



# ARCHITECTURE & ENGINEERING

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# Architecture and Engineering

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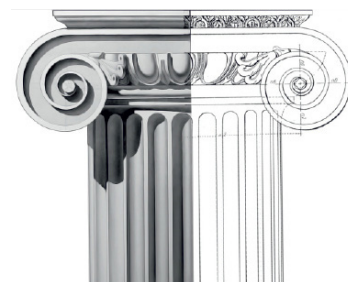


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# CONTENTS

## *Architecture*

- 3 **Enes Bostan, Burçin Şenol Şeker, Lale Yılmaz**  
Spatial investigation and structural analysis of the narthex in Ottoman mosques: the case of Edirne Selimiye Mosque
- 19 **Farah Kefif, Zakaria Bendjima**  
From social housing to heritage: assessing the architectural quality and heritage values of modernist large housing estates in Oran (1950–1962), Algeria
- 33 **Ozhet Arshyn, Seimur Etibar Ogly Mamedov, Turlybek Turkpenovich Musabayev**  
The school of modernity: the architecture of eight intelligences

## *Restoration and reconstruction*

- 43 **Ahmad Moghaddasi, Mohammad Hossein Moghaddasi**  
Decorative heritage in transition: a study of the Imamzadeh Abdullah and Naein's Jame' Mosque

## *Building operation of buildings and constructions*

- 55 **Mohammadmehdi Moulaii, Maryam Younesi**  
Balancing thermal and visual comfort through multi-objective parametric form optimization: a case from Yazd, Iran

## *Civil Engineering*

- 65 **Irina Stepina, Valeria Strokova, Viktoria Il'ina**  
Modern trends in the chemical modification of "green" building materials
- 84 **Mingyuan Wang, Vasily Sergeevich Rudnov, Zheng Li**  
Investigation of the trigger mechanism of self-healing of concrete by microgranules

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## SPATIAL INVESTIGATION AND STRUCTURAL ANALYSIS OF THE NARTHEX IN OTTOMAN MOSQUES: THE CASE OF EDİRNE SELIMIYE MOSQUE

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### Abstract

**Introduction.** Anatolia has been home to numerous civilizations throughout history. Many civilizations, from antiquity to the present day, have created various kinds of works. Among these works, mosques offer strong spatial and structural paradigms within the complex group of buildings constructed by the Ottomans. **Methods.** In this research, the spatial character of the main entrance of Mimar Sinan's work Edirne Selimiye Mosque, which consists of colonnades that are referred to as the narthex, will be analyzed with semiotic methods and theoretical with architectural background. The second objective is to determine the spatial character as well as, the size (height and span), geometric typology of the columns and material parameters and to investigate the static and dynamic responses to the earthquake factor. In this process, two different parallel models were created for the structural analysis, in addition to the existing narthex of Selimiye, and these three models were analyzed using the finite element method in the ANSYS Workbench environment. **Results.** Based on the results obtained, the spatial, geometric and structural aspects and requirements of the building are evaluated and structural strategies are proposed.

**Keywords:** spatial character; semiotic; structural analyses; mosque; narthex; pushdown; pushover analyses.

### Introduction

#### *Historical Background*

The Ottoman Empire (1299–1922) produced a diverse range of religious, civil, cultural, and military architectural works in the region that constitutes modern-day Turkey. Among this rich architectural output, Ottoman mosques stand out as monumental, complex religious structures. They emphasize proportion, symmetry, and spatial continuity with a dome cladding system in conjunction with a central plan scheme, combining static balance and acoustic features with comprehensive engineering techniques to provide both functionality and aesthetics (Kuran, 2018; Goodwin, 2003; Freely, 2011).

Generally, an Ottoman mosque is surrounded by an outer courtyard that separates the building from the crowds of the city and protects it from possible fire risks. Mosques are built according to the direction of the qibla, which in Turkey's geography lies between south and east. For this reason, the main entrance doors of all mosques are located on the northwest wall, ensuring that the entrance always faces Mecca. The inner courtyard, which is accessed through a large crown gate, is surrounded by a gallery of columns called the "portico". The space between the row of columns at the entrance façade of the inner courtyard to the mosque and the mosque's body

wall is known as the "final gathering place/last place of congregation/narthex/last prayer hall, etc". This narthex is a space architecturally identified with the concept of the mosque. Historically, it has functioned as a transitional area between the interior and exterior of the mosque (Eyice, 1993). It was built to provide shelter from the sun and rain for those who arrive late for worship or who want to pray in a clean space next to the mosque when there is no more space inside. It also serves as a preparatory and semi-open space, preventing direct access to the mosque and reinforcing the communal nature of Islamic worship.

The developmental phases of the narthex in Ottoman mosques can be traced back to Byzantine and early Islamic architectural traditions. Before the Ottoman Empire, under the influence of the Great Seljuks and the Anatolian Seljuks, the open portico system was introduced, and this feature gradually became characteristic of Ottoman mosque design (Necipoğlu, 2005). Over time, structural developments in building techniques, the adoption of mathematical and geometric constructions, and the availability of different materials transformed the simple and linear design of the narthex into a more complex and rich space (Katoğlu, 1966; Kocaman and Gürbüz, 2023; Kuban, 2010). Researchers of Anatolian-Turkish architectural history suggest

that single-room, single-domed masjids and small mosques with narthexes were built from the 14<sup>th</sup> century onwards. These types of mosques essentially consist of a square floor plan, four main walls, a main dome covering the walls, and a narthex. So, the narthex, in particular, was incorporated into traditional mosque architecture in the 14<sup>th</sup> century (during the time of the principalities) (Ettinghausen, 2001; Katoğlu, 1966).

In the classical Ottoman period, narthex developed under the influence of well-known architects such as Architect Sinan. Sinan's works emphasize that narthexes are compatible with the general composition of the mosque and feature moderate and aesthetically balanced design elements (Necipoğlu, 2007). Examples such as the Süleymaniye Mosque in Istanbul and the Selimiye Mosque in Edirne demonstrate that material alternatives, structural order, and geometric sensitivity were used to develop the specific spatial experience of the narthex. The colonnaded courtyard, the prayer hall, and the narthex of the Selimiye Mosque in Edirne, which is one of the qualified buildings of the Ottoman period and Architect Sinan, are spatially defined in Fig. 1.

The Selimiye Mosque in Edirne is one of the most remarkable monuments by Architect Sinan. It reflects the basic principles of classical Ottoman architecture in terms of both structure and aesthetics (Kuban, 2007). Construction of the Selimiye Mosque began in the 16<sup>th</sup> century, in 1568, and the mosque was

completed and opened for worship in 1575. It was built during the reign of Selim II, the son of Suleiman the Magnificent (Yaşaroğlu, 2021; Sönmez and Sönmez, 1996).

The Selimiye Mosque was built in the center of the city, on Kavak Square. After the construction of the mosque, other buildings such as schools, madrasas, fountains, and arastas, which can be found in classical Ottoman mosques and complexes, were built around the colonnaded courtyard (Rifat, 1989).

The narthexes are divided into different typologies such as single-row porticoes, double-row porticoes, and central domes. In classical Ottoman architecture, porticoes are an important design element, with examples like flat, horseshoe, and Bursa arches. Although these models are similar in function to the narthexes of Ottoman mosques, they differ in their arch shapes (Necipoğlu, 2005; Blair and Bloom, 1994). The narthex of the Selimiye Mosque represents one of the most advanced examples of classical Ottoman porticoes. It features large spans, elongated dimensions, well-proportioned arches, and a centrally arranged dome, distinguishing it structurally from the other models examined in Analyze Chapter. Having established the historical context and the significance of the narthex in Ottoman mosque architecture, the following section outlines the aim and methodology employed in this research.

#### Aim and Methodology

The conservation of monumental religious buildings from disasters, especially earthquakes, is a common goal of all societies. This requires the analysis of the spatial and structural characteristics of these buildings and the evaluation of their behavior, especially under dynamic loads (Sözen, 2024). The conservation of these buildings enables not only the enhancement of the tourism potential of countries and their sustainability but also the transmission of cultural heritage to future generations. With this in mind, the scope of the study is further clarified using the mind maps (Fig. 2).

A review of existing literature consistently shows that non-linear analysis methods are widely employed to evaluate the seismic behavior of historic buildings. For instance, a study on Turkey's Çilehane complex in Amasya (Sözen, 2024) used finite element analysis to reveal that the building's horizontal bearing capacity was only 30 % of its total load, predicting severe damage in the event of an earthquake. Similarly, research on a stone tower in Italy (Scamardo et al., 2022) evaluated various finite element modeling techniques, achieving a balance between computational efficiency and reliable results with a shell model. Additionally, an analysis of a clock tower in Sungurlu, Turkey (Gökdemir and Baki, 2024), utilizing SAP2000 software, determined that deformation, stress, velocity, and acceleration parameters were within safe limits. In all these

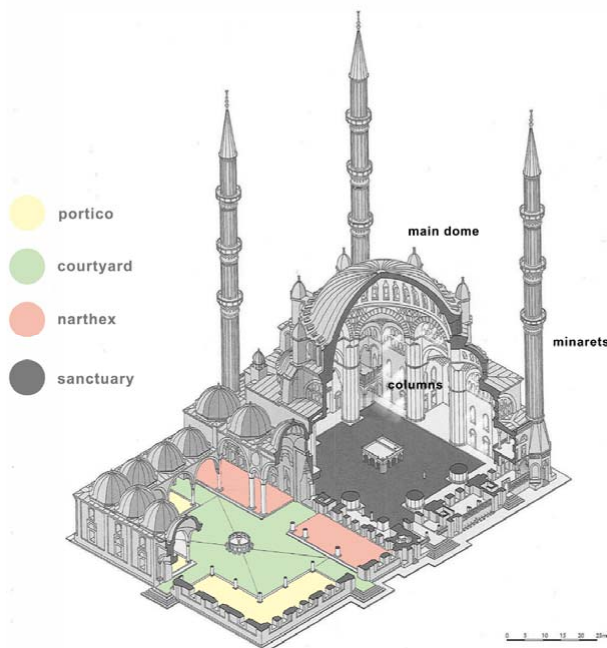


Fig. 1. Definition of the courtyard, the narthex, the portico and the sanctuary/harim in the axonometric perspective of the Edirne Selimiye Mosque (Kuban, 2010; the image, taken from the given source, was redesigned by the corresponding author)

types of research, the current condition of historical buildings with regard to earthquakes is analyzed in different contexts with different concepts. Together, these studies emphasize the need for regular maintenance and appropriate technical interventions to preserve and strengthen historical buildings.

The research by Kocaman and Gürbüz examines the collapse mechanisms under earthquake action in the narthexes of Cenabi Ahmet Paşa (Ankara / Turkey), Lala Mustafa Paşa (Erzurum / Turkey), and Şerafettin (Konya / Turkey) mosques (Kocaman and Gürbüz, 2023). Apart from this study, no comprehensive analysis of the planning principles, geometric typology, and structural durability effects of the narthex of mosques was found in the related literature. Considering all this research, it is assumed that the idea of considering both spatial character and structural analysis together with an architectural perspective can lead to better results. In light of this information, the character of the space for the narthex, the planning principles, the size, the typology of the columns, and the structural response to earthquake factors can be examined in detail with analysis using the Edirne Selimiye Mosque, built by Architect Sinan. Thus, this study, which focuses on the spatial and structural analysis of the narthex sections of historical masonry mosques, fills an important gap in the literature, demonstrates the close relationship between architecture and structural engineering principles, and contributes to conservation processes.

### *Spatial Characteristics and Significance of Edirne Selimiye Mosque Narthex*

The space, which has various names such as the Last Congregation Place or Narthex, has become an important architectural element in terms of spatial, historical, cultural, and symbolic aspects in Ottoman mosques (Bonner, 2016; Blair and Bloom 1994). It serves as a transitional space between the main sacred / sanctuary / worship space (the harim) and the external environment (Eyice, 1993). This space fulfills the symbolic, functional, and social needs of Islamic worship in terms of spatial and architectural aspects. Historically, this space reached its highest quality during the Classic Ottoman period, evolving in response to the multi-layered dynamics of the interaction of culture, material, and geometry at the intersection of religion and architecture, and continues to evolve today. Although regional differences are noticeable over time, structural arrangements can be recognized that always reflect their particular function (Sönmezer, 2002). In addition to its practical function, the narthex also has a symbolic and cultural significance. It represents a transitional area between the world and the sacred. This situation is emphasized by architectural elements such as inscriptions, domes, and muqarnas that adorn the narthex and lead the faithful into the sacred interior (harim) (Erzen, 2011; Kuban, 2010).

### *Architectural Planning and Principles*

The narthex is usually located on the northwest side of the mosque, directly in front of the main prayer

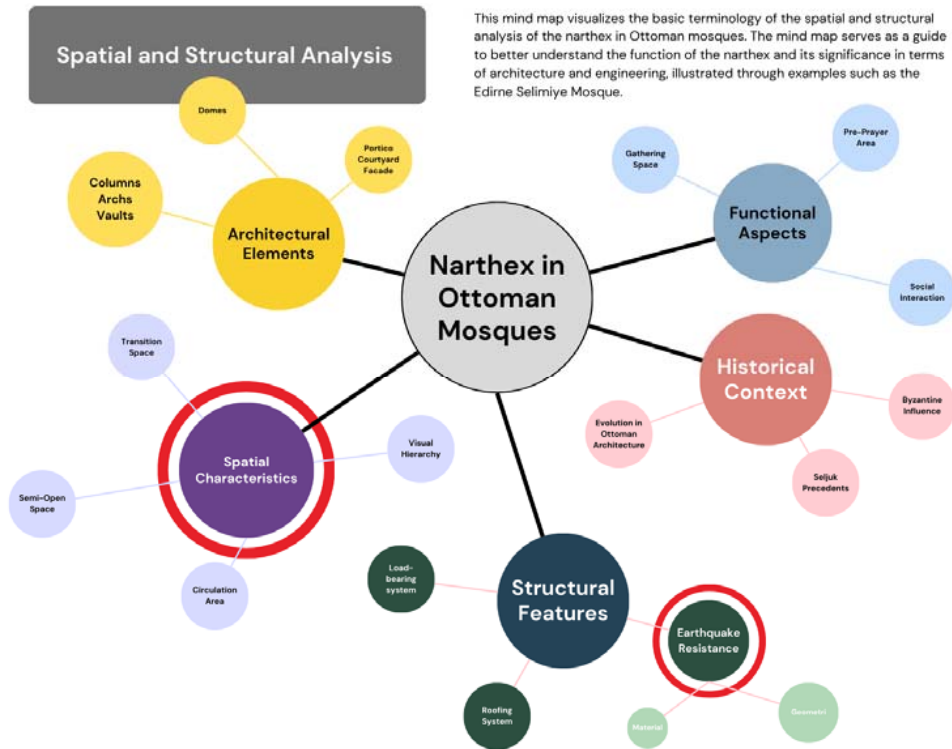


Fig. 2. Classifications and analysis scope of the research with mind map

area, the harim. This space consists of a series of mostly open or semi-open vestibules supported by arches and columns (Goodwin, 2003; Frishman and Khan, 2002). When examining the planning system of the narthex, it becomes clear that the geometric order applied is related to the proportion and modular system used in the other rooms of the mosque. While spatial units covered with more than one dome are generally built with a symmetrical and modular planning system (Orbeyi, 2016), this order can be read as a linear and rectilinear planning system in smaller mosques (Hakim, 2008). The spatial organization of the narthex is fundamentally shaped by linear arrangements aligned with the qibla direction, a central plan scheme, and geometric principles. This design strategy aims to guide worshipper movement and enhance their spatial experience (Hill, 1993). Historical mosque architecture frequently incorporates geometric and mathematical arrangements, reflecting a blend of engineering acumen and contemporary aesthetic sensibilities. Specifically, the porch systems prevalent in Ottoman and Seljuk architecture, including the narthex, were constructed using precise mathematical ratios and geometric systems to ensure static equilibrium. The geometric and mathematical parameters (spatial order) employed in narthex planning are crucial for achieving a monumental form and increasing structural permanence. Ottoman architects, particularly Architect Sinan, emphasized the aesthetic, structural, and functional qualities of these spaces through a focus on proportions, symmetry, and modular design (Aksoy, 2015; Orbeyi, 2012). For instance, the meticulously calculated geometry dictates the arch openings and column spacing within the column rows that define the narthex. In domed spaces, the golden ratio and circular geometry significantly enhance aesthetics, structural openings, and the sense of spatial balance. Furthermore, these mathematical and geometric principles augment the durability of load-bearing elements (Sutton, 2007; Wichmann and Wade, 2017). Emerging in Islamic architecture during the 14<sup>th</sup> century, the narthex (Fig. 3) achieved its most refined form and function in the Selimiye Mosque, which Sinan considered his masterpiece (Petersen, 1996; Yaşaroğlu, 2021).

The narthex of the Selimiye Mosque was designed as an important part of the overall architectural character of the mosque. It is an assembly that gains importance with its functional, aesthetic, symbolic, and structural features together with the other spaces of the mosque. Surrounded by porticoes, this group of buildings is supported by six marble columns resting on five different arches. The narthex is larger and longer than the porticoes of the inner courtyard, a situation that is in structural harmony (Fig. 4) with the main outer wall of the

mosque. The barrel arch in the middle (Arch 4) has a larger opening space than the others.

On either side of the wide-open central arch are two different pointed arches (Arch 3 and Arch 5) with narrower and shorter openings. Next to the pointed arches are symmetrical barrel arches (Arch 2 and Arch 6), which are similar to the central arch (Kuban, 2017). The arches at the very beginning are arranged to form the area where the other colonnades converge in the mosque's courtyard (Fig. 4).

The muqarnas decorations on column capitals function as both aesthetic and structural components, embodying the abstract qualities of Islamic art alongside harmonious rhythmic and geometric patterns (Necipoğlu, 2005). The narthex ceiling features a dome cladding system with an exterior plaster enriched by hand-drawn decorations that blend vegetal and geometric motifs characteristic of Ottoman architecture. The vestibule floor is composed of diverse stone materials, textures, and colors, incorporating geometric mosaic techniques (Goodwin, 2003).

This harmonious design in the entrance area creates a striking aesthetic order, making the spiritual essence of Ottoman and Islamic aesthetics palpable within the space. Furthermore, the narthex adheres to the principles of symmetry and proportion, a consistent aesthetic throughout the Selimiye Mosque. The rhythmic arrangement of columned spaces and arches defines the building's overall composition, particularly its entrance. This classical horizontal and vertical order, typical of Ottoman architecture, contributes to the space's monumental harmony (Kuban, 2007; Hillenbrand, 2021).

#### *Semiotic Analyses of the Narthex Space*

A semiotic approach provides a valuable framework for analyzing the spatial characteristics of the Selimiye Mosque's narthex and entrance. This perspective allows for an examination of the space's structural codes, symbolic meanings, and its semantic relationship with the user, drawing upon theories from scholars like Umberto Eco and Charles Sanders Peirce. Semiotics views space as a "meaning-producing system".

Charles Sanders Peirce's semiotic theory, in particular, classifies signs into three categories based on their meaning-production: Icon, Index, and Symbol. An icon establishes a relationship of similarity between the signifier and the signified; for instance, the dome of the Selimiye Mosque serves as an iconic sign emphasizing eternity, unity, and heaven (Peirce, 1931-1958). An index indicates a concrete causal relationship between the signifier and signified; the minarets of the Selimiye Mosque, directly linked to the call to prayer, function as indexical signs (Peirce, 1991). A symbol is a signifier where the connection between signifier and signified is defined by tradition and culture; a divine word in calligraphy, for example,



Fig. 3. Front view of the Selimiye Mosque in Edirne and model of the mosque parts and the narthex (TRT News, 2025; revised and remodeled by the corresponding author)

can be interpreted as a symbolic sign representing God in Islamic culture (Eco, 1976).

This classification offers a clear methodology for analyzing how historical spaces and architectural elements generate meaning. Applying this method to the Selimiye Mosque's narthex can elucidate its meaning-making processes. Two primary semiotic approaches are relevant here: analyzing the space's meaning production through Saussurean semiotics (signifier-signified) or Peircean semiotics (sign-interpreter-objective meaning) (Table 1).

### *Structural Analyses of Edirne Selimiye Mosque Narthex*

#### *Material*

The structure discussed in this article is the portico of the narthex of the mosque. This section comprises 3 large and 2 smaller pointed arch systems in the lower sections, which can be seen from the front facade. The main beams are monolithic marble columns. Therefore, these columns were assigned the material property stone found in the ANSYS library and the arched portico walls in the upper

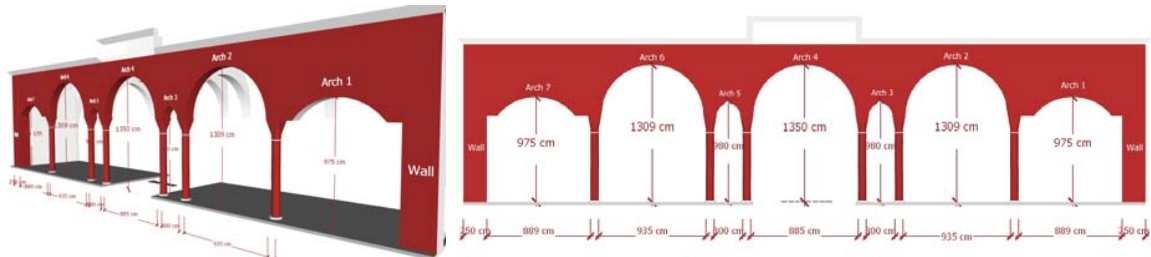


Fig. 4. Model and dimensions of the narthex of the Selimiye Mosque in Edirne (Baran, 2021; models created by the corresponding author)

section were assigned the material property Drucker-Prager (Drucker and Prager, 1952), also found in the ANSYS library, taking into account the compressive and tensile strengths. To determine the engineering properties of masonry building materials, the average values for the mechanical properties of the masonry material given in the Earthquake Risk Management Guide for Historical Buildings (TYDRYK, 2017) were used. As a result of the static and dynamic analyses carried out using these material properties used in the study, inelastic permanent deformations and stresses could be determined. The material values used in the analyses are listed in Table 2 (TYDRYK, 2017).

**Method**

In the first phase, the models to be investigated were defined. Within the framework of the article, arcade models were to be created for the meeting place, consisting of arches with three different geometries, and their comparative analyses were to

be carried out. The arcade model of Selimiye Mosque was selected as the main model and the other two models were created with the same opening, height and width but depending on different arch typologies. The model for the meeting room, which we refer to as Model 1, consists of five equal openings, all of which are round arch arcades. Model 2 consists of five equally sized openings with a pointed arch in the middle and round arch arcades on the sides. In Model 3, the final meeting place of the Selimiye Mosque was recreated (Fig. 1). By comparing the three different models, conclusions were to be drawn about the differences in the structural behavior of the model of the narthex used by Architect Sinan in the Selimiye Mosque.

For the structural analysis, three distinct models were systematically developed: two representing alternative narthex configurations and one accurately replicating the actual narthex of the Edirne Selimiye

**Table 1. Analysis of the narthex space with architectural data and semiotic methods**

Architectural Elements	Indicator Type (Icon/Index/Symbol)	Indicator	Meaning/Interpretation
Cloister/ Courtyard	Symbol & Icon	Transition Area (Threshold)	A transitional area between the secular and the sacred space, a preparatory area before worship.
Domes and Columns	Index & Symbol	Divine power and unity	It can be associated with heaven and symbolizes centrality and eternity. It can refer to the representation of divine qualities, the connection to heaven, centrality and order. It also emphasizes the monumentality of the building, its continuity and the sense of unity that brings the community together.
Muqarnas and Decorations	Icon & Symbol	Monumentality	It can be interpreted as an architectural visualisation of architectural order, eternity, aesthetics and divine knowledge.
Door and Arch Opening Spaces	Symbol	Opening / Door / Transition Symbolism	It stands for transition and continuity and is part of the rhythmic and symmetrical repetition in Ottoman and Islamic architecture.
Traditional Calligraphy / Hand-drawn Ornaments	Symbol	Quotations from the holy book quran	It emphasizes holiness by conveying divine messages.
Main prayer areas	Index	Entrance area to the main place of worship under the portico	The process of preparing the congregation for worship, the organization of the functional areas of the mosque, the social area that allows the congregation to come together, the sense of community and togetherness.
Lighting and Shading and Visual Hierarchy	Index & Icon	Orientation, Spiritual Feelings	The flow of movement and physical experience, the purpose of the worship area, the sense of depth, the separation of the original space and the interior and exterior spaces, the emphasis on symmetry, proportion and monumentality are palpable.

**Table 2. Material Properties used in the structure**

Structure Part	Compressive Strength (MPa)	Tensile Strength (MPa)	Unit weight (kg/m <sup>3</sup> )	Poisson ratio	Elasticity Modulus (MPa)
Main Bearing Columns	34	3,4	2500	0,23	34000
Upper part with Arches	1,75	0,175	2100	0,2	1750

Mosque as implemented by Architect Sinan. After detailed examination of these three models, their results were collectively evaluated, focusing on stress distribution and identifying critical areas where stresses were observed. Equal analytical procedures were applied to all models to ensure a consistent comparative assessment.

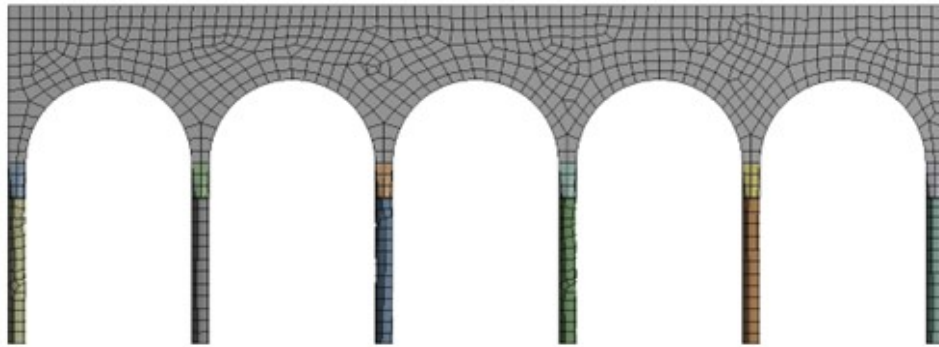
The final models of the meeting room with 3 different geometries were created in a 3D computer environment. The most important parts of the model are the supporting columns, the column capitals, the upper row of arches, and the walls of the portico. These three-dimensional models, created in the ANSYS Workbench environment, were discretized into solid elements using the finite element method. A mesh size of 150 mm was used for this solid mesh, enabling the desired analyses to be carried out on the models. As part of the analyses, the columns, which are the main

beams of the models, were assumed to have fixed (encastre) support conditions at their base, firmly connecting them to the ground at the support points. Horizontal and vertical loads were applied to the models after assigning material properties to the respective model parts. The material model used for these analyses was as described in the “Material” section of this article. In this way, an attempt was made to determine the horizontal and vertical load-bearing capacities of the relevant models within the framework of the relevant regulations (TYDRYK, 2017). The finite element models of the relevant structures are shown in Fig. 5.

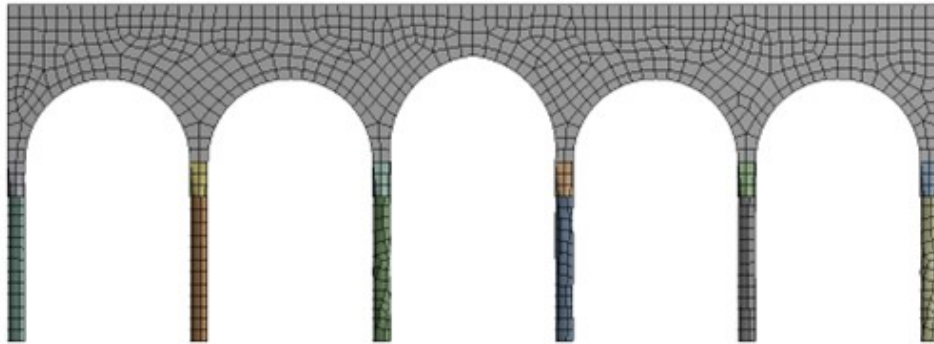
## Results

### Analyses

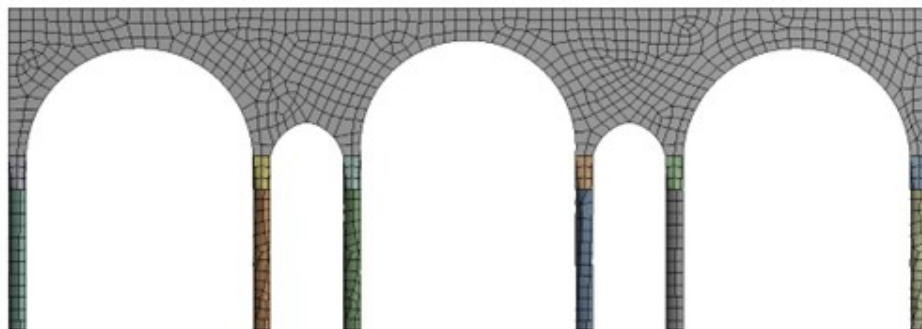
The three-dimensional finite element models created in a computer environment were subjected to static and dynamic analysis. In this way, an attempt was made to determine the reactions and



*Model I: Finite element model of the round-arched narthex*



*Model II: Finite element model of the narthex with a pointed arch in the middle*



*Model III: Existing finite element model of the narthex of the Selimiye Mosque*

Fig. 5. Three types of finite element models of the narthexes

capacities of the models in question to different types of loads.

**Pushdown Analyses**

In this section, the models were subjected to compressive stresses in the vertical direction from their upper edge and the analyses were carried out by increasing the applied load values. As a result of the analyses, stress, displacement and plastic deformation values were determined and the results are shown in the figures as a colour scale for each model.

**Pushdown Analyses for Model I**

Increasing compressive stresses were applied vertically to Model I, which consists of round arch portals with 5 identical openings; the direction of loading is shown in Fig. 6.

The displacement values (mm) and the distribution in the horizontal direction (X-axis) resulting from the compressive stresses applied vertically to Model I are shown in Fig. 7. The maximum displacement values in Model I, which consists of circular arch portals with 5 equal openings, reached a maximum value of 3.74 mm at the column heads, which are the support points at the stirrup points of the arches at both ends. It can be seen that the displacements

in the other arches have lower values in the middle openings.

The vertical (Z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model I are shown in Fig. 8. The maximum vertical displacement values reached a maximum value of 3.56 mm around the keystone at the centres of the arches at both ends. In the other arches in the middle spans, the displacements were 2.74 mm and 1.92 mm in the keystone of the arch in the middle. In the columns supporting the porticoes, the minimum value of the displacement was 0.11 mm.

The distribution of plastic deformations occurring after the vertical loading of Model I is shown in Fig. 9. It can be observed that the maximum plastic deformations occur at the centres of the initial and final arches (0.00069) and are distributed over a larger area over time. It is predicted that deformations are observed at the key points and column heads of these arches when the load applied in the vertical direction is increased.

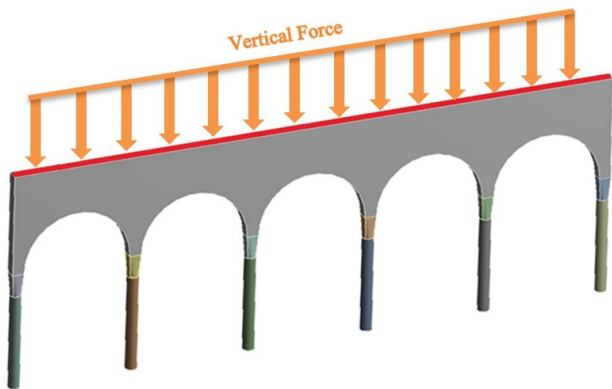


Fig. 6. Loading direction for Model I

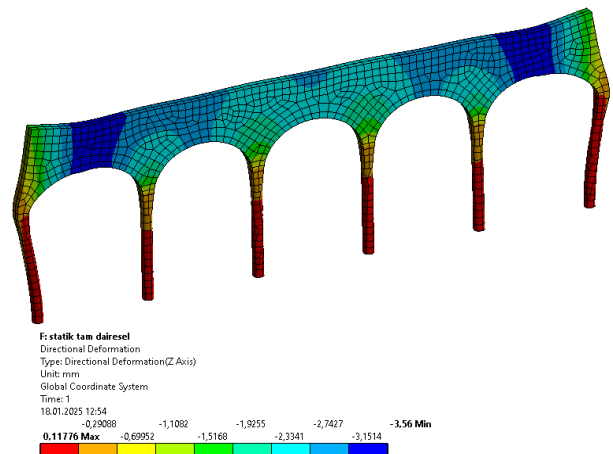


Fig. 8. Vertical Directional Deformation of Model I

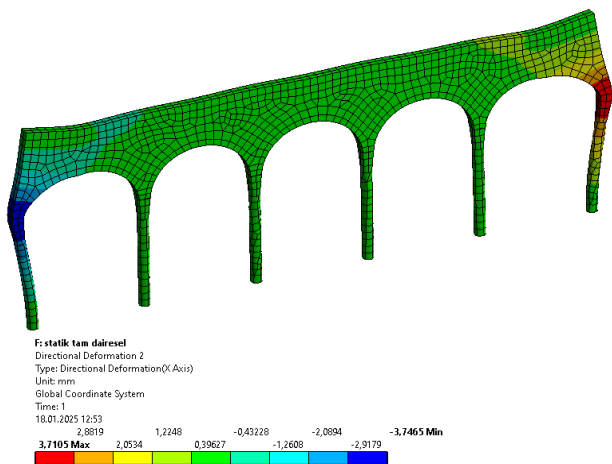


Fig. 7. Horizontal Directional Deformation of Model I

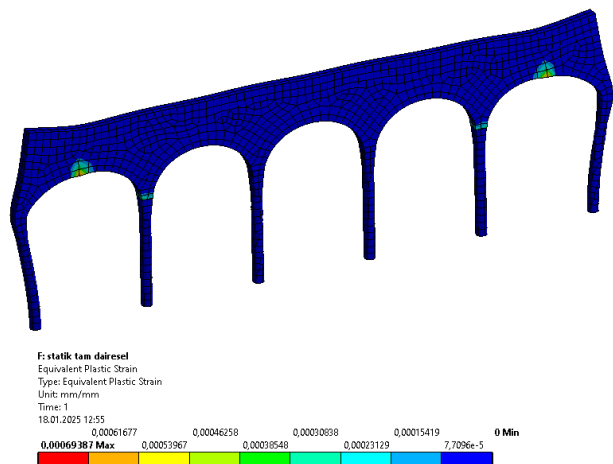


Fig. 9. Plastic Strains distribution of Model I

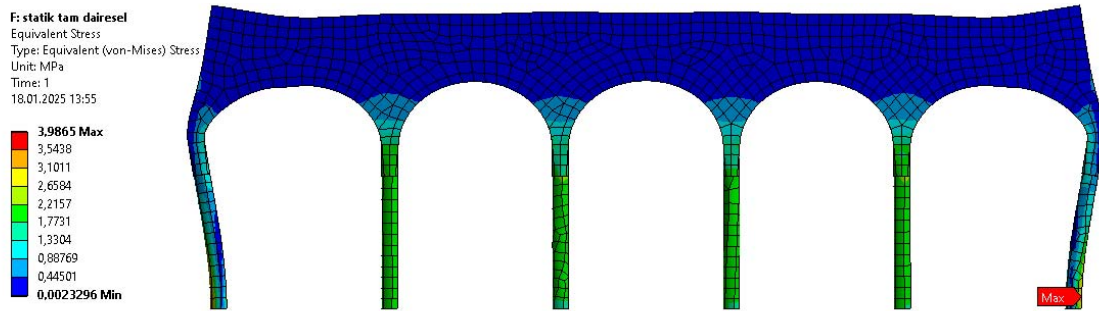


Fig. 10. Equivalent (von-Mises) Stress of Model I

When looking at the comparative stress distribution in Fig. 10, it can be seen that the stresses increase downwards as a result of the vertical loading of Model I. The stresses are particularly concentrated in the columns and reach a maximum value of 3.98 MPa at the bottom of the first and last column. The stresses in the second and fifth columns reach a value of 3.10 MPa and in the middle column a value of 2.21 MPa. The minimum stress in the walls of the column hall above the arches is 0.002 MPa.

#### Pushdown Analyses for Model II

In Model II, which has five identical openings, a pointed arch in the middle and round arch portals on the sides, compressive stresses were applied by raising them in the vertical direction; the direction of loading is shown in Fig. 11.

The displacement values (mm) and the distribution in the horizontal direction (X-axis) resulting from the compressive stresses applied vertically to Model 2 are shown in Fig. 12. The maximum displacement values in Model II reached a maximum of 3.73 mm at the column heads, which are the support points of the arches at both ends. Displacements of 2.08 mm were recorded at the stirrup points of the arches at the start and end. For the other arches in the middle spans, the displacements are smaller (1.22 mm).

The vertical (Z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model II are shown

in Fig. 13. The maximum vertical displacement values reached a maximum value of 3.70 mm around the centre of the first and last round arch and the keystone of the pointed arch in the middle. It can be seen that the displacements at the centres of the second and fourth round arches are smaller (2.85 mm). The displacements at the column heads, which are the support points of the arches with the columns, are 0.73 mm. For the columns supporting the porticoes, the minimum value of the displacement is 0.11 mm.

The distribution of plastic deformations occurring after the vertical loading of Model II is shown

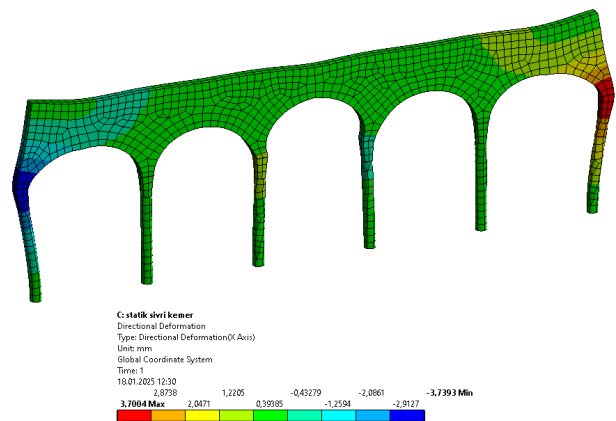


Fig. 12. Horizontal Directional Deformation of Model II

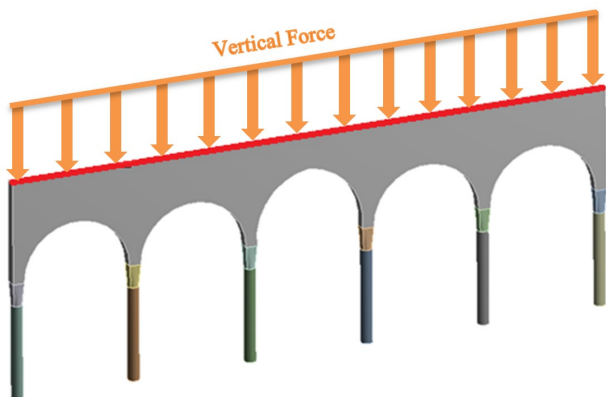


Fig. 11. Loading direction for Model II

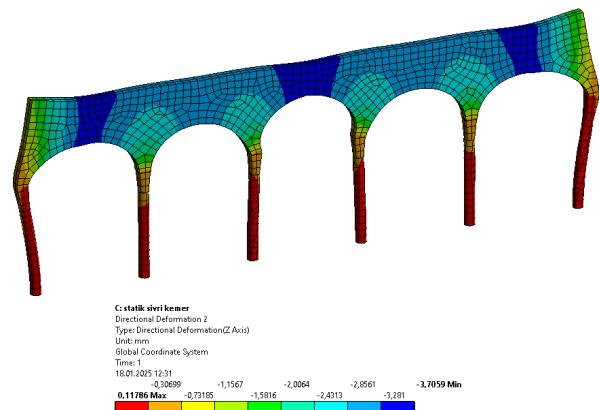


Fig. 13. Vertical Directional Deformation of Model II

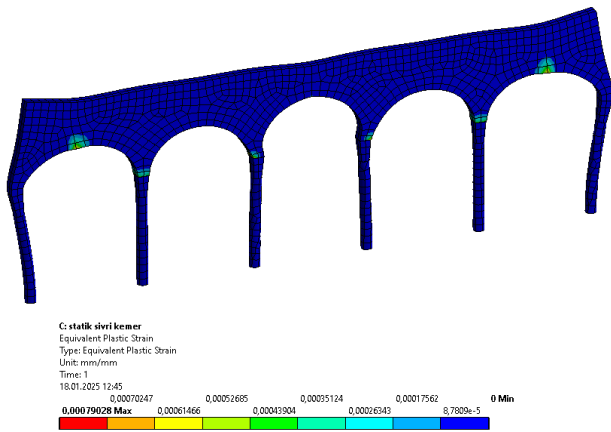


Fig. 14. Plastic Strains distribution of Model II

in Fig. 14. It can be observed that the maximum plastic deformations occur at the centres of the initial and final arches (0.00079). It is predicted that the plastic deformations propagate over time and reach smaller values (0.00043) at the column heads, which are the support points of the arches.

Looking at the comparative stress distribution shown in Fig. 15, it can be seen that the stresses increase downwards as a result of the vertical loading of Model II. The stresses are mainly concentrated at the lower ends of the columns and reach a maximum value of 3.96 MPa at the lower ends of the columns at the beginning and at the end. The stresses in the middle columns reach a value of 2.64 MPa. The stresses in the portico walls above the arches are at a minimum value of 0.001 MPa.

*Pushdown Analyses for Model III (Edirne Selimiye Mosque Narthex)*

The vertical compressive stresses were increased and applied to Model III, the porch of the Selimiye Mosque, and the direction of loading is shown in Fig. 16.

The horizontal displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model III are shown in Fig. 17. The maximum displacement values in Model III reached a maximum value of 49.22 mm at the column heads, which are the support points of the arches at both

ends. Displacements of 37.38 mm were recorded at the stirrup points of the arches at the start and end. It can be seen that the displacements in the small arches in the 2<sup>nd</sup> and 4<sup>th</sup> openings and in the middle arch are smaller (4.90 mm).

Although the horizontal displacement values seem to be larger in this model than in the other two models, Architect Sinan added another arch at the beginning and end of the colonnades to prevent this large displacement at the narthex of the Selimiye Mosque and connected the structure to the main mass in the other direction.

The vertical (z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model III are shown in Fig. 18. The maximum vertical displacement values reached a maximum value of 36.44 mm at the centres of the round arches at the beginning and end. It can be seen that the displacements at the central point of the round arch in the middle are smaller (6.07 mm). The vertical displacement value in the columns supporting the arcades is 2.59 mm. At the centres of the small pointed arches in the 2<sup>nd</sup> and 4<sup>th</sup> openings, the displacements decrease even more and reach a minimum value of 1.74 mm.

The distribution of the plastic deformations occurring after the vertical loading of Model III is illustrated in Fig. 19. The highest plastic strains are observed at the midpoints of the outermost arches, reaching up to 0.0148. Additionally, plastic deformations of approximately 0.0098 are concentrated around the upper segments of the arch barrels. These deformations gradually propagate over time and reduce to lower magnitudes, reaching about 0.00659 at the column capitals, which serve as the primary support points for the arch system.

Looking at the comparative stress distribution shown in Fig. 20, it can be seen that the stresses increase downwards as a result of the vertical loading of Model III. The stresses are particularly concentrated at the lower ends of the head and tail columns and reach a maximum value of 29.928 MPa. The stresses in the middle columns reach a value of 13.31 MPa. The stresses in the

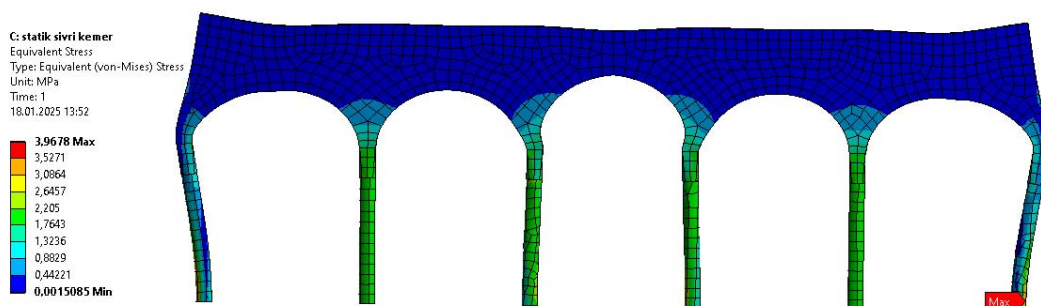


Fig. 15. Equivalent (von-Mises) Stress of Model II

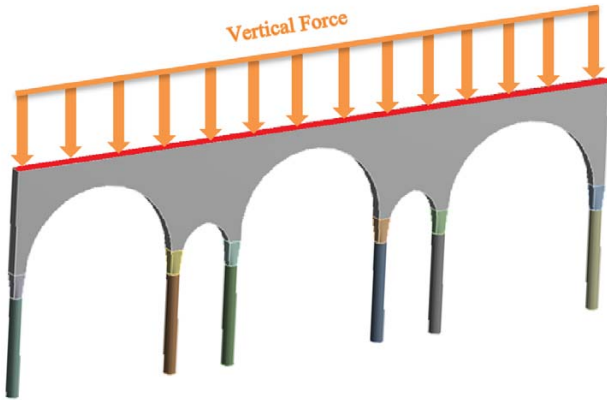


Fig. 16. Loading direction for Model III (Edirne Selimiye Narthex)

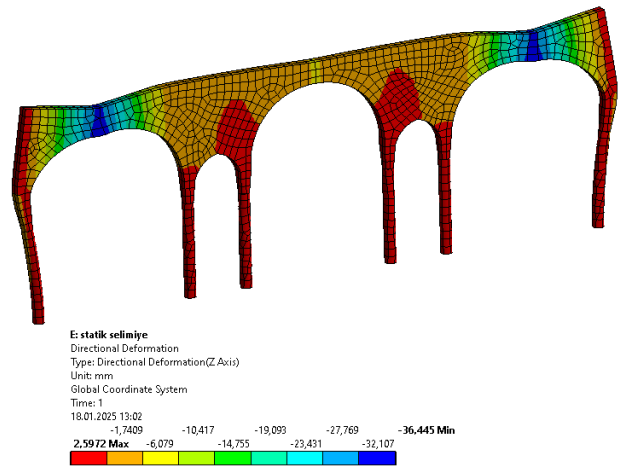


Fig. 18. Vertical Directional Deformation of Model III (Edirne Selimiye Narthex)

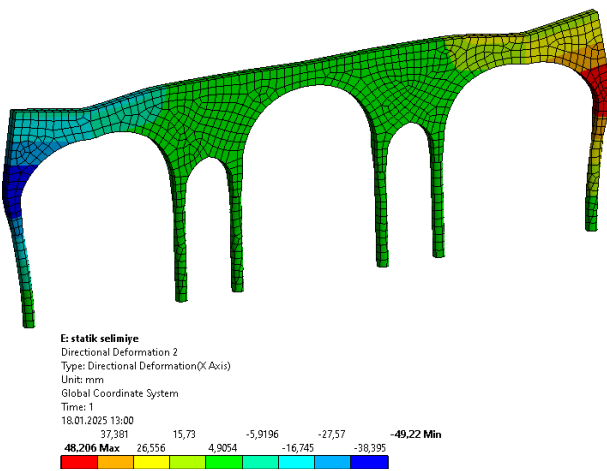


Fig. 17. Horizontal Directional Deformation of Model 3 (Edirne Selimiye Narthex)

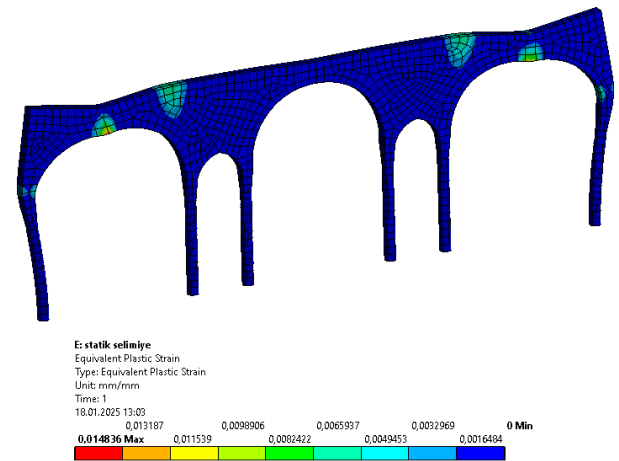


Fig. 19. Plastic Strains distribution of Model III (Edirne Selimiye Narthex)

portico walls above the arches are at a minimum value of 0.0203 MPa.

#### Comparison of Pushdown Analysis Results

The pushdown analysis results reveal significant differences in the structural performance of the three narthex models under increasing vertical loads (Table 3). Models I and II, which incorporate simple and repetitive arch configurations (either five round arches or a central pointed arch flanked by round arches), exhibited

comparable horizontal and vertical deformations, inelastic strains, and stress concentrations, with maximum horizontal displacements remaining under 4 mm and von Mises stresses below 4 MPa. In contrast, Model III, representing the actual Selimiye Mosque narthex designed by Architect Sinan, demonstrated markedly higher values in all measured parameters. The maximum

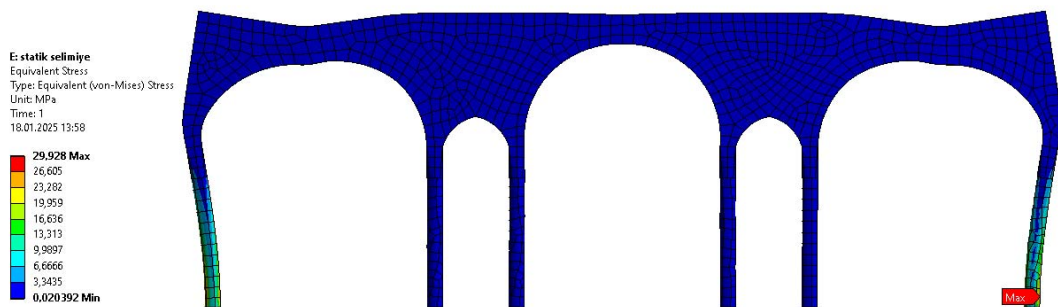


Fig. 20. Equivalent (von-Mises) Stress of Model III (Edirne Selimiye Narthex)

Table 3. Comparison of Pushdown Analysis Results for Three Narthex Models

Models	Horizontal Directional Deformation (mm)	Vertical Directional Deformation (mm)	Plastic Strain	Equivalent (von-Mises) Stress (MPa)
Model 1	3.74	3.56	0.00069	3.98
Model 2	3.73	3.70	0.00079	3.96
Model 3	49.22	36.44	0.0148	29.93

horizontal and vertical displacements reached 49.22 mm and 36.44 mm respectively, while the plastic strain and stress values peaked at 0.0148 and 29.93 MPa.

Although Model 3 exhibits higher stress and deformation values compared to the other models, it is observed that these stresses are primarily concentrated at the support points of the first and last columns. Despite the relatively high deformation values recorded in the analysis, the actual structure's revak arches are connected to the massive exterior walls along the X-axis through additional arches, which prevents the occurrence of lateral displacements at the magnitudes predicted by the simulation. This suggests that, in reality, the structure behaves in a more balanced and rigid manner than the analysis model indicates.

These elevated analysis values are directly associated with the more complex geometric configuration and broader spatial span of the Selimiye Mosque's narthex. Nevertheless, Architect Sinan's original design includes a series of structural precautions that go beyond mere aesthetic considerations. These include the addition of extra arches, the integration of the portico system with the surrounding solid walls, the application of confinement (ringing) at column capitals and support points, and the establishment of structural continuity with the main mosque body. Such structural arrangements are believed to facilitate a more balanced distribution of stress and significantly enhance the seismic resilience of the structure.

#### *Pushover Analyses*

Pushover analysis is a type of static analysis that examines how far a building can penetrate into the inelastic range before it collapses completely or partially. First, a small horizontal force is applied and the deformations are calculated. A diagram is then drawn up showing the extent of the deformation with gradually increasing forces. This diagram can be used to determine the maximum load that the building can withstand. The collapse mechanism can be investigated using this diagram. At each step of the process, the inelastic shape and displacements in the load-bearing elements and the approximate limits of the collapse mechanism can be checked against the drift ratio limits (TYDRYK, 2017). Based on the results of the non-linear analysis, the ratio of the maximum horizontal displacement ( $\Delta$ ) to the relevant wall height (H) ( $\Delta/H$ ) is calculated as

a percentage and compared with the drift ratio limits in (TYDRYK, 2017).

The distributions of the horizontal deformations in the models due to the horizontal load in the pushover analysis before and after are shown in Fig. 21.

The diagram in Fig. 22 shows the horizontal displacements resulting from the gradually increasing forces acting on the models in the pushover analyses. When the horizontal loads on Model 1 were gradually increased and a force of 44.55 tons was applied, the  $\Delta$  value reached 165.04 mm. When the horizontal loads were gradually increased on Model 2 and 44.55 tons of force was applied, the  $\Delta$ -value reached 183.46 mm. While the horizontal displacements of Model 1 and Model 2 are approximately the same, the horizontal load of Model 3 increased to 65.34 tons when the same displacement values were reached. It can be concluded that the load capacity of Model 3 is greater than that of the other models.

#### **Conclusions**

This article analyzes the spatial and structural qualities of the narthex, one of the most important spatial elements of classical Ottoman architecture, with particular reference to the Edirne Selimiye Mosque by Architect Sinan. The geometric and symmetrical planning principles, structural balance, and aesthetic design approach of historical Ottoman mosques are discussed at the intersection of architecture, engineering, mathematics, and art.

The research results show that Architect Sinan, one of the leading Ottoman architects, used mathematical proportions and modular systems in his works to ensure an optimal static and dynamic balance of space. The arch openings, colonnades, and load-bearing elements used in the vestibules were designed according to specific engineering and architectural principles, not only for aesthetic purposes but also in terms of earthquake resistance, spatial continuity, and functionality in worship. The symmetry, the golden ratio, and the central arrangement — particularly evident in the Selimiye Mosque — demonstrate that this space is not merely an entrance area in classical Ottoman architecture but also a significant transitional / boundary space that defines spatial hierarchy and functional distinctions. The semiotic analyses carried out as part of the study indicate that the narthex of the Selimiye Mosque is not only a physical architectural element but also a ritual and symbolic space. The spatial

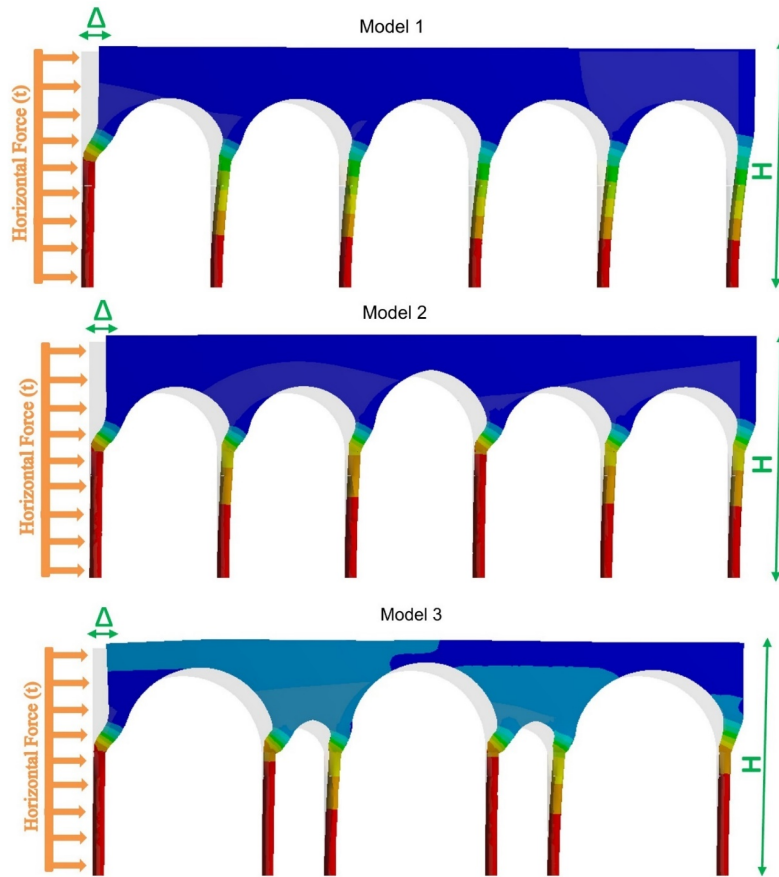


Fig. 21. Models before and after deformations resulting from horizontal loading

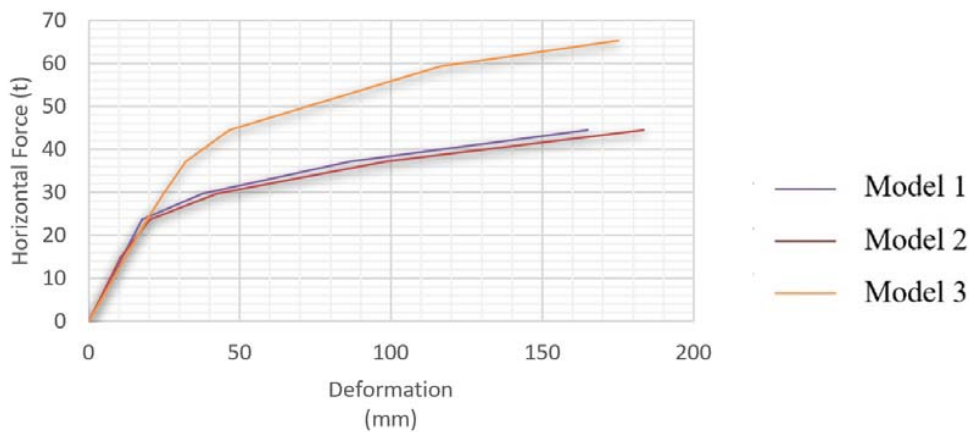


Fig. 22. Force-displacement curves obtained from pushover analyses

organization provides a system that guides the movement of worshippers (user experience) and enriches the spatial experience. It also shows that muqarnas, arch openings, calligraphy, and the use of light are significant not only architecturally but also theologically and sociologically. Also this study primarily aimed to provide a qualitative examination of the structural behavior of the narthex, investigating why this structural system functions as it does, and to highlight the distinguishing features of the Edirne Selimiye Mosque's design.

The architectural studies also demonstrate that the seismic safety and structural durability of an important Ottoman building such as the Edirne Selimiye Mosque are critical aspects to be considered in conservation and restoration efforts. Computer-aided structural analysis, widely used in the literature, offers essential and advanced methods for evaluating the seismic behavior of such structures. In the future, advanced digital simulation techniques, 3D modeling, and structural analysis methods should be utilized

more effectively for the conservation of similar historical mosques.

The analyses of the three different narthex models yielded the following structural findings:

- Model 3 (narthex of the Selimiye Mosque) shows the highest values in terms of horizontal displacements and stresses.

- Although the highest values occur in Model 3, Architect Sinan added an additional arch at the beginning and end of the arcades and connected them to the arcades and the main mass in the other direction using buttresses to eliminate this weakness.

- Fig. 18 shows that the load-bearing capacity of Model 3 is greater than that of the other models when reaching the same displacement values.

- When the differences between these three models are evaluated, it becomes clear that the values of the round arch with equal spans and the model with a pointed arch in the middle are approximately the same, indicating that arch geometry has minimal effect on load-bearing capacity; however, Model 3, designed by Architect Sinan, significantly increases the load-bearing capacity.

- Fig. 18 also indicates that Model 3 has a higher energy absorption capacity due to its larger surface area.

- The pushover analyses were performed in the longitudinal direction of the models; the other direction, where the narthex is structurally weaker, was not evaluated. The structure was connected to the main mass in that other direction.

When examining the models in terms of stress distribution, it is observed that the stresses in the arcade systems of Models 1 and 2 are distributed along the main axes of all columns. These stresses are particularly concentrated at the column bases and capitals. It is known that these sections were architecturally built wider than the column diameter and that iron rods were cast in lead at these joint areas, connecting the columns at the support points to the upper arch sections and the stone foundation at ground level. The obtained analysis results demonstrate the importance and necessity of this application. This knowledge and the experience

accumulated throughout history were likely passed down to subsequent generations.

To counteract the effects of stress and deformation, it was concluded that the cross-sections at the column capitals and support points should be enlarged. The column bases not only meet technical requirements but also satisfy aesthetic considerations and provide architectural unity. Additionally, it was noted that tension rods were inserted between the two colonnades to balance supports and stresses, which is expected to enhance the structure's durability.

When examining the stress results in the model of the Selimiye Mosque's portico, it is found that significant stresses are only distributed along the main axes of the first and last columns. No noticeable stress values are observed in the middle column bays. These tensile stresses, which could pose a threat to masonry structures, are confined to a limited area and thus reduced to two columns. The fact that these columns are connected to the solid sidewalls through porticoes perpendicular and parallel to their axes seems to have mitigated the negative effects on these columns. This affirms that Sinan demonstrated his engineering mastery not only within the main mosque but also in the design of the narthex.

In this context, it is stated that the Edirne Selimiye Mosque and its architecture are not only aesthetic and cultural heritage but also represent an advanced structural and engineering system. The narthex of the Selimiye Mosque stands as a prominent architectural example that reflects the close relationship between geometry, engineering, and religious practice in classical Ottoman architecture. This study, therefore, contributes to the protection and sustainability of cultural heritage by offering a novel, interdisciplinary perspective on the spatial and structural analysis of Ottoman mosques.

It is anticipated that future studies may deepen the structural analyses of Ottoman mosques through more refined digital modeling and artificial intelligence-based engineering approaches. In this way, it will be possible to preserve this architectural heritage, protect it from high-risk natural disasters such as earthquakes, and develop sustainable conservation strategies.

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## ПРОСТРАНСТВЕННОЕ ИССЛЕДОВАНИЕ И СТРУКТУРНЫЙ АНАЛИЗ НАРТЕКСА В ОСМАНСКИХ МЕЧЕТЯХ: ПРИМЕР МЕЧЕТИ ЭДИРНЕ СЕЛИМИЕ

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### Аннотация

**Введение.** Анатолия на протяжении истории была родиной многочисленных цивилизаций. Многие цивилизации, от античности до наших дней, создали различные виды сооружений. Среди этих сооружений мечети представляют собой сильные пространственные и структурные парадигмы в рамках сложной группы зданий, построенных османами. **Методы.** В данном исследовании пространственный характер главного входа в мечеть Эдирне Селимие, построенную Мимаром Синаном, который состоит из колоннад, называемых нартексом, будет проанализирован с помощью семиотических и теоретических методов с учетом архитектурного контекста. Вторая задача — определить пространственные характеристики, а также размеры (высоту и пролет), геометрическую типологию колонн и свойства материалов, а также исследовать статические и динамические реакции на сейсмическое воздействие. В этом процессе были созданы две различные параллельные модели для структурного анализа, в дополнение к существующему нартексу Селимие, и эти три модели были проанализированы с использованием метода конечных элементов в среде ANSYS Workbench. **Результаты.** На основе полученных результатов оцениваются пространственные, геометрические и структурные аспекты и требования к зданию, а также предлагаются конструктивные решения.

**Ключевые слова:** пространственные характеристики; семиотика; структурный анализ; мечеть; нартекс; продавливание; анализ на предельную прочность.

# FROM SOCIAL HOUSING TO HERITAGE: ASSESSING THE ARCHITECTURAL QUALITY AND HERITAGE VALUES OF MODERNIST LARGE HOUSING ESTATES IN ORAN (1950–1962), ALGERIA

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## Abstract

**Introduction.** Thus far, no study has systematically developed criteria for assessing the heritage value of social housing as a built legacy, despite their significant role in shaping urban and architectural identity. **The purpose of this study** aims to identify and evaluate the architectural significance of such estates, with the goal of informing strategies for their potential preservation and contributing to broader reflections on heritage production. In this context, a comparative assessment was carried out on four large housing estates in the city of Oran, selected based on key factors including the architect's reputation, the diversity of urban forms, and the mixed designation of housing for both Muslim and European communities, which reflects the complex social and historical fabric of the city. The research adopts a Mixed **Methods Research** (MMR) approach, integrating qualitative and quantitative data to provide a comprehensive assessment. The qualitative component relied on semi-structured interviews, allowing for the identification of new evaluation criteria grounded in expert and local knowledge. The quantitative component involved 200 questionnaires distributed to two groups' inhabitants and professionals whose responses were systematically analyzed using ATLAS.ti software to reveal patterns and perceptions regarding heritage value. **Findings** from this comparative study indicate that heritage values vary across cases depending on the relevance of specific criteria, highlighting the importance of selecting contextually meaningful indicators. These criteria not only influence the evaluation of each estate but also inform heritage conservation strategies tailored to local urban and social contexts. Ultimately, the study provides essential reference points for the recognition, appreciation, and preservation of Algerian domestic architecture from the second half of the twentieth century, offering insights that may guide similar assessments in other urban contexts.

**Keywords:** social housing; heritage values; assessment criteria; stakeholders; modern architecture; Oran (Algeria).

## Introduction

This study examines the spatial and social formation of urban structures built in the suburban areas surrounding Oran, which served as zones of urban expansion. Many of these neighborhoods, initially located on the outskirts of the historic center, began to develop significantly in the 1950s, a period characterized by their construction as symbols of modernity and reflections of evolving “ways of living and housing,” designed to address a persistent housing shortage (Trainer, 2018; Granath Hansson and Lundgren, 2019). Over time, due to the city's continuous eastward expansion, these estates are now located closer to the urban core.

In the context of heritage recognition and valorization, the large housing estates of the 1950s often regarded as modern colonial architectural heritage have frequently been stigmatized, marginalized, and largely overlooked in official

heritage policies. Nevertheless, attempts to reveal their aesthetic and historical value through rehabilitation, preservation, exhibitions, and public events have been proposed, though these remain limited due to insufficient awareness of this “shared heritage” (Legget, 2018). These estates embody the transition from substandard living conditions to innovative housing solutions and serve as witnesses to a continuous architectural history, linking the arrival of the French in Oran in 1831 to their departure in 1962.

Regarding the original position occupied by recognized architects in the field of social housing, some large housing estates illustrate the commitment to a singular architecture “traditional with a modern allure” that marries the requirements of the Algerian context with the signature and culture of master builders integrated into a rich and rational design process. This has given rise to different “ideal

types” of large housing estates marked by their complexities. They can be described as heritage if the various actors in the field identify their values, or they may be rejected based on perceived lack of quality. This categorization of major complexes recalls Paul Valéry’s statement that “*some are mute, others speak, and others, who are the rarest, sing*” (Amougou, 2006).

The core of this research lies in proposing a novel approach to heritage evaluation. We introduce a model evaluation grid that moves beyond conventional criteria by emphasizing distinctive indicators for determining the heritage status of this modern architectural legacy, acknowledging the diversity of elements necessary to identify and assess value. To guide this investigation, three key questions are posed: What relevant criteria should inform the heritage status of large housing estates? What elements constitute heritage within these estates? Are there examples in Oran that merit heritage protection? In addressing these questions, we hypothesize that heritage value is assessed according to criteria that form a dynamic and evolving model, continuously shaped by societal perceptions and contextual factors, which vary across different regions. The reconsideration of social housing as heritage reflects this shifting logic of heritage recognition (Hadbi, 2020); however, its validation requires rigorous scientific methods. This approach constitutes the primary objective of the present study.

To verify the hypothesis, a combination of investigative techniques was employed, beginning with an ethno-architectural analysis approach. This was reinforced by surveys conducted by the author, including semi-structured interviews with various actors involved in the heritage process and the inhabitants of the large housing estates, followed by questionnaires for the attribution of scores. The paper begins with a review of the scientific production on the notion of “heritage values” and its development over time. Furthermore, this paper explores a criteriology for each heritage value by elaborating an “evaluation grid” as a driving force to measure the heritage interest score for each large complex in Oran, allowing a passage from restrictive to modern thinking. We then proceed to compare their heritage profiles. In conclusion, the study answers the questions raised and indicates the open challenges offered by the importance of the patrimonialization of large modern Algerian housing estates.

#### *Literature Review: Dynamic Values of Modern Heritage*

The broadening of the notion of heritage has led to a proliferation and wealth of scientific literature on the term “value”. Identifying what makes heritage begins with the recognition of values – properties that distinguish a heritage object (Davallon, 2006). This

has become the most favored approach to heritage conservation, whether at national or international level through UNESCO (Poulios, 2014), while others consider it a mobile concept, a passage from fact to right, from desired to desirable (Laurent, 2003), a term most often used in discourses formulated in three dimensions: economic, aesthetic, and ethical (Bos et al., 2023). According to A. Versloot, each value is determined by the degree to which an object meets certain “criteria,” which has always been the *raison d’être* of heritage conservation.

The history of the theory of value was inaugurated by the founding father Alois Riegl in 1902. It stands for a system of values that identifies the qualities for which a monument is valued. Harrer (2017) considered built heritage as a masterpiece endowed with historical value, contemporary value, intentional remembrance value, use value, art value, and antiquity value. However, this original typology has continued to be revisited and even remodeled according to well-defined requirements by various expert researchers who have compared different variables. Essentially, the work of selecting sets of value typologies linked to the built heritage has been summarized in the development of an explanatory table in the research carried out by Fredheim and Khalaf (2016). This updating of values can in no way be complete or durable but rather perpetually in mutation over time and according to societies. Thus, a universal set of value typologies is impossible (Rudolf, 2006) because several elements intervene in the elaboration of a value typology, such as the type of object with patrimoniality (habitat or building, monument), the country context, and the nature of the actors (expert or non-expert (citizens, inhabitants)).

Certainly, this panoply of organizations on the elaboration of different typologies of values has focused on built heritage of nobility, beauty, and monumental character, notably archaeological and historical objects. Nonetheless, this does not deny their contribution to academic and practical work (De La Torre, 2014), as they have strengthened the consolidation of heritage values of objects (Fredheim and Khalaf, 2016). These values are endowed, not intrinsic, changing, not static (De la Torre, 2014), and cannot apply to all types of objects. There is another type of built heritage that arose during the modern movement: the large housing estate as social heritage, to which various researchers have contributed in order to identify values with the aim of including it in heritage lists. Undoubtedly, not considering values as a norm, rule, or law, this field of investigation inaugurates a work of value modeling, depending on several factors that cannot be defined outside any geographical, social, and historical context (Courbebaisse and Issot, 2022). This highlights a body of work focusing on the heritage values of large housing estates, with

each researcher focusing on one or two values for their evaluation a field so fragile and complex that it has become “a laboratory for new thinking” (Reichen, 2000). Positively, this research engine must not be limited to a few common architectural, aesthetic, or historical values (Amougou, 2006). With the method of rehabilitation of a large complex, “Ancely”, located in Toulouse, France, the value of use is analyzed as a potential approach to enhance practices, perceptions, and appropriations as a strategy for understanding a changing space (Issot, 2023). Among other things, the historical value of large housing estates in Algeria represents a radical break with rural architectural style. Regarding artistic value, it refers to the topical value theorized by Riegl, which lies in a modernity that does not free itself from the local and from history. Furthermore, Tapie (2014) introduces other “quality” values linked to large housing estates, which are spatial, urban, proximity, and, finally, reputational. In virtue of which, the values shared by various researchers are merely personal experiences for the purpose of identifying and determining an object for heritage status.

The review of diverse literature in this field has not only helped sharpen the objectives and refine the methodology of the present study but also facilitated the development of a value framework tailored to large housing estates. This framework must remain focused yet comprehensive, using clear language and minimizing overlap between values (Fredheim and Khalaf, 2016). It enables the classification of “cold” values, which are objective and yield consistent results for a given case study such as urban and architectural values into two

distinct categories. In contrast, “warm” values are interpreted variably by different researchers, leading to divergent outcomes. For instance, use value reflects residents’ experiences and perceptions, expressed through their level of attachment to places and their active role in shaping the living environment, as illustrated in Table 1.

### Materials and Methods

The objective of this study is to identify the criteria for evaluating the architecture of large housing estates from the 1950s, which represent a significant component of the spatial structure of the mid-twentieth century. These estates were designed to provide a healthy living environment, high architectural quality, and well-planned urban composition, with some projects created by internationally renowned architects and specialists in mass housing. This research combines two complementary empirical approaches quantitative and qualitative forming a high-quality Mixed Methods Research (MMR) design. The study was conducted in four sequential phases, with an overview of the research stages illustrated in Fig. 1.

- **Step 1:** The research began with a literature review, which enabled us to construct a typology of values for housing in large estates. At that time, we collected technical data by means of ethno-architectural analysis (Pinson, 2016), comparing inhabited statements with photographs. This made it possible to carry out direct investigations in the field to substantiate the previously defined hypothesis (Baribeau, 2005).

- **Step 2:** 242 semi-structured interviews were carried out with three samples of the

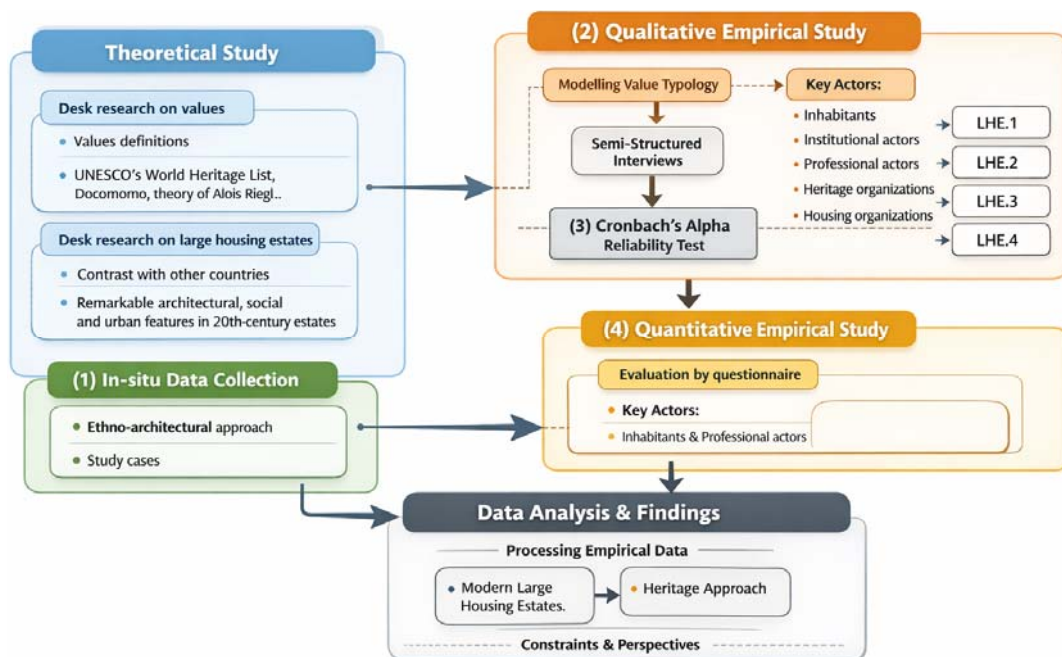


Fig. 1. Study framework

Table 1. Toward a conceptual framework of objective and subjective values in social housing

Objective heritage values	Subjective heritage values
1. Historical	6. Use
2. Urban	7. Memory
3. Architectural (conceptual, contextual, aesthetic, technical)	8. Artistic
4. Reputational	9. Aesthetic
5. Proximity	

Developed by the authors based on the literature review.

population (Robert, 2023): 20 institutional actors, 62 professional actors, and 40 residents for each major complex. Their knowledge of heritage is essential to this identification and assessment work. These groups were selected for their role in learning about, designing, maintaining, and living in these buildings. The semi-structured interview was organized according to the order of heritage values previously defined in the literature review. It began with key questions addressing the defined theme, progressively reframing the interviewees' discourse, accompanied by secondary questions to explore the subject matter in depth with the objective of collecting rich and detailed data (Angers, 1996).

As for the evaluation criteria, they were selected on the basis of the data obtained during the interviews; the discourses were grouped into categories and theoretically justified, seeing that they are part of the same globe of meaning for each value. These evaluation criteria have explanations that refer to the comments obtained from the interviewees' discourses. Consequently, this is a deduction based on newly acquired empirical data.

- **Step 3:** Credibility Test (Cronbach's Alpha): For a pilot methodology in which the data collected have been re-introduced through several instruments and methods, data analysis seems fundamental to test their reliability, which will help identify the gaps and limitations of the research tools selected. Cronbach's Alpha was adopted to examine reliability in this study since it is recommended in social science research to assess the reliability of methodological tools (Kim et al. 2016; Chileshe et al., 2015).

- **Step 4:** The assessment of values using the defined criteria is based on a quantitative approach using a questionnaire distributed in the field to two samples of the population (25 professional stakeholders and 200 residents for each major complex), bearing in mind that the questionnaire was formulated according to the destination of the stakeholders. The questionnaire enabled us to collect complete responses from 825 people, with the objective of converting them into quantitative data to give a score for each criterion identified beforehand for a comparative assessment of the heritage values of each major complex. Finally, on-site observation was carried out to complete what

was said with what was seen, looking for coherences and inconsistencies (Elizondo, 2024).

We are currently observing the third generation of residents of large housing estates, from the time they first moved in to the present day. In our sample of respondents, there is a notable predominance of young residents aged 28, representing 50 % of the sample, and middle-aged people up to 45, who make up 35 %. Those aged 70 and over make up a smaller proportion, 15 %. The field survey included perspectives from all three generations (older people, adults, and teenagers) and ensured balanced representation between genders (male / female) and between tenants and homeowners.

**Presentation of the Case Studies**

The city of Oran has a strong identity, reflected in its rich and diverse architectural heritage. These traces of the past help to make Oran a modern city: "Oran, on the contrary, is a city without suspicion, specifically, a completely modern city" (Camus, 1947).

For both its inhabitants and tourism, with the 19<sup>th</sup> edition of the Mediterranean Games held in 2022, Oran has become a place of exchange and encounter. Its public buildings and urban assemblies from earlier periods are generally the subject of assignment and classification. However, this heritage management is affiliated particularly by the continuation of colonial approaches (Aouchal, 2023). If no steps have been taken to recognize their heritage at its true value, it is because there is a lack of mechanisms for assessing the value of this modern colonial architectural heritage. The large housing estates that were located outside the city, far from the center, are, relatively speaking, better located today, as the city has expanded since then. They are generally well connected to the city center by public transport (Fig. 2).

The work of locating and identifying the initial corpus of large housing estates from the years 1950–1962 is an essential stage that precedes the phase of selecting and analyzing the large housing estates put forward for classification as national heritage. Some have been selected on the basis of relevant elements, both geographically and in terms of the architect's signature and their reputation. Two waves of their construction are distinguished by timing, political and social context, facade design, and volume layout.



Fig. 2. Map of the Oran metropolitan area showing selected large housing estates and distance markers from the city center to each neighborhood, compiled by the authors using a Google Earth © image

LHEM Housing, financed by the Algerian Cooperative Society for Muslim Housing, presents a new way of conceiving modern architecture adapted to Algerian traditions, an alternative solution to the design of traditional houses (Fig. 3). The large housing estate “La Quiétude (El Hanaa)” was built by the French architect Justin Marie between 1955 and 1956, using standardization and economy in design, with an average of 254 flats, four storeys, and a central courtyard area, but no integrated facilities or essential services. It contains three models of housing in a linear and monotonous layout. Additionally, the co-owned building on the Mirauchaux plateau, built in 1958 at the same time

as the adoption of the Constantine plan<sup>1</sup> by Messrs. Mauri, Pons, and Atbat, of which architect Georges Candilis is a part, includes different housing models, totaling 144 units marked by a wealth of architectural elements.

LHEE Housing: With the exception of the two examples chosen, these were originally intended for the families of naval officers, civil servants, and workers from mainland France. For the case of the large Dar Beida housing estate, built by Pierre Jean Guth, winner of the Grand Prix de Rome in 1951, it comprises 580 housing units in a program identical to housing in mainland France called “H.L.M. Improved”, with appreciable surface areas. Considered a human and social work, it is composed of remarkable architectural ensembles. The layout of these buildings has been chosen so that the main façades face roughly north and south, to benefit from maximum sunlight in winter and sea breezes in summer (Keffif and Hendel, 2024). They are equipped with district-wide facilities and public spaces. As for the Valmy housing estate, designed between 1954 and 1956 by the architect Fernand Pouillon, a specialist in social housing, it comprises 614 flats. The location of this major development was chosen in the municipality of Valmy, which offered a number of advantages, particularly in terms of climate and communication with Oran. The architectural ensemble was designed in broad, airy shapes, in keeping with new urban planning

<sup>1</sup> According to Deluz (1988), this was a last-ditch attempt to win back the Algerian population in its struggle against the colonial system.

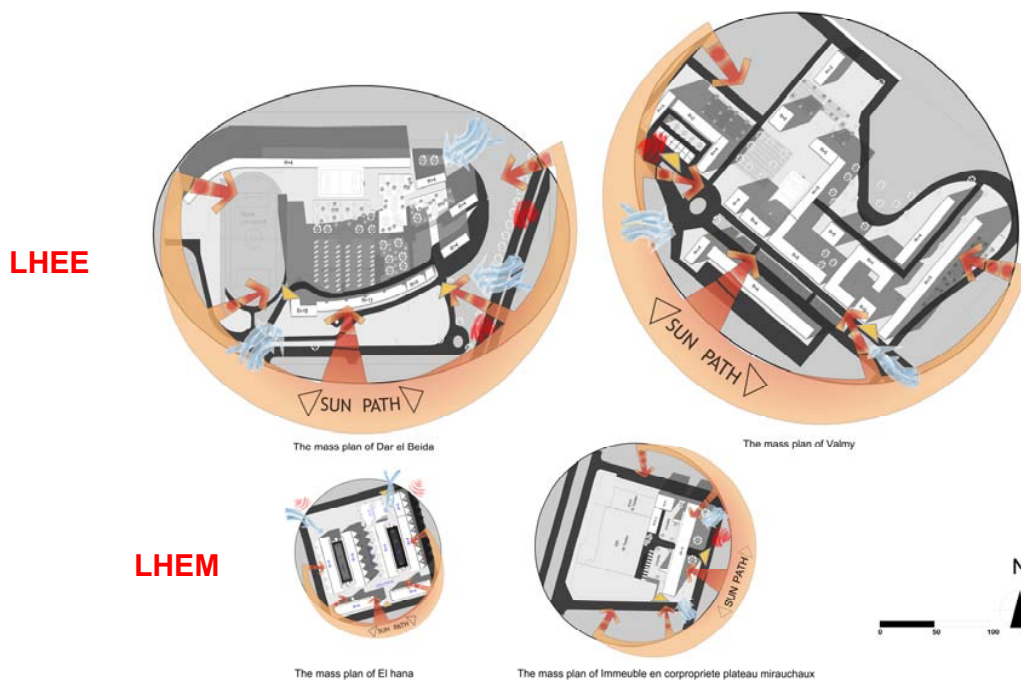


Fig. 3. Mass layout made for each case study. Source: Elaborated by the authors

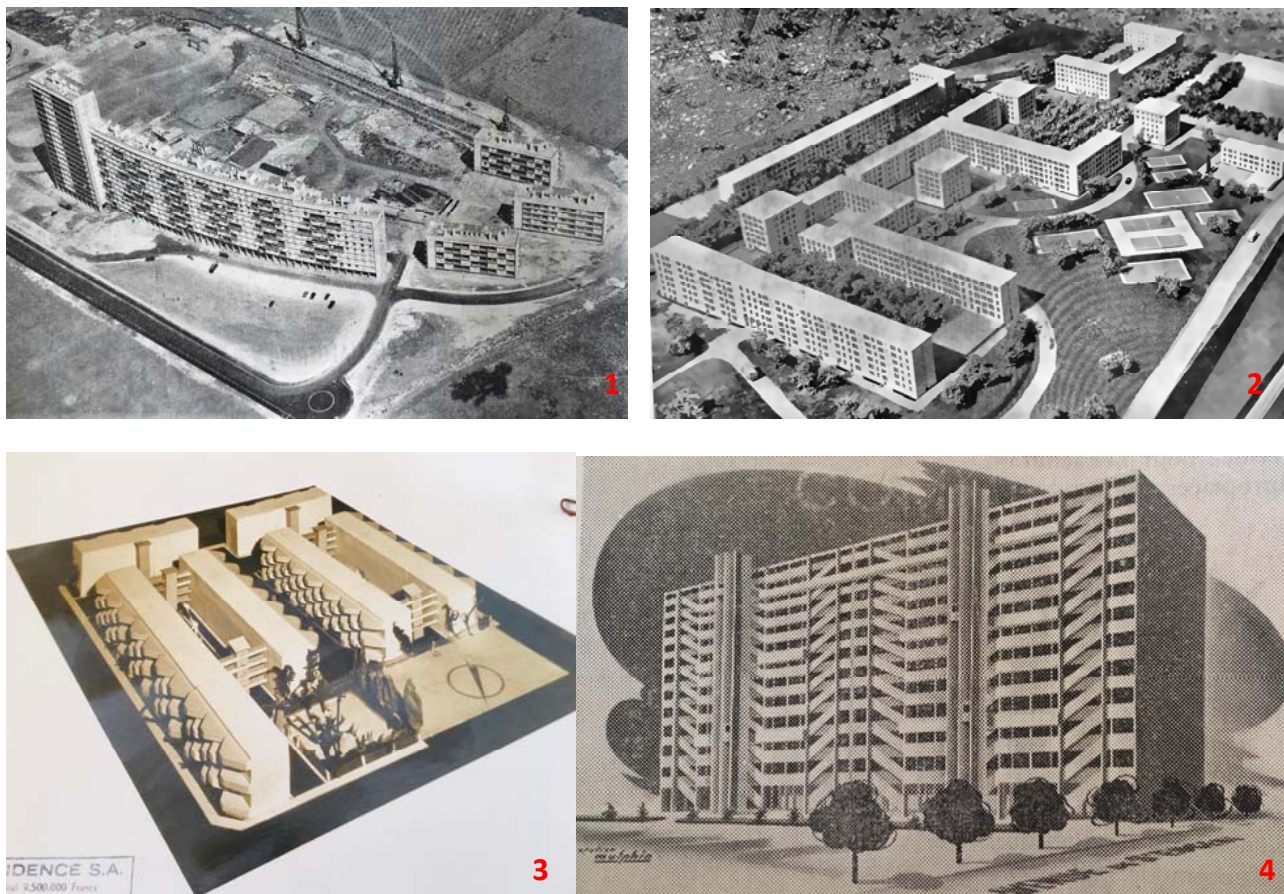


Fig. 4. Photos of: 1. Dar Beida; 2. The Valmy; 3. El Hana; 4. Immeuble en copropriété. Photos from Oran archives

principles. The number of homes at LHEE is 60 % higher than at LHEM (Fig. 4).

**Results**

***Developing and Field-Testing an Evaluation Criteriology***

Criteriology indicates the nature of the scale used to measure values that indicate a level of quality or its absence. It is defined by various actors in the possible perspective for protection purposes, either in its monumental dimension or simply to recognize it as a heritage element. This sort of criteria is considered an objective foundation (Brunel, 2015). In the case of large housing estates, the identification of criteria is based on references to the methodology deployed by the services involved in the “fabrication of Algerian heritage”, combining semi-directive interviews carried out in the field, where the integration of inhabitants is essential through the deciphering of their discourse, which revealed relevant elements to us. This approach to highlighting architectural heritage built in the twentieth century concerns not only experts such as architects, conservators, and architectural historians but also a much wider public (Grignolo, 2018), whose inhabitants are synchronized with an important stage in the life cycle of this architectural product.

Among other things, the criteria developed for large housing estates, which will enable them to enter the heritage field, are specific because this type of social heritage is fragile; it is a way of living that existed and continues to exist in perpetuity. The relevance of using consistent criteria is fundamental. This would mean distinguishing them from the remarkable, exceptional (monumental), and ordinary. The definition of the criteria is translated by passages of words (author, inhabitant, actor in heritage) as follows in Table 2.

***Credibility Test***

After testing the reliability of the responses obtained for each of the questions and items defined in the questionnaire, the result of the reliability test was reliable (Table 3), with a Cronbach’s Alpha of 0.889 for the heritage values and 0.951 for the evaluation criteria concerning the housing of the large housing estates of the 1950s (higher than 0.7). This justifies the coherence of the items and the perceptions of the interviewees and indicates that the questionnaire can be used for the collection of main data for similar themes.

***Assessing Heritage Values: A Comparative Approach***

Table 4 summarizes the comparative assessment of the previously developed values,

composed of a set of criteria identified from the survey conducted in the field, while incorporating a questionnaire distributed to both populations to situate the positioning of each major complex in the heritage approach. The results were processed using the ATLAS.ti tool and then transferred to Microsoft Excel for the graphical series, with the objective of

tracing the profile of the heritage approach. The first questionnaire relating to 5 out of 9 values was intended for the inhabitants of each large complex, while the second questionnaire relating to 4 out of 9 values was completed by various actors.

To observe the status of each criterion, we plan for ourselves according to the results processed

Table 2. **Assessment Criteria for Large Housing Estates According to the Survey**

Assessment Criteria <sup>2</sup>	Definition
1.1 Notable personalities	Presence or historical association with important or influential individuals who contributed to the cultural, political, or social development of the area.
1.2 Significant events	Occurrence of important historical, cultural, or social events that contributed to the identity or historical value of the place.
1.3 The structure provides as proof of actions	The building or site serves as physical evidence of past human activities, achievements, or historical developments.
2.1 Innovative and extraordinary technical demonstration	The structure illustrates exceptional engineering, construction techniques, or architectural innovation for its time.
2.2 The use of unique materials	The building incorporates rare, locally specific, or technologically distinctive materials that enhance its value or uniqueness.
2.3 Remarkable designer's reputation	The project is associated with a well-known architect, planner, or designer recognized for their contribution to architecture or urbanism.
2.4 Ample lodging	Availability of adequate residential space capable of accommodating inhabitants comfortably.
2.5 Adapting to local requirements	The design responds effectively to local social, environmental, climatic, and cultural needs.
2.6 Rarity	The element, design, or typology is uncommon or unique within the regional or architectural context.
2.7 Integrity	The degree to which the original design, materials, structure, and character of the building or site remain preserved and intact.
3.1 Optimum sunlight	The extent to which the building or space receives adequate natural sunlight for comfort, health, and energy efficiency.
3.2 Orientation	The positioning of the building in relation to cardinal directions to optimize light, climate response, and environmental performance.
3.3 Wind protection	The ability of the design or urban layout to reduce the impact of strong winds and provide sheltered spaces.
3.4 Natural ventilation	The capacity of the building to allow air circulation through passive design strategies, improving indoor air quality and thermal comfort.
3.5 The culture of the architects	Reflection of the architects' cultural background, design philosophy, and architectural knowledge in the project.
4.1 Existence of sufficient public facilities	Availability of essential communal infrastructure such as schools, health centers, transportation, parks, and services.
4.3 Ecological sites	Presence of natural or environmentally valuable areas that contribute to ecological balance and environmental quality.
5.1 Quantity of households with a high level of education	Proportion of households where members possess higher educational qualifications, reflecting socio-educational conditions of the community.
5.2 Crime rate = number of crimes / population	Indicator measuring public safety, calculated by dividing the number of reported crimes by the total population in a given area.
6.1 The concept of genuine and distinctive ownership of shared spaces revolving around the notions of identity and security	Degree to which residents feel a sense of belonging, responsibility, and security toward shared community spaces.
6.2 Genuine and exclusive possession of the cell (identity, comfort)	The feeling of personal ownership and identification residents have with their private living unit, ensuring comfort and privacy.
6.3 Genuine and distinctive possession of public facilities (attachment and affection)	Emotional attachment and sense of collective ownership residents develop toward community facilities and public spaces.
7.1 High degree of ethnicity	Presence of diverse or strongly identifiable ethnic groups that contribute to the cultural and social character of the community.

<sup>2</sup> For this research, the word criterion also encompasses characteristics and factors, and this has been organised in a single table in order to avoid spreading out the explanatory diagrams.

Table 3. Reliability Statistics

Reliability Statistics on the Heritage Values of Large Housing Estates in the 1950s

Cronbach's Alpha	Number of Items
0.899	9

Reliability Statistics on the Criteria for Assessing Heritage Values

Cronbach's Alpha	Number of Items
0.942	30

Table 4. Comparative assessment of the heritage values of the large housing estate case studies

	Assessment Criteria	LHEE1	LHEE2	LHEM3	LHEM4
Objective Heritage Values	1. Historical value	1.66	2.66	0.33	1
	1.1 Notable personalities	0	2	0	0
	1.2 Significant events	2	3	1	3
	1.3 The structure providing as proof of actions	3	3	0	0
	2. Architectural value	2.42	3.14	2.42	2.57
	2.1 Innovative and extraordinary technical demonstration	2	2	4	4
	2.2 The use of unique materials	1	3	1	2
	2.3 Remarkable designer's reputation	3	4	1	3
	2.4 Ample lodging	3	4	1	1
	2.5 Adapting to local requirements	2	3	4	3
	2.6 Rarity	3	3	4	4
	2.7 Integrity	3	3	2	2
	3. Urban value	3	3.8	2.8	3.6
	3.1 Optimum sunlight	3	4	3	3
	3.2 Orientation	3	4	3	3
	3.3 Wind protection	2	3	3	4
	3.4 Natural ventilation	3	4	3	4
	3.5 The culture of the architects	4	4	2	4
	4. Proximity value	2.66	2	2.33	2.66
	4.1 Existence of sufficient public facilities	3	2	3	4
	4.2 Different modes of transport	3	1	3	4
	4.3 Ecological sites	2	3	1	0
	5. Reputational value	positive	positive	negative	negative
5.1 Quantity of households with a high level of education	2	3	1	1	
5.2 Crime rate = number of crimes / population	0	0	2 (0.06)	2 (0.034)	
Subjective Heritage Values	6. Use value	1.66	3	2.33	3
	6.1 The concept of genuine and distinctive ownership of shared spaces revolves around the notions of identity and security	3	3	3	4
	6.2 Genuine and exclusive possession of the cell (identity, comfort)	1	4	2	2
	6.3 Genuine and distinctive possession of public facilities (attachment and affection)	1	2	2	3
	7. Memory Value	2	2	2	2
	7.1 High degree of ethnicity	0	0	2	2
	7.2 Personal representation with positive connotations	4	4	2	2
	8. Artistic value	2.33	2	3	3.66
	8.1 Indicates an original appearance	3	2	4	4
	8.2 Epitomises a novel genre of artistic expression	2	2	2	4
	8.3 The interpretation of its meaning	2	2	3	3
	9. Internal and external aesthetic value	2.5	3.25	3	3.5
	9.1 Perception and enjoyment of visual or aural stimuli	3	2.5	3	4
9.2 Infused with cognition, creativity, and sentiment	2	4	3	3	

by ATLAS.ti that their sum corresponds to an overall score expressed in Figs. 5-6 (number of responses). We have established a correspondence between five scoring groups with a numerical rating (4, 3, 2, 1, and 0), with the criteria status structured in the following order: Exceptional, Superior, Strong, Medium, and Weak. Finally, all the ratings are converted into numerical values.

- 161 to 200: (Exceptional criterion) = 4;
- 121 to 160: (Superior criterion) = 3;
- 81 to 120: (Strong criterion) = 2;
- 41 to 80: (Medium criterion) = 1;
- 1 to 40: (Weak criterion) = 0.

The evaluation of the values revealed a strong connection between the heritage approach and the characteristics of the large housing estates. To understand the challenges and limitations of the heritage approach, the values were assessed based on the criteria evaluating the four large housing estates (Fig. 5).

### Discussion

In light of the results obtained by adopting the main methodology (MMR), which is effective in determining the objective (Matović and Ovesni, 2023) and composed of several tools and approaches, this study has made it possible to bring together the trio of key and fundamental actors in the identification and assessment of hot and cold heritage values. The MMR enabled a much deeper understanding of the meaning of the data collected from different sources, as well as a great openness to different points of view, whose contextual criteria were easily identified, becoming the backbone of a heritage assessment with the aim of encouraging reasoned and respectful heritage intervention. The novelty of this methodology developed for this research is its provision of an opportunity for the inhabitant, considered a central actor (Grignolo, 2018), to collaborate in a heritage process for both stages, whether identification or evaluation. This has made it possible to define the Valmy City and the joint-ownership building on the Mirauchaux plateau as the most distinctive and remarkable housing estates, rich in heritage values (Table 4, Figs. 5, 6). Designed by the international architects specialized in social housing, Mr. Pouillon and Mr. Candilis, the first is distinguished by the coherence of the project's layout in its entirety, and the second as a unique artistic work of a new form (Score 4), with authentic and singular appropriation of common spaces that positively contributes to the maintenance of the social identity of the large housing estate (Score 3), despite its bad reputation in the city of Oran (negative), which has led to its marginalization. This confirms that the values of the large housing estate are intimately linked to the context of their identification as well as to those who express them (Courbebaisse and Issot, 2022). These two large housing estates bear witness to

an adaptation to local requirements, with a Score 3 recorded and Score 4 for their rarities, particularly the joint-ownership building on the Mirauchaux plateau, whose strategic location may facilitate its accessibility for visiting, surrounded by a variety of means of transport. The joint-ownership building on the Mirauchaux plateau has not undergone any formal modification or rehabilitation since its construction, which explains its technical solidity and has generated the preservation of its authenticity.

As for the Dar Beïda city, located in the vicinity of the joint-ownership building on the Mirauchaux plateau, it has a deficit (Table 4, Fig. 6) in terms of the degree of autochthony and memorable characters and idols (Score 2); the authentic and singular appropriation at the level of the cell and the facilities is weak (Score 1), due to the perpetual departure and arrival of families given its military status. Its curvilinear shape gives visual pleasure, with two identical scores of 3 — a specificity and principle that the architect Pierre-Jean Guth uses for his projects, being considered a renowned architect (Score 3) (Table 4, Fig. 6). Its strategic location has favored its visibility.

On the other hand, the City “La Quiétude” (El Hanaa) represents a new artistic form (Score 3) that the architect was able to combine with the audacity of having a modern form adapted to local requirements (Score 4), with a remarkable technical demonstration by the individual and collective patio (Score 4), which gave an architectural rarity in the Oran landscape (Score 4) (Table 4, Fig. 6). However, this large ensemble has a high rate of uneducated families from the slum, which has influenced the reputational value (negative), and an absence of memory characters or activity (Score 0). This considerable imbalance leads to acts that can harm the large ensemble in question, including destruction and mismanagement. Regarding the developed methodology, several limitations were confronted, including the lack of consensus between the inhabitants and the professional actors, particularly on communication techniques, which entailed considerable time in the progress of this research, as well as their lack of knowledge of the values identified by the inhabitants. Therefore, it will be necessary for future studies to train professional experts so that they develop additional skills in communication (Bacqué and Gauthier, 2011).

### Conclusions

The results of this research illustrate that heritage values vary from one large complex to another according to the characteristics of each in terms of its identity, the experience of its inhabitants (translated by use and appropriation), its creator, and its history — which stands as a resource and has a greater bearing on its destiny as heritage in the making. Finally, the results encourage the

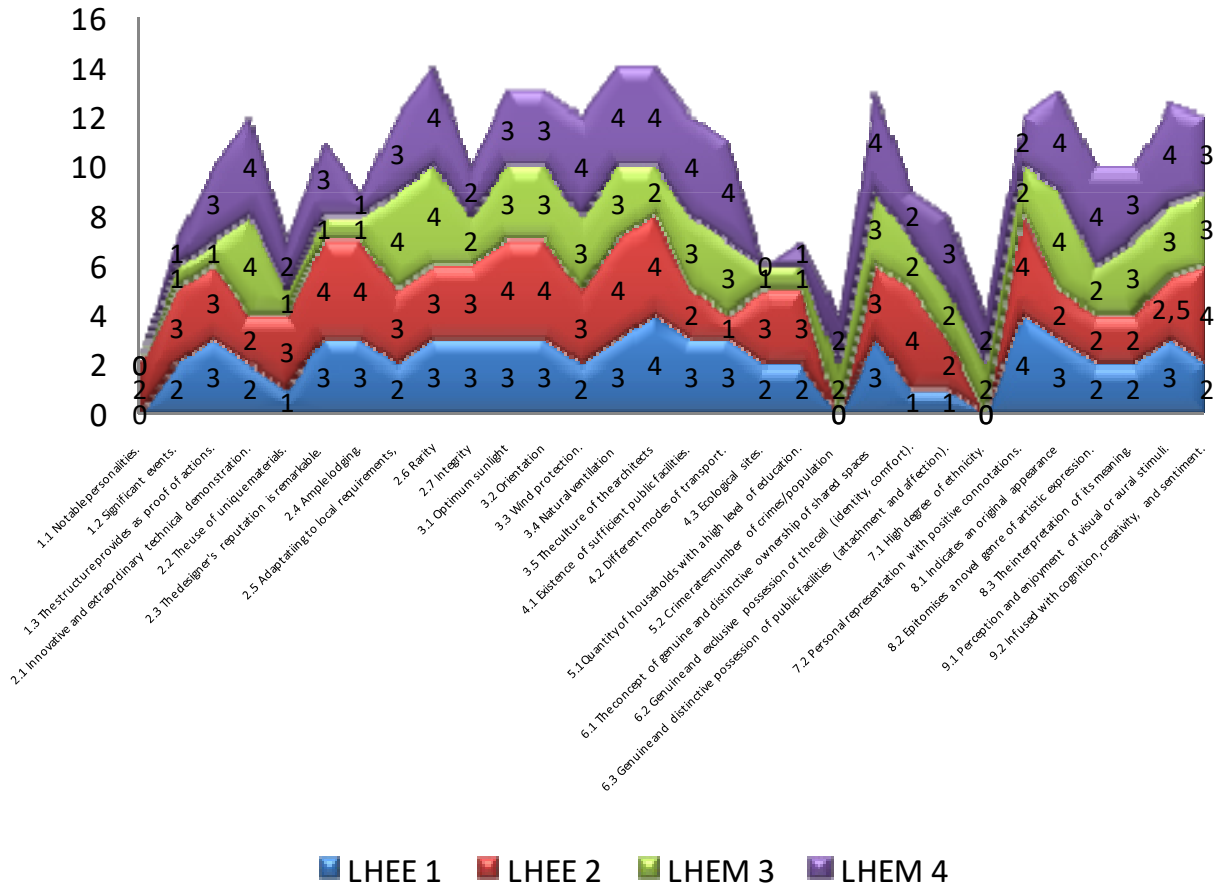


Fig. 5. Profile of heritage criteria for the large housing estates analyzed. Source: Authors

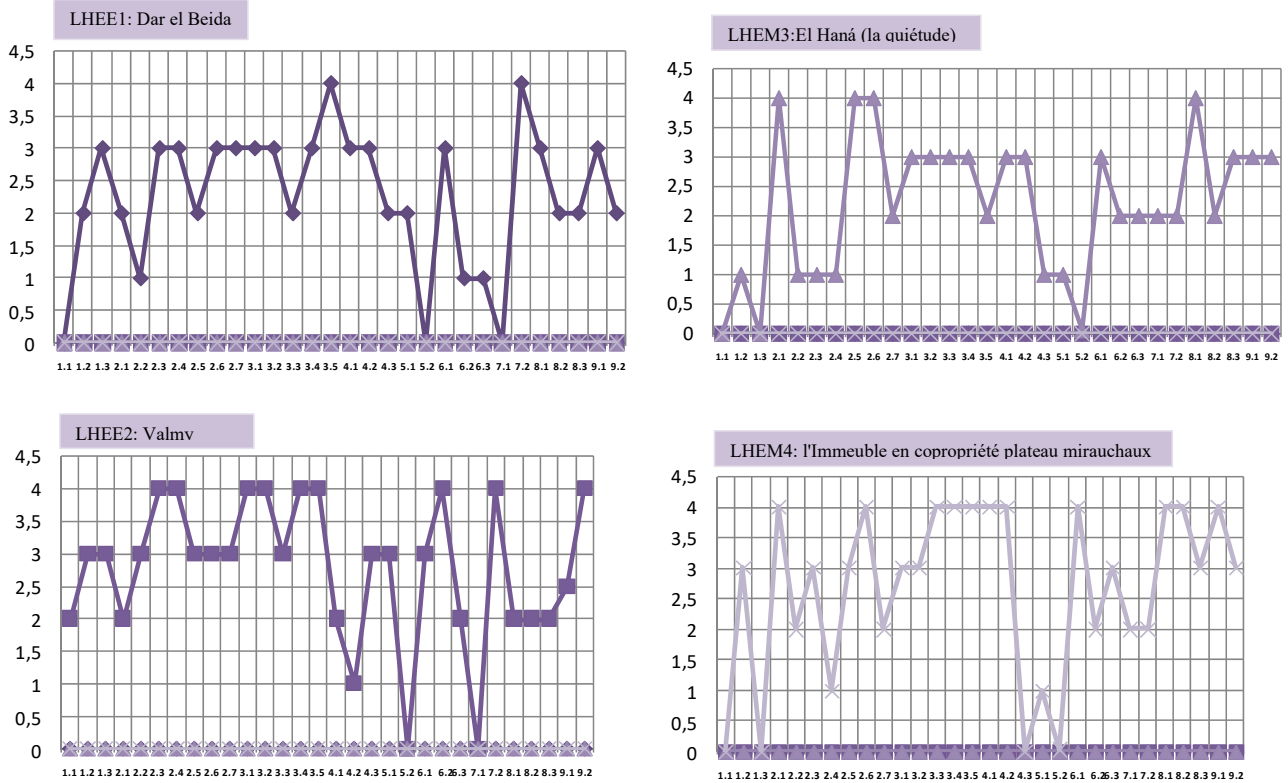


Fig. 6. Heritage graphs illustrating each large housing estate. Source: Authors' elaboration

attribution of heritage status in a certain way, given the diversity and richness of the heritage values identified while taking into account the historical and social context of the site. This research joins authors such as Bos et al. (2022), who defines the grid of heritage values as an operational scientific tool inducing a reasoned approach to the object to be evaluated, and Lemaitre (2020), where the “typology of values” is a “methodological tool” available to “evaluate a cultural property”, a form of “theoretical model” to “organize cultural values among themselves” and, based on which, “define the ‘value’ of a cultural asset”. Though the identification and evaluation of values presents a powerful search engine that draws consensus from different disciplines, such as social sciences, engineering, health, and economics, and they offer reliable tools and methods that could be applied by heritage experts. As attested by the results, this typology of inheritance produces a feeling of attachment and a lively social mode for the inhabitants, which contributes to social, architectural, and urban diversity on a local scale. In this regard, the comparative approach of values, with the involvement of inhabitants, facilitates the evaluation of large groups to express their experiences and other important information so as to support decision-making from above. That said, they often try to propagate and affirm the status of “expert”. Likewise, the results are in line with Johnston’s (2017) assertion that the evaluation approach through the participation of inhabitants in the heritage framework will allow the management of places, values, significance, and conservation.

One of the limitations of this study is that the common areas of LHEM have not been landscaped as planned in the plans approved by the architects, which has affected the appropriation of the spaces and could not be taken into account and analyzed. Further research could be carried out to compare the results of this study with those of large Maghreb assemblies with similar socio-political characteristics, with the intention of determining whether or not the model is extensible or should be simply a means of empowerment for each country.

In conclusion, the sample size of the case studies on the measurement of heritage values by the identification of criteria was limited to just four examples, which may prevent the identification of other criteria relevant to the evaluation of heritage values of large ensembles of the 1950s for a heritage approach of preservation or classification. To this end, future research efforts could multiply them by taking into consideration methodologies allowing them to be explored in a multi-perspective way, since this type of domestic heritage is complex and fragile at the same time. This underlines the need to continue to promote a wide inclusion of criteria to allow decision-makers to take charge of their conservation, mainly to develop more definitions – such terminology used by the trio of actors has shown to be easily understood.

#### **Notations**

LHEE — Large Housing Estate European

LHEM — Large Housing Estate Muslim

MMR — Mixed Methods Research

Atlas.ti — Tool of Qualitative Data Analysis (QDA)

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# ОТ СОЦИАЛЬНОГО ЖИЛЬЯ К НАСЛЕДИЮ: ОЦЕНКА АРХИТЕКТУРНОГО КАЧЕСТВА И ЦЕННОСТИ НАСЛЕДИЯ КРУПНЫХ СОВРЕМЕННЫХ ЖИЛИЩНЫХ КОМПЛЕКСОВ В ОРАНЕ (1950–1962), АЛЖИР

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## Аннотация

**Введение.** До настоящего времени ни одно исследование не разработало систематических критериев оценки исторической ценности социального жилья как архитектурного наследия, несмотря на его значительную роль в формировании городской и архитектурной идентичности. **Цель данного исследования** — выявить и оценить архитектурную значимость таких жилых комплексов с целью разработки стратегий их потенциального сохранения и внесения вклада в более широкое осмысление процесса создания культурного наследия. В этом контексте была проведена сравнительная оценка четырех крупных жилых комплексов в городе Оран, выбранных на основе ключевых факторов, включая репутацию архитектора, разнообразие городских форм и смешанное назначение жилья для мусульманской и европейской общин, что отражает сложную социальную и историческую структуру города. В исследовании используется подход смешанных **методов исследования** (MMR), интегрирующий качественные и количественные данные для обеспечения всесторонней оценки. Качественный компонент основывался на полуструктурированных интервью, что позволило выявить новые критерии оценки, основанные на экспертных и местных знаниях. Количественная часть исследования включала 200 анкет, распространенных среди двух групп населения — жителей и специалистов, ответы которых были систематически проанализированы с помощью программного обеспечения ATLAS.ti для выявления закономерностей и представлений о ценности культурного наследия. **Результаты** этого сравнительного исследования показывают, что ценность культурного наследия варьируется в зависимости от значимости конкретных критериев, подчеркивая важность выбора контекстно значимых показателей. Эти критерии не только влияют на оценку каждого объекта, но и определяют стратегии сохранения наследия, адаптированные к местным городским и социальным условиям. В конечном итоге, исследование предоставляет важные ориентиры для признания, оценки и сохранения алжирской жилой архитектуры второй половины XX века, предлагая идеи, которые могут помочь в проведении аналогичных оценок в других городских условиях.

**Ключевые слова:** крупные жилые комплексы; ценности культурного наследия; критерии оценки; заинтересованные стороны; современная архитектура; Оран (Алжир).

# THE SCHOOL OF MODERNITY: THE ARCHITECTURE OF EIGHT INTELLIGENCES

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## Abstract

**Introduction.** The architecture of school buildings plays a vital role in shaping the educational environment and influencing learning processes. **Purpose of the study:** To investigate how the architectural and spatial organization of modern school buildings in Astana can be aligned with the theory of Multiple Intelligences, with the goal of identifying planning principles and design strategies that support the comprehensive intellectual development of students across all eight intelligence types. **Methods:** The study defines temporal and territorial boundaries, analyzes urban structure analysis, employs field survey methods, collection and analysis of architectural documentation, and a review of theoretical foundations. An additional focus is placed on methods of interaction, interpreted as architectural-spatial typologies of communication and environmental stylistics that support different modes of learning and engagement. **Results:** The analysis revealed that the existing school architecture typologies in Astana predominantly support linguistic and logical-mathematical intelligences through traditional classroom-based layouts. However, architecture elements that encourage the development of other types of intelligence — such as music rooms, art studios, outdoor learning zones, and flexible collaborative spaces — are inconsistently present and often marginalized in spatial hierarchy. The study identified architectural features that correlate with the activation of different intelligences, including amphitheater-style gathering spaces (interpersonal), green inner courtyards (naturalistic), maker spaces (bodily-kinesthetic), and modular classroom arrangements (intrapersonal). Based on the findings, the authors propose a planning model for a multi-intelligence-oriented school, in which functional zones are organized to provide spatial stimuli aligned with each intelligence type. This model demonstrates a potential direction for rethinking school architecture as an adaptive and inclusive educational infrastructure.

**Keywords:** school architecture; educational system; types of intelligence; book-frontal method; classroom-lesson system; comfortable environment; architectural and planning methods.

## Introduction

The school, being one of the most important institutions of society, is, on the one hand, inherently conservative, yet on the other, highly sensitive to social changes and progressive scientific advancements (Samoilova and Chislova, 2017). Modern schools are largely a legacy of the industrialization era, when educational processes were built upon the principles of standardization and the unification of knowledge (Samoilova and Chislova, 2017). During Kazakhstan's time as part of the USSR, changes took place in the architectural and planning structures of schools, reflecting broader trends in Soviet urban planning policies. In the 1920s–1940s, schools were constructed according to standardized designs emphasizing economic balance and standardization. In the 1950s–1960s, a period of mass urban school construction began, aimed at accommodating growing student populations. By the 1970s–1980s, school projects became more specialized, incorporating multifunctional spaces such as sports halls and laboratories, reflecting the development of polytechnic and technical education (Amanzhol and Yerkin, 2006). These standard school designs

continue to play an important role in Kazakhstan's educational architectural system. Today, Astana, as the rapidly growing capital of Kazakhstan, is experiencing significant pressure on its educational infrastructure. According to statistics, during the 2024–2025 academic year, there are 188 general education schools in Astana, including 109 public, 72 private, and 7 republican schools. Currently, it is crucial to cultivate children's abilities to search for and critically interpret information, to develop psychological flexibility, communication skills, and a high level of general cultural competence (Mark, 2000). Consequently, there is a growing demand for diverse educational programs and various learning environments. For individuals to generate new ideas, they must cultivate a broad range of interests and develop comprehensively. Equally important is the ability and motivation to find and utilize information from a variety of sources (Gladilina et al., 2022). In the context of Astana's rapid urban development and the legacy of standardization from industrial and post-industrial periods, it is necessary to integrate the needs of an information-driven, multi-intelligent society when planning new educational facilities.

The theory of multiple intelligences, developed by American psychologist and Harvard University professor Howard Gardner, emerged from research into human creative potential. According to Gardner, any type of intelligence can be developed through appropriate educational tools and methodologies (Gardner, 2007). The adaptation of multiple intelligences theory into the architecture of general education schools is based on a multi-aspect approach, integrating the works of leading scholars in this field. Researchers such as H. Gardner, L. S. Vygotsky, D. Goleman, R. B. Cattell, and R. Sternberg emphasize that intelligence is not a uniform construct but manifests in multiple forms. Their studies demonstrate that, beyond traditional logical-mathematical reasoning, emotional, social, creative, and practical intelligences also play critical roles in the educational process. This perspective enables a more comprehensive consideration of learners' individual characteristics and supports the creation of educational environments conducive to holistic personal development. The theory of multiple intelligences has gained widespread recognition in pedagogy and is actively being experimented with in educational systems worldwide. In this study, the authors adapt Gardner's concept into an architectural model, creating learning environments that nurture and develop different types of intelligence. These models allow for the design of educational institutions where each space corresponds to a specific type of intelligence, thereby fostering individual growth. Such environments provoke different behavioral models, (Upitis, 2004) ultimately shaping a new type of multi-intelