planning of restoration priorities. M. Buldo *et al.* (2024) demonstrated the effectiveness of using AI for the semantic enrichment of point clouds of architectural heritage, using the Palacio de Sástago in Zaragoza as an example. AI improved recognition and classification accuracy of the structural and decorative elements of a historic building, thereby increasing the informativeness of the digital model and reducing the risk of data loss during the preparation of restoration documentation. G. Sugiyama *et al.* (2025) proposed a comprehensive methodology for evaluating Heritage Digital Twins based on Portuguese case studies. The digital twin emerged not merely as a visual copy of a heritage site, but as an integrated environment for diagnostics, condition analysis and modelling the consequences of intervention. H. Hosamo & S. Mazzetto (2025) developed this line of research by combining knowledge graphs and digital twins for the preservation of historic buildings. As a result, a path was outlined towards an intelligent system capable of linking geometry, historical data, material characteristics and expert judgement rules within a single information field. M. Zhang *et al.* (2025) proposed an automated method for surveying architectural heritage based on semantic point cloud segmentation. This development demonstrated that AI can accelerate the preparation of accurate geometric characteristics of a monument, which directly influenced the quality of the design of restoration measures.

Research conducted in Ukraine confirmed the value of using digital technologies to document, visualise and monitor the condition of historical and architectural heritage sites. I. Kovalchuk *et al.* (2025) demonstrated the significance of laser scanning and Building Information Modelling (BIM) for visualising historical and architectural heritage. This confirmed that digital modelling was not only a means of representation but also a basis for further analysis, compatible with AI tools. O. Chumak & J. Gorkovchuk (2023) refined approaches to the preliminary calculation of the accuracy of monitoring cultural heritage sites using unmanned aerial vehicles (UAVs) and laser scanning. This result was fundamental, as the effectiveness of any AI models in restoration directly depended on the reliability of the raw data. However, existing research had mainly focused on specific technological applications of AI, whilst its integration into the restoration process as a coherent sequence of documentation, diagnosis, forecasting and decision support had not yet been sufficiently systematised. The conditions for the scientifically sound use of such technologies also remained insufficiently defined, particularly regarding the quality of source data, expert verification, the compatibility of digital environments, the transparency of algorithmic processing, and adherence to the principles of authenticity preservation. Therefore, the study aimed to determine the role of digital tools in assessing the condition of architectural heritage sites and preparing well-founded intervention measures. To achieve this aim, the following tasks were set: to investigate the areas and methods of AI application in the process of digital documentation, condition analysis and change forecasting to justify restoration interventions on architectural heritage sites, to identify global and Ukrainian regulatory and ethical principles for the application of AI in the field of architectural heritage restoration, and to analyse global and Ukrainian experience of using AI in the field of architectural heritage conservation to outline the prospects for its further application.

MATERIALS AND METHODS

The study combined methods of systematisation, comparative and comparative legal analysis, and case analysis to classify the areas of application of AI in the field of architectural heritage restoration. Using the systematisation method, the areas of AI application in the field of architectural heritage restoration were summarised – Unmanned

Aerial Vehicle (UAV) photogrammetry and AI-enhanced Three-Dimensional (3D) reconstruction, computer vision for automated detection of cracks and defects, AI-based point cloud segmentation and the Scan-to-HBIM approach (Cotella, 2023; Ge *et al.*, 2024; Yiğit & Uysal, 2024). Moreover, digital twins, Structural Health Monitoring (SHM), predictive modelling, and AI as a system for supporting restoration decisions (Sharma, 2025; Tan *et al.*, 2025; Wang *et al.*, 2025). The selection of these approaches was based on their representativeness of the key stages of the restoration cycle – from digital documentation of the object and initial diagnosis to monitoring of technical condition, prediction of degradation processes, and support for decision-making. The synthesis was based on the following criteria: the method's function within the restoration cycle, key integration challenges, and the benefits of application. This approach had made it possible to organise the diverse areas of AI application and establish a comparative framework for further analysis of the possibilities and limitations of using AI in the restoration of architectural heritage. Using a comparative analysis, approaches relating to the digital documentation and 3D modelling of objects, the automated analysis of the technical condition of heritage sites, and the prediction of the consequences of restoration interventions were compared. The comparison was conducted in terms of the following aspects: the role of the technology in the restoration process, practical application possibilities, significance for assessing the condition of a monument, and the main limitations of implementation. This made it possible to systematise the areas of application of AI in the restoration of architectural heritage and to clarify the role in supporting professional restoration decisions.

Using a comparative legal analysis to identify the similarities and differences between the international and Ukrainian frameworks, this study compared the global and Ukrainian regulatory frameworks that defined the permissible limits and conditions for the use of AI in the field of architectural heritage restoration. The analysis was based on international documents – the International Charter for the Conservation and Restoration of Monuments and Sites. (The Venice Charter – 1964) (1964), a normative and principled document in the field of heritage conservation, and the United Nations Educational, Scientific and Cultural Organization (2021) policy document. The analytical report by M. Pasikowska-Schnass & Y.-S. Lim (2023) and the policy document by the Steering Committee for Culture, Heritage and Landscape (CDCPP) (2024) were analysed. Ukrainian legislation was represented by Law of Ukraine No. 1805-III (2000) and the United Nations Educational, Scientific and Cultural Organization (2024a). These documents were selected for their representativeness regarding key levels of regulation governing the application of AI in the field of architectural heritage restoration. It reflected the basic principles of heritage protection, ethical requirements for AI, specialised recommendations for the cultural sector, and the Ukrainian legal framework. This was done to identify commonalities and differences between the international and Ukrainian frameworks, outline existing gaps in national regulation, and clarify the conditions for the responsible use of AI in restoration practice.

Using a case-study approach, the study systematised global and Ukrainian examples of AI implementation in cultural heritage conservation and restoration processes – the Dunhuang Mogao Grottoes (China) (Yu *et al.*, 2022), Mezgit Castle (Turkey) (Yiğit & Uysal, 2024). The study also covered St. Peter's Basilica (Vatican) (Smith, 2025; Microsoft, n.d.) and Lausanne Cathedral (Switzerland) (Vogel, 2025). The Ukrainian experience was represented by case studies – Lviv – Historic Centre Ensemble (UNESCO World Heritage Centre, n.d.a), Odesa – Historic Centre of Odesa (UNESCO World Heritage Centre, n.d.b) and associated cultural heritage sites), and the T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre, 2025 (Skamantzari *et al.*, 2025). The selection of international case studies was based on their representativeness of the main areas of AI application in restoration practice: automated restoration, damage detection, the creation of digital twins, and the prediction of the technical condition of monuments. The selection of Ukrainian case studies was determined by the nature of the publicly available source base. Since open sources provided the most comprehensive coverage of practices in digital documentation, 3D recording and damage assessment, these were selected for analysis. Due to the limited public representation of completed cases of comprehensive AI applications in Ukraine, these examples were considered AI-ready practices that formed the basis for the further integration of AI into the field of cultural heritage preservation. The case studies were compared using the following criteria: AI method or tool, functional purpose, and practical significance for restoration. This was done to analyse practical models of AI use in the restoration of architectural heritage and to identify the prerequisites for the further implementation of AI, particularly in Ukraine.

RESULTS AND DISCUSSION

Areas of application for AI in the restoration of architectural heritage

AI was one of the key tools for the digital transformation of the architectural heritage conservation sector. In the field of architectural heritage restoration, AI should be viewed not as a replacement for a professional restorer, but as a tool for technologically enhancing professional expertise, expanding the possibilities for documentation, diagnosis, forecasting and decision-making in restoration projects (Kotsiubivska *et al.*, 2024; Shevchuk & Tarasiuk, 2025). Its significance lain not only in the automation of individual technical operations, but also in expanding the possibilities for recording, analysing, forecasting, and scientifically substantiating restoration decisions. In this context, AI should be viewed as a supportive analytical and predictive tool that works with large sets of visual, spatial and technical data and supported the professional expertise of architects, engineers and conservators (Sharma, 2025). Its application encompassed the digital documentation and modelling of objects, automated damage detection, analysis of technical condition, prediction of degradation processes, as well as support for decision-making within the framework of conservation and restoration measures (Tan *et al.*, 2025). At the same time, in the field of architectural heritage, AI does not function as an autonomous agent in the restoration process, but merely accelerated data processing, identified patterns, compared intervention scenarios and formed an analytical basis for further professional conclusions. Therefore, integration of AI should be viewed not as a replacement for professional restoration expertise, but as a form of technological enhancement (Pasikowska-Schnass & Lim, 2023). To systematise the main areas of AI application in the restoration of architectural monuments, it was useful to summarise the key methods, their functions within the restoration cycle, the main challenges of integration, and the practical impact (Table 1).

Table 1. Methods for integrating AI into the restoration process of architectural heritage sites

Method/approach	Role in restoration cycle	Key challenges of integration	The benefits of AI use
UAV photogrammetry and AI-enhanced 3D reconstruction	Digital documentation of the monument, creation of 3D models, and comparison of the monument's condition	Image quality requirements, large data volumes, and processing complexity	Shift towards faster and geometrically more accurate 3D reconstruction of historical objects, particularly for digital preservation, restoration and post-damage documentation
Computer vision for the automatic detection of cracks and defects	Automated inspection, fault localisation, initial diagnosis	Reliance on the quality of models and images, the need for expert validation, and a lack of specialised data	Integration of automated defect detection with routine monitoring systems and digital twins
AI-based point cloud segmentation and the Scan-to-HBIM approach	Transferring data to an HBIM model: integrating geometry, semantics and defects	Complexity of historical geometry, incomplete automation, and the limitations of existing solutions	Development of a semi-automated HBIM workflow as a basis for documenting interventions, analysing the condition and long-term management of the monument
Digital twin, SHM and predictive modelling	Monitoring of condition, recording of changes over time, and prediction of deterioration	Need for high-quality multi-source data, infrastructure, interoperability and metadata	Development of an integrated workflow: documentation → diagnosis → prognosis → post-intervention monitoring
AI as a decision support system in restoration	Risk assessment, prioritisation of interventions, and comparison of scenarios	The risk of a "black box", the need for transparency, human oversight and professional verification	Development of a data-driven but not autonomous restoration workflow, in which AI enhances expert judgement rather than replacing it

Source: based on V.A. Cotella (2023), Y. Ge *et al*. (2024), A.Y. Yiğit & M. Uysal (2024), H. Sharma (2025), X. Tan *et al*. (2025), H. Wang *et al*. (2025)

The effectiveness of integrating AI into restoration depended on several fundamental conditions: the quality of the source data, expert validation, the compatibility of digital systems, the availability of infrastructure, and the transparency of algorithmic processing. Therefore, AI in this field should be viewed as a tool to support restoration decisions, rather than as an autonomous mechanism for making them. The application of AI in the restoration of architectural heritage was complex in nature and encompassed several sequentially linked stages of work on a heritage site. At the initial stage, AI was used for the digital documentation and modelling of the object, which created the basis for the collection, structuring and visualisation of data regarding its geometry, materials and condition. The next level involves automated damage analysis, where computer vision algorithms can be used for rapid detection of defects, their classification, and the identification of the most vulnerable areas. Further sophistication of AI functions was evident in predictive modelling and the use of digital twins, which facilitate the transition from recording the current state to assessing potential changes over time. As a result, AI was increasingly becoming a valuable decision-support tool, enabling the comparison of intervention scenarios, the prioritisation of work, and the enhancement of the soundness of the restoration process. At the same time, the effectiveness of AI integration depended directly on the quality of the input data, the technical infrastructure, the transparency of the algorithms, and the essential combination of automated analysis with professional expert assessment.

The digital documentation of architectural heritage was one of the most advanced areas of AI application, as it provided an accurate spatial and informational foundation for further analysis, monitoring and the planning of restoration work. It was most often based on a combination of photogrammetry, laser scanning and algorithms for the automated processing of spatial data. Photogrammetry provided a large volume of visual data on façades, structural elements and damaged areas, whilst laser scanning provided highly accurate information on the monument's geometry in the form of point clouds, enabling the recording of deformations, material loss and the slightest deviations in form. In this process, AI was used to accelerate data processing, its automated classification and preparation for further modelling (Sharma, 2025; Tan *et al.*, 2025). A significant step was the construction of 3D models of historic buildings, which integrated the geometric, visual and technical characteristics of the site and form the basis for analysis, comparison of conditions over time and the preparation of scientific and design documentation. Equally relevant was the transition from point clouds to HBIM, where AI facilitated the automated recognition of elements and the structuring of data, which was essential for complex historic structures with heterogeneous composition (Cotella, 2023). A separate area of focus involved the use of digital twins, which combined a spatial model with monitoring data, damage assessment and predictions of the object's future condition, enabling continuous monitoring and analysis of the consequences of various intervention scenarios (Ge *et al.*, 2024). Thus, digital recording and modelling using AI was not only a means of documentation but also an analytical basis for assessing condition, planning restoration and monitoring effectiveness.

Automated analysis of the condition of heritage sites expanded the capabilities of digital recording, moving beyond mere documentation to the diagnosis and interpretation of a site's technical condition. Practical value was determined by faster detection of defects, more accurate classification of damage, and systematic comparison of observation results over time. The most common task in this field was the detection of cracks and other localised defects using computer vision algorithms, which analysed images of façades, decorative elements or structural surfaces and can be used for recording of signs of deterioration in the technical condition of the object. The combination of UAV photogrammetry and digital twin technology created an effective basis for the automatic detection of cracks and structural surveys of historic buildings (Yiğit & Uysal, 2024). In addition to detecting individual defects, AI can classify damage by type, location, severity and potential hazard, which was essential for structures with complex damage patterns and limited resources for intervention (Wang *et al.*, 2025). Another function was the identification of high-risk areas based on a combination of digital survey data, information on existing defects and external impact parameters. Equally urgent was the automated comparison of a site's condition before and after intervention, which can help assess changes, record new damage and determine the effectiveness of stabilisation or restoration, particularly in the context of multi-stage monitoring or recurring threats. Thus, automated analysis of the condition of heritage sites facilitated a transition from piecemeal recording of defects to a systematic assessment of the site's technical condition.

In contrast to digital recording and automated condition analysis, which focused primarily on documentation and diagnosis, predictive modelling was geared towards assessing the potential consequences of restoration decisions in advance. In this context, AI performed not only an analytical but also a predictive function, enhancing the scientific rigour of design decisions and reducing risks to the heritage site. One of the main areas of such application was the modelling of possible restoration scenarios based on data regarding the object's geometry, the nature of the damage, material properties, previous interventions and external influences. This made it possible to compare alternative courses of action and preliminarily assess their feasibility without replacing the restorer's professional judgement. Another significant aspect was predicting the consequences of different intervention methods, particularly the risk of further crack propagation, deformation, material loss, or disruption of structural equilibrium following the restoration. In practical terms, AI can also be used to prioritise restoration by ranking problem areas according to risk level, urgency of response and the potential consequences of inaction. This provided a basis for a more rational allocation of resources and systematic planning of interventions, particularly in cases of monuments that have suffered emergency damage or were partially destroyed. AI can reduce the risk of incorrect or excessive interventions, as preliminary digital modelling made it possible to identify potentially dangerous solutions even before practical work begins. In this sense, it supported the principle of minimal intervention, assisting in the selection of courses of action that were sufficient to stabilise or restore the site, but do not result in excessive alteration of its historical structure.

Therefore, the effectiveness of restoration in the context of AI application should be assessed according to criteria such as stabilising the condition of the site, reducing the risks of further deterioration, minimising interference with the historical structure of the monument, the accuracy and soundness of restoration decisions, as well as the ability to monitor results over time by comparing the condition of the object before and after the works. In this sense, predicting the effectiveness of restoration measures using AI should be viewed as a tool for enhancing the soundness of the restoration process, the effectiveness of which directly depended on the quality of the input data, the accuracy of the digital model, and the combination of algorithmic analysis with professional restoration expertise. Despite its high potential, the application of AI in the restoration of architectural heritage has several limitations. First and foremost, these included dependence on the quality of the input data, the need for expert validation, incomplete automation when dealing with complex historical geometry, and the requirement for compatibility between different digital environments. Transparency of algorithmic processing and the preservation of human control during the decision-making process for restoration also remained challenges. The findings of the study indicated that AI in the field of architectural heritage restoration should be viewed not as an autonomous decision-making mechanism, but as a tool for technologically enhancing professional expertise. This interpretation was consistent with the study by İ. Karadag (2023), who demonstrated that machine learning can be beneficial in the conservation of architectural heritage, not only as a means of technical automation but also as a tool for the restoration and interpretation of lost or damaged parts of historical sites. The author's study proposed a mixed methodological framework and confirmed that the effectiveness of such solutions depended to a large extent on the completeness and quality of the dataset and on the context, in which this data was generated. Accordingly, the use of AI in restoration practice should be viewed as a supporting analytical tool, the effectiveness of which depended on the quality of the input data and the professional interpretation of the results obtained.

O.E. Dragomir & F. Dragomir (2025) proposed a hybrid neuro-fuzzy approach for the proactive maintenance of cultural heritage sites, which combined feedforward neural networks for pattern recognition with Mamdani-type fuzzy logic inference systems (fuzzy inference system) for interpretable decision-making. The authors emphasised that in conservation practice, high predictive accuracy alone is insufficient, as transparency, explainability and the possibility of professional verification of the recommendations obtained are no less critical. This approach was consistent with the findings of the study, according to which the key conditions for the effective integration of AI into conservation were data quality, expert validation, transparency of algorithmic processing, and the preservation of human oversight. In this context, AI should be viewed not as an autonomous decision-making mechanism, but as a tool to support professional analysis and the justification of interventions. This logic was also supported by the study by L.E. Mansuri & D.A. Patel (2022), in which AI was used to build an automated visual inspection system for architectural heritage sites. The authors noted that such a system made it possible to reduce inspection time, cut costs, minimise the risk of human error and improve the consistency of defect recording. This was consistent with proposed research indicating that AI enhanced the capabilities of documentation and initial diagnosis but does not eliminate the need for a specialist to interpret the results. Consequently, automated visual inspection confirmed the value of using AI specifically as a tool to support the restoration process during the stage of identifying and initially analysing damage.

The results of the study showed that the priority stage in integrating AI into the restoration cycle was the transition from the accumulation of spatial data to its structured semantic organisation. This approach was consistent with that of A. Gil & Y. Arayici (2025) proposed a hierarchical approach to the segmentation and classification of large datasets of point clouds of historic buildings using the Random Forest algorithm and the Uniclass system. In the context of this study, this supported the interpretation of AI as a tool that not only processes geometric information but also transferred it into a semantically organised environment, which was necessary for subsequent HBIM modelling, condition analysis and long-term management of the heritage site. The application of AI in working with point clouds had not only technical but also methodological significance, as it created a basis for integrating data into the digital restoration cycle. In their study, A. Felicetti & F. Niccolucci (2025) developed the concept of the Reactive Heritage Digital Twin and demonstrated that combining AI with ontologies made it possible not only to structure complex data about a heritage object but also to expand the analytical and predictive capabilities of the digital twin. This approach involved integrating diverse information about the object's condition, its materials, damage and possible intervention scenarios into a single digital environment. This was consistent with the findings of the proposed study, according to which the effectiveness of AI in restoration was determined not only by the accuracy of individual algorithms but also by the ability to integrate different types of data within a cohesive digital environment. In this context, the digital twin emerged not as a means of autonomising decisions, but as a tool for enhancing professional analysis, forecasting and justifying restoration interventions. Artificial intelligence can therefore be effectively applied at various stages of the restoration cycle, from digital documentation and analysis of the technical condition to predictive modelling and support for restoration decisions. Its use improved the accuracy of documentation, expanded the scope for detecting damage, aids risk assessment and justified interventions; however, it does not eliminate the need for the restorer's professional expertise. At the same time, the effectiveness of AI implementation was determined by the quality of the input data, the level of expert validation, the compatibility of digital systems, the transparency of algorithmic processing, and the maintenance of human oversight. This provided grounds for viewing AI not as an autonomous decision-making mechanism, but as a tool for technologically enhancing professional restoration practice.

Regulation and prospects for the use of AI in restoration of architectural heritage: International and Ukrainian contexts

International regulations governing the use of AI in the restoration of architectural heritage should be viewed as a combination of traditional principles of heritage conservation and ethical requirements for digital technologies. The International Charter for the Conservation and Restoration of Monuments and Sites. (The Venice Charter – 1964) (1964) remained the foundational document in this field, as it defined the limits of permissible intervention in a monument through the principle of authenticity and respect for reliable sources. As applied to AI, this means that algorithmically generated reconstructions and digital interpolations may be used as analytical or research tools, but not as a self-sufficient basis for the physical reconstruction of lost parts of a site. A general ethical framework for the use of AI was provided by United Nations Educational, Scientific and Cultural Organization (2021), which shifted the emphasis from technical efficiency to human control, explainability, accountability, traceability and the auditability of AI systems. This was of fundamental importance for restoration practice, as decisions regarding a heritage site cannot be based solely on the formal accuracy of an algorithm. A more specialised framework for the field of culture and heritage was established by the Steering Committee for Culture, Heritage and Landscape (CDCPP) (2024), which specified these requirements in terms of data quality, open standards, a trust infrastructure, and the impermissibility of replacing human participation with algorithmic procedures. An analytical supplement to this regulatory framework was a study by the European Parliament (Pasikowska-Schnass & Lim, 2023), which identified the key risks associated with the use of AI in the cultural sector, including algorithmic opacity, the "black box" effect, copyright issues and data governance. Thus, the international framework formed a comprehensive system of guidelines within, which AI can be regarded as a professionally and ethically acceptable tool for restoration practice.

In Ukraine, the context for the application of AI in the field of architectural heritage restoration differs from the global context. Whilst international documents primarily establish a value-based and ethical framework, the Ukrainian context was defined by a combination of legal regulations governing the protection of cultural heritage and practical challenges arising from the consequences of russia's full-scale war against Ukraine, the mass documentation of damage, and post-war reconstruction. The key document was Law of Ukraine No. 1805-III (2000), which established the priority of preserving the subject of heritage protection, the scientific nature of restoration measures, and the requirement for proper documentation. At the same time, it does not regulate AI as a separate technology; therefore, under current Ukrainian law, AI can only be regarded as a tool for research, design and analytical support for restoration, but not as an autonomous decision-making mechanism. The present state of the Ukrainian sector was reflected in United Nations Educational, Scientific and Cultural Organization (2024a), which stipulated the main priorities: the standardisation of data collection for damage assessment, the introduction of protocols for data collection, protection and dissemination, as well as the training of specialists in the field of documentation and damage assessment. This indicated that, in the Ukrainian context, the issue of AI was directly linked to data quality, the standardisation of methodologies, and the institutional capacity to work with digital tools. Consequently, the Ukrainian practical context focused primarily on standardising damage assessment, field documentation, standardised procedures and professional training, rather than on delegating decisions to AI.

The international and Ukrainian frameworks do not contradict but serve different functions. International documents established a value-based and normative framework: authenticity, the prevention of speculative interference, human oversight, transparency, accountability and the use of reliable data. Ukrainian documents, on the other hand, stipulated procedural and practical level: conservation protocols, documentation, damage assessment, standardisation of methodologies, training of specialists and development of digital infrastructure. At the same time, it was precisely within the Ukrainian context that the main gaps were evident. Current sector-specific legislation does not contain specialised provisions regarding AI in restoration, so the legal admissibility of its use was currently derived indirectly – through general requirements for scientific rigour, proper documentation and the preservation of the object of conservation. For Ukraine, the issues of data standardisation, compatibility of methodologies and the dissemination of standardised damage assessment procedures remain critical. Therefore, the main task was determined not by accelerated implementation of autonomous AI solutions, but by the creation of the institutional, methodological and digital prerequisites for their responsible and scientifically verified use in the future. The outlined regulatory, ethical and institutional differences between the global and Ukrainian contexts provided grounds for moving from the level of principles to that of practical implementation. In this context, an analysis of specific case studies, in which AI was already being used for digital documentation, automated damage detection, technical condition forecasting and supporting restoration decisions was noteworthy. Such examples can trace how technological tools were integrated into cultural heritage conservation processes, what functions they performed and what practical significance they had for restoration; a summary was presented in Table 2.

Table 2. Case studies on the implementation of artificial intelligence in cultural heritage conservation and restoration processes

Case/ object	AI method/tool	Function	Practical significance for restoration
Dunhuang Mogao Caves, China	Deep learning, automated restoration, object detection algorithms, search and analysis tools, style transfer, and AI for the Dunhuang specialised dataset	Automated restoration of wall paintings, accelerated analysis of large visual datasets, and support in building a thematic library of elements for research and conservation	More accurate reconstruction of lost or damaged sections of the mural, systematisation of visual elements, and greater justification for restoration decisions
Mezgit Castle, Turkey	UAV photogrammetry, digital twin technology and deep learning methods for automated crack detection	Automated crack detection on 3D models, support for the preparation of repair plans and subsequent monitoring of damage progression	Prompt identification of defects, assessment of the extent of damage and planning of restoration work based on a precise digital model of the building
St. Peter's Basilica, Vatican	Photogrammetry, AI techniques and cloud computing for creating a high-precision digital twin of an object	Digital replica was created using around 400,000 high-resolution images; AI helped to improve the visualisation and identify signs of potential structural deterioration, including cracks and missing mosaic fragments	Provides a highly accurate digital framework for assessing the condition of a heritage site, planning conservation work and long-term monitoring of changes to the structure and decorative elements

Table 2. Continued

Case/ object	AI method/tool	Function	Practical significance for restoration
Lausanne Cathedral, Sweden	AI-powered digital co-pilot, digital twin, augmented reality, 3D modelling based on laser scanning and photogrammetry	Assessment of the condition of historic stone structures, integration of structural and materials science data, and support for inspection and restoration decisions	Provides a digital framework for interdisciplinary analysis, early identification of problem areas and justification of conservation interventions

Source: based on T. Yu *et al*. (2022), A.Y. Yiğit & M. Uysal (2024), B. Smith (2025), B. Vogel (2025), Microsoft (n.d.)

The case studies analysed cover sites with a variety of conservation needs. In particular, the Dunhuang Mogao Grottoes complex in China presents the challenge of preserving wall paintings that were deteriorating; therefore, AI was used for digital restoration, analysis of large visual data sets, and to support conservation without direct intervention on the original. For Mezgit Castle, the key challenge was the detection and documentation of cracks, which necessitated the use of UAV photogrammetry, digital twins and automated diagnostic algorithms. In the case of St. Peter's Basilica, AI was used as part of digital surveys and conservation monitoring to identify subtle structural vulnerabilities and support long-term monitoring of the monument's condition. In contrast, Lausanne Cathedral in Switzerland demonstrated the need for continuous monitoring of the degradation of stone materials, early detection of problem areas and justification of conservation interventions. It was possible to argue that the application of AI in the field of cultural heritage reflected a gradual transition from the local use of digital tools to the comprehensive integration of intelligent technologies into the processes of documentation, diagnosis, monitoring and support for professional decision-making.

Thus, the practical potential of AI was implemented in several interrelated areas: the automated reconstruction of damaged sections, the detection of defects based on digital models, the creation of digital twins, and the prediction of spatio-temporal changes in the technical condition of heritage sites. In the examples given, AI does not function as a standalone replacement for a conservator but acts as an analytical support tool that enhanced the accuracy of documentation, the soundness of interventions and the possibility of long-term monitoring of the site. Taken together, this indicated a shift in the very logic of heritage conservation: from a reactive response to existing damage to proactive monitoring, risk prediction and scientifically grounded planning of restoration measures. While international case studies predominantly reflected mature forms of AI integration into cultural heritage conservation processes, Ukrainian practices primarily represented the stage of establishing the digital and methodological foundations for such implementation. In this sense, it was appropriate to regard them as AI-ready approaches that lay the groundwork for the subsequent use of AI in documenting, forecasting the condition of heritage sites and planning restoration interventions (Table 3).

Table 3. Ukrainian practices in digital documentation and AI-ready approaches to the preservation of cultural heritage

Case/object	Technologies/tools	Primary benefit	Value for further AI use
Lviv, 2024 (buffer zone of the UNESCO World Heritage Site "Lviv – Historic Centre")	3D visualisation, damage and risk assessment, standardised UNESCO/ ICCROM form	An inspection of the damaged cultural heritage sites has been carried out, a detailed assessment of their condition has been conducted, and the groundwork has been laid for urgent conservation measures	Creates a structured database for subsequent AI-based risk analysis, damage classification and prioritisation of interventions
Odesa, 2025 (the UNESCO World Heritage Site "Historic Centre of Odesa" and associated cultural heritage sites)	Standardised methodology for assessing damage and risks, 3D architectural laser scanning, and professional training	The documentation of damage, analytical assessment and preparation of emergency stabilisation measures have been combined	Supports the transition to a digitally controlled restoration cycle, within which AI can be used to predict the condition of the tooth and plan interventions
The T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre, 2025	Ground-based laser scanning, photogrammetry, and geospatial analysis	Comprehensive digital documentation of the damaged site and a methodological framework for post-conflict condition assessment have been produced	Provides high-precision data for subsequent modelling, digital twins and algorithmic analysis of the monument's technical condition

Note: table does not list completed AI-based restoration projects, but rather the most representative examples of Ukrainian AI-ready practices found in open sources; ICCROM – International Centre for the Study of the Preservation and Restoration of Cultural Property

Source: based on United Nations Educational, Scientific and Cultural Organization (2024b; 2025), M. Skamantzari *et al*. (2025)

The analysed Ukrainian practices cover sites damaged as a result of russian attacks or those under immediate threat. In Lviv, these sites included monuments in the buffer zone of the World Heritage site, damaged by the attack on 3 September 2024, for which an in-depth damage assessment was carried out, and priority stabilisation measures were identified. In Odesa, the focus was on the historic centre, which had been inscribed on both the World Heritage List and the List of World Heritage in Danger since January 2023; repeated attacks have necessitated assessment missions, the provision of technical assistance, and the implementation of urgent repair and restoration measures. In Chernihiv, the case of the T. Shevchenko Music and Drama Theatre, which suffered significant damage in August 2023, was examined; consequently, 3D documentation, photogrammetry and geospatial analysis formed the basis for a post-conflict assessment of its condition. A summary of these practices suggested that Ukraine's experience in the field of cultural heritage preservation focused primarily on digital documentation, recording damage, standardising assessments and preparing data for further analytical use. The case studies demonstrated that the Ukrainian context represented not so much fully-fledged models of AI integration into the restoration process as the development of an AI-ready environment, within which structured datasets were created, survey methodologies were refined, and a digital foundation was built for future algorithmic analysis. A common feature of these practices was the combination of 3D documentation, damage assessment, geospatial analysis and professional training, which formed the basis for a transition from reactive documentation of the consequences of destruction to a more systematic, digitally driven approach to heritage conservation. Thus, the significance of the Ukrainian case studies presented was determined by the creation of the methodological, informational and infrastructural foundation necessary for the further implementation of AI in the practice of monitoring, condition forecasting and planning restoration interventions.

The prospects for applying AI in the field of architectural heritage conservation, therefore, lie primarily in the transition from the piecemeal use of digital tools to comprehensive, integrated systems for analysis, modelling and supporting restoration decisions. Whilst AI was used mainly for the digital documentation of sites, automated damage detection and the prediction of technical condition, its role may expand significantly in the future through the combination of 3D models, HBIM, digital twins, monitoring systems and predictive analytics algorithms. This created the possibility of continuous monitoring of the condition of heritage sites, comparing alternative intervention scenarios, and improving the soundness of restoration decisions. One of the most promising areas was the development of predictive models capable of assessing the likely consequences of various conservation and restoration measures even before their practical implementation. Such systems can be used to analyse the risk of crack propagation, deformation, material loss and other adverse changes, as well as to prioritise interventions under conditions of limited resources. Further refinement of automated analysis of the technical condition of heritage sites was required, in particular, the classification of damage, the identification of areas of increased vulnerability, and comparative analysis of the site's condition over time. At the same time, the development of such technologies must take place in accordance with the fundamental principles of cultural heritage conservation. The promising approach was not the autonomous replacement of professional restoration judgement by an algorithm, but rather the enhancement of a specialist's analytical capabilities using intelligent digital tools. Therefore, further integration of AI into this field must combine technological efficiency with the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight.

In the Ukrainian context, the prospects for applying AI in the field of architectural heritage conservation were linked primarily to the development of digital documentation, the systematisation of data on damage, and the establishment of an information infrastructure for the subsequent analytical use of AI. Several practical tasks were of paramount importance for Ukraine. First and foremost, it was advisable to establish unified standards for the digital recording of cultural heritage sites, which would ensure the compatibility of data obtained from different projects and regions. The creation of national and regional databases of damage, 3D models and technical survey results, which can be used for training and testing AI algorithms. Furthermore, interdisciplinary collaboration between conservators, architects, engineers, architectural historians and data analysts was essential, as the effective application of AI in this field was only possible through the combination of technical and humanities expertise. Implementation of pilot projects, in which AI could be used for the automated detection of damage, the ranking of problem areas by risk level, the comparative analysis of digital models before and after intervention, and the prediction of defect development was notable. It was also necessary to train staff, adapt digital tools to the existing cultural heritage protection system, and ensure that new technologies were compatible with existing procedures for scientific, design and restoration support. Under these conditions, AI in Ukraine could become not a replacement for a professional restorer, but an effective tool for supporting well-founded, timely and less risky decisions in the field of architectural heritage conservation.

The findings of the study revealed that the regulation of AI use in the restoration of architectural heritage should be based not only on technical efficiency, but also on ethical and regulatory principles, in particular transparency, accountability, control over data use, and the prevention of speculative interference with heritage sites. This was consistent with A. Wagner & M.-S. de Clippele (2023), viewing the digitisation of cultural heritage as a critical challenge, primarily linked to issues of intellectual property, access and law enforcement in the digital environment. In this context, the authors' conclusions support the interpretation of the present study, according to which digital technologies in the heritage sector require not only technical but also legal and ethical regulation. The effective use of AI in the restoration of architectural heritage was possible only if technological effectiveness was combined with ethical principles and legal regulatory mechanisms. The study by U. Bachmann-Gigl & Z. Dabiri (2024) investigated the assessment of damage to cultural heritage sites in Ukraine using multi-temporal analysis of Sentinel-1 SAR (Sentinel-1 satellite radar data obtained using the SAR method) and demonstrated that a semi-automated approach was suitable for the rapid identification of areas of destruction in crises, although it has limitations regarding localised or isolated damage. This was consistent with the findings of this study, which characterised the Ukrainian context as an AI-ready environment focused on digital documentation, damage assessment, standardisation of procedures and data collection for subsequent analytical use. Therefore, for Ukraine, it was not autonomous AI solutions that were of primary importance, but reliable digital methods for recording and assessing damage, which can form the basis for the future integration of intelligent systems.

The study by L. Cecere *et al.* (2024) examined the combination of IoT and digital twins as a promising approach to predictive maintenance in the field of cultural heritage, emphasising the importance of continuous monitoring and an integrated digital environment for the long-term preservation of heritage sites. This interpretation was consistent with the findings of the present study, in which digital twins and predictive modelling were identified as one of the key areas of AI development in the restoration of architectural heritage. Both studies provided grounds for considering digital twins as the basis for predictive monitoring and restoration planning. The results of the study showed that the practical potential of AI in the field of architectural heritage conservation was realised across several interrelated areas – ranging from digital documentation and automated damage detection to the creation of digital twins and the support of restoration decisions. This conclusion was consistent with the approach of F. Gîrbacia (2024), who analysed research trends in the application of digitalisation in the field of cultural heritage and demonstrated that AI was increasingly being used for classification, computer vision, 3D reconstruction and other tasks involving the digital processing of heritage. The development of 21st-century AI in the heritage sector was systematic in nature and reflected a gradual transition from the piecemeal use of digital tools to their comprehensive integration. D. Ocón *et al.* (2026) proposed an ethical framework for the use of Generative AI in the restoration, reconstruction and reproduction of movable cultural heritage, emphasising the tension between the technological capabilities of GenAI and the requirement to preserve historical authenticity. Although the authors' study primarily addressed movable heritage, it was relevant to the present study as it aligns with the conclusion regarding the need to subject AI to the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight. The authors' conclusions were therefore consistent with the findings of this study, which demonstrated that an international regulatory and ethical framework was a prerequisite for the acceptable use of AI in restoration practice. Thus, the application of AI in the field of architectural heritage conservation was developing within the framework of a combination of regulatory and ethical requirements, digital documentation, damage assessment, predictive modelling and support for restoration decisions. The effective and acceptable use of AI in restoration practice was only possible if technological effectiveness was combined with the principles of authenticity, scientific verification and mandatory human oversight.

CONCLUSIONS

The study's findings established that the application of AI in the field of architectural heritage conservation follows a consistent functional structure: from the digital documentation and modelling of a site to diagnostics, forecasting and support for the selection of restoration scenarios. Digital recording based on photogrammetry, laser scanning, 3D modelling and the transition from point clouds to HBIM forms not only a documentary but also an analytical basis for assessing the condition of a monument and monitoring the results of intervention. Automated damage analysis using computer vision expanded the possibilities for inspecting heritage sites, as it can be used for localisation of defects, their classification, the identification of high-risk areas, and the comparison of the site's condition over time. Predictive modelling using AI can be used for preliminary assessment of the consequences of various intervention methods, the ranking of problem areas by risk level, and the reduction of the probability of incorrect or excessive restoration decisions. International and Ukrainian frameworks for the application of AI were not contradictory but serve different functions: international documents stipulated ethical and value-based guidelines, whilst the Ukrainian context focused on documentation procedures, damage assessment and the development of digital infrastructure.

International case studies – including the Dunhuang Mogao Grottoes, Mezgit Castle, St Peter's Basilica and Lausanne Cathedral – have shown that AI was transforming the approach to heritage conservation, shifting it from reactive damage repair to proactive monitoring, diagnostics and risk-based planning of interventions. In Ukraine, however, practices tested on examples such as the Lviv Historic Centre Ensemble, the Odesa Historic Centre and the T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre were, for the time being, primarily forming an AI-ready foundation rather than complete models of full-scale AI integration into the restoration process. Thus, whilst international experience demonstrated the expansion of AI's role from digital documentation to monitoring, forecasting and supporting professional decisions, the priority for Ukraine remained the creation of a digital and methodological foundation for the further implementation of such tools. A limitation of the study was its theoretical nature, as the conclusions do not include empirical testing of AI solutions in restoration practice. Future research should address empirical testing of AI tools in restoration practice, the standardisation of digital data, the creation of specialised datasets, and the development of integrated systems based on HBIM, digital twins and predictive analytics.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abusaleh, S.W. (2024). Enhancing preservation outcomes for architectural heritage buildings through machine learning-driven future search optimization. *Asian Journal of Civil Engineering*, 25, 5277-5292. doi: 10.1007/s42107-024-01112-x.

[2] Bachmann-Gigl, U., & Dabiri, Z. (2024). Cultural heritage in times of crisis: Damage assessment in urban areas of Ukraine using Sentinel-1 SAR data. *ISPRS International Journal of Geo-Information*, 13(9), article number 319. doi: 10.3390/ijgi13090319.

[3] Buldo, M., Agustín-Hernández, L., & Verdoscia, C. (2024). Semantic enrichment of architectural heritage point clouds using artificial intelligence: The Palacio de Sástago in Zaragoza, Spain. *Heritage*, 7(12), 6938-6965. doi: 10.3390/heritage7120321.

[4] Cecere, L., Colace, F., Lorusso, A., Messina, B., Tucker, A., & Santaniello, D. (2024). IoT and digital twin: A new perspective for cultural heritage predictive maintenance. *Procedia Structural Integrity*, 64, 2181-2188. doi: 10.1016/j.prostr.2024.09.334.

[5] Chumak, O., & Gorkovchuk, J. (2023). Prior calculation of the accuracy of monitoring of cultural heritage objects using UAVs and laser scanning. *Geodesy and Cartography*, 49(3), 133-136. doi: 10.3846/gac.2023.18008.

[6] Cotella, V.A. (2023). From 3D point clouds to HBIM: Application of artificial intelligence in cultural heritage. *Automation in Construction*, 152, article number 104936. doi: 10.1016/j.autcon.2023.104936.

[7] Croce, V., Caroti, G., Piemonte, A., De Luca, L., & Véron, P. (2023). H-BIM and artificial intelligence: Classification of architectural heritage for semi-automatic scan-to-BIM reconstruction. *Sensors*, 23(5), article number 2497. doi: 10.3390/s23052497.

[8] Dragomir, O.E., & Dragomir, F. (2025). AI-based proactive maintenance for cultural heritage conservation: A hybrid neuro-fuzzy approach. *Future Internet*, 17(11), article number 510. doi: 10.3390/fi17110510.

[9] Felicetti, A., & Niccolucci, F. (2025). Artificial intelligence and ontologies for the management of heritage Digital Twins data. *Data*, 10(1), article number 1. doi: 10.3390/data10010001.

[10] Ge, Y., Guo, B., Zha, P., Jiang, S., Jiang, Z., & Li, D. (2024). 3D reconstruction of ancient buildings using UAV images and neural radiation field with depth supervision. *Remote Sensing*, 16(3), article number 473. doi: 10.3390/rs16030473.

[11] Gil, A., & Arayici, Y. (2025). Point cloud segmentation based on the Uniclass Classification System with random forest algorithm for cultural heritage buildings in the UK. *Heritage*, 8(5), article number 147. doi: 10.3390/heritage8050147.

[12] Gîrbacia, F. (2024). An analysis of research trends for using artificial intelligence in cultural heritage. *Electronics*, 13(18), article number 3738. doi: 10.3390/electronics13183738.

[13] Hosamo, H., & Mazzetto, S. (2025). Integrating knowledge graphs and digital twins for heritage building conservation. *Buildings*, 15(1), article number 16. doi: 10.3390/buildings15010016.

[14] International Charter for the Conservation and Restoration of Monuments and Sites. (The Venice Charter – 1964). (1964). Retrieved from https://civvih.icomos.org/wp-content/uploads/2022/03/Charter-of-Venice_1964.pdf.

[15] Karadag, İ. (2023). Machine learning for conservation of architectural heritage. *Open House International*, 48(1), 23-37. doi: 10.1108/OHI-05-2022-0124.

[16] Kotsiubivska, K., Tymoshenko, O., & Vasylevsky, A. (2024). Artificial Intelligence tools for preservation and popularization of cultural heritage. *Digital Platform: Information Technologies in Sociocultural Sphere*, 7(2), 275-282. doi: 10.31866/2617-796X.7.2.2024.317736.

[17] Kovalchuk, I., Kozhemiako, M., Kozhemiako, P., Kutsenko, O., & Matviichuk, D. (2025). Laser scanning and creation of a BIM model of the building No. 1 NTUU "Igor Sikorsky KPI" as a method of visualizing historical and architectural heritage. *Land Management, Cadastre and Land Monitoring*, 4, 82-94. doi: 10.31548/zemleustriy2025.04.06.

[18] Law of Ukraine No. 1805-III "On Protection of Cultural Heritage". (2000, June). Retrieved from https://zakon.rada.gov.ua/laws/show/1805-14.

[19] Mansuri, L.E., & Patel, D.A. (2022). Artificial intelligence-based automatic visual inspection system for built heritage. *Smart and Sustainable Built Environment*, 11(3), 622-646. doi: 10.1108/SASBE-09-2020-0139.

[20] Microsoft. (n.d.). *A virtual Renaissance for St. Peter's Basilica thanks to AI*. Retrieved from https://surl.lu/mieqfm.

[21] Mishra, M. (2021). Machine learning techniques for structural health monitoring of heritage buildings: A state-of-the-art review and case studies. *Journal of Cultural Heritage*, 47, 227-245. doi: 10.1016/j.culher.2020.09.005.

[22] Mishra, M., & Lourenço, P.B. (2024). Artificial intelligence-assisted visual inspection for cultural heritage: State-of-the-art review. *Journal of Cultural Heritage*, 66, 536-550. doi: 10.1016/j.culher.2024.01.005.

[23] Ocón, D., Yin, C., & Luna, J. (2026). Artificial insights or historical fidelity? Crafting an ethical framework for the use of GenAI in the restoration, reconstruction and recreation of movable cultural heritage. *AI & Society*, 41, 121-134. doi: 10.1007/s00146-025-02454-z.

[24] Pasikowska-Schnass, M., & Lim, Y.-S. (2023). Artificial intelligence in the context of cultural heritage and museums. Complex challenges and new opportunities. *European Parliament*. Retrieved from https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747120/EPRS_BRI%282023%29747120_EN.pdf.

[25] Sharma, H. (2025). Applications of artificial intelligence and machine learning in the preservation and analysis of heritage structures: A comprehensive review. *Archives of Computational Methods in Engineering*, 33, 3001-3033. doi: 10.1007/s11831-025-10393-7.

[26] Shevchuk, T., & Tarasiuk, M. (2025). The role of artificial intelligence in the preservation of historical monuments. *Problems of World History*, 30, 183-190. doi: 10.46869/2707-6776-2025-30-10.

[27] Skamantzari, M., De Vos, P.-J., Revenko, S., & Ferreira, V.M. (2025). Advanced 3D documentation and capacity building for post-conflict damage assessment: The case of the Taras Shevchenko Chernihiv Regional Academic Music and Drama Theatre, Ukraine. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 68(9), 1373-1378. doi: 10.5194/isprs-archives-XLVIII-M-9-2025-1373-2025.

[28] Smith, B. (2025). Unlocking data to advance European commerce and culture. *Microsoft*. Retrieved from https://blogs.microsoft.com/on-the-issues/2025/07/20/eudigitalunlock/.

[29] Steering Committee for Culture, Heritage and Landscape (CDCPP). (2024). *Guidelines given the latest technological developments, such as AI, complementing Council of Europe standards in the fields of culture, creativity and cultural heritage. Policy guidelines*. Strasbourg: Culture and Heritage for Democracy Division, Democratic Institutions and Freedoms Department.

[30] Sugiyama, G., Bourgeois, I., & Rodrigues, H. (2025). A holistic methodology for the assessment of Heritage Digital Twin applied to Portuguese case studies. *Digital Applications in Archaeology and Cultural Heritage*, 36, article number e00390. doi: 10.1016/j.daach.2024.e00390.

[31] Tan, X., Xie, H., Xia, C., Ying, Y., Hokoi, S., & Li, Y. (2026). Artificial intelligence in five key phases of architectural heritage conservation: A systematic review. *Journal of Building Engineering*, 117, article number 114862. doi: 10.1016/j.jobe.2025.114862.

[32] UNESCO World Heritage Centre. (n.d.a). *L'viv – the Ensemble of the Historic Centre*. Retrieved from https://whc.unesco.org/en/list/865.

[33] UNESCO World Heritage Centre. (n.d.b). *The Historic Centre of Odesa*. Retrieved from https://whc.unesco.org/en/list/1703.

[34] United Nations Educational, Scientific and Cultural Organization. (2021). *Recommendation on the ethics of artificial intelligence*. Retrieved from https://www.unesco.org/en/legal-affairs/recommendation-ethics-artificial-intelligence.

[35] United Nations Educational, Scientific and Cultural Organization. (2024a). *Action plan for culture in Ukraine*. Retrieved from https://surl.li/bgintq.

[36] United Nations Educational, Scientific and Cultural Organization. (2024b). *UNESCO assesses damage to cultural heritage after attack in Ukrainian city of L'viv*. Retrieved from https://www.unesco.org/en/articles/unesco-assesses-damage-cultural-heritage-after-attack-ukrainian-city-lviv.

[37] United Nations Educational, Scientific and Cultural Organization. (2025). *Ukraine: UNESCO steps up support for the World Heritage site in Odesa amid escalating damage*. Retrieved from https://whc.unesco.org/en/news/2800.

[38] Vogel, B. (2025). AI and extended reality help to preserve built cultural heritage. *ETH Zurich*. Retrieved from https://ethz.ch/en/news-and-events/eth-news/news/2025/11/ai-and-extended-reality-help-to-preserve-built-cultural-heritage.html.

[39] Wagner, A., & de Clippele, M.-S. (2023). Safeguarding cultural heritage in the digital era – a critical challenge. *International Journal for the Semiotics of Law*, 36, 1915-1923. doi: 10.1007/s11196-023-10040-z.

[40] Wang, H., Gong, Y., Zhang, Y., & Li, F. (2025). Artificial intelligence for sustainable cultural heritage: Practical guidelines and case-based evidence. *Sustainability*, 17(20), article number 9192. doi: 10.3390/su17209192.

[41] Yiğit, A.Y., & Uysal, M. (2024). Automatic crack detection and structural inspection of cultural heritage buildings using UAV photogrammetry and digital twin technology. *Journal of Building Engineering*, 94, article number 109952. doi: 10.1016/j.jobe.2024.109952.

[42] Yu, T., *et al.* (2022). Artificial intelligence for Dunhuang cultural heritage protection: The project and the dataset. *International Journal of Computer Vision*, 130, 2646-2673. doi: 10.1007/s11263-022-01665-x.

[43] Zhang, M., Sun, S., & Li, Z., (2025). An automatic measurement method for architectural heritage based on point cloud semantic segmentation algorithm: A case study of the hollow watchtowers of the Ming Great Wall. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 68(9), 1691-1698. doi: 10.5194/isprs-archives-xlviii-m-9-2025-1691-2025.

Олег Нестер
Магістр, асистент
Ужгородський національний університет
88000, пл. Народна, 3, м. Ужгород, Україна
https://orcid.org/0009-0003-9321-0532

Інтеграція штучного інтелекту в процес реставрації архітектурних пам'яток: методи та перспективи

Анотація. Метою дослідження було виявлення можливостей інтелектуальних цифрових технологій у оцінюванні стану об'єктів архітектурної спадщини та обґрунтуванні необхідних втручань. Були використані методи систематизації, порівняльного та порівняльно-правового аналізу, кейс-аналізу. Встановлено, що штучний інтелект у сфері збереження архітектурної спадщини підсилює фахову експертизу, забезпечує цифрову фіксацію, аналіз стану, прогнозування та підтримку реставраційних рішень. Його ефективність визначається якістю даних, експертною валідацією, сумісністю систем і прозорістю алгоритмів. Водночас ключовими викликами залишаються неповна автоматизація, складність інтеграції цифрових середовищ і потреба в людському контролі. Глобальна нормативно-етична рамка визначає, що застосування штучного інтелекту у реставрації має ґрунтуватися на принципах автентичності, людського контролю, підзвітності та використання надійних даних. Виявлено, що українське законодавство поки не містить спеціалізованого правового регулювання штучного інтелекту у реставрації, тому його застосування пов'язується передусім із документацією, стандартизацією оцінювання пошкоджень, підготовкою даних і професійною підготовкою фахівців. Кейси Dunhuang Mogao Grottoes, Mezgit Castle, St. Peter's Basilica та Lausanne Cathedral засвідчили вже сформовані підходи до застосування штучного інтелекту у реставраційній практиці, моніторингу й прогнозування стану пам'яток. Українські практики у Львові (Ансамбль історичного центру), Одесі (Історичний центр Одеси) та Чернігові (Чернігівський обласний академічний музично-драматичний театр ім. Т. Шевченка) репрезентували переважно готове до штучного інтелекту середовище для майбутнього впровадження таких рішень. Тому можливості застосування штучного інтелекту пов'язані з переходом до комплексних інтегрованих систем аналізу, моделювання й підтримки рішень, за умови дотримання принципів автентичності, мінімального втручання, наукової верифікації та обов'язкового людського контролю. Практична значимість полягає у можливості застосування результатів реставраторами, архітекторами, інженерами та органами охорони культурної спадщини у реставраційній практиці, під час документування, оцінювання стану пам'яток і планування заходів їх збереження

Ключові слова: спадщина; цифрова фіксація; пошкодження; цифрові двійники; моніторинг стану

ARCHITECTURAL STUDIES
International Journal about Architecture

Volume 12, No. 1
2026

Managing editor:
O. Kviatkovska

Signed to the print 24.02.2026
Format 60×84/8
Conventional Printed Sheet 12.5
Circulation 100 copies

Publisher: Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
Tel.: +380322584100
E-mail: info@arch-studies.com.ua
https://arch-studies.com.ua/en

АРХІТЕКТУРНІ ДОСЛІДЖЕННЯ
Міжнародний науковий журнал про архітектуру

Том 12, № 1
2026

Відповідальний редактор:
О. Квятковська

Підписано до друку 24.02.2026 р.
Формат 60×84/8
Ум. друк. арк. 12,5
Наклад 100 прим.

Видавництво: Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
Тел.: +380322584100
E-mail: info@arch-studies.com.ua
https://arch-studies.com.ua/uk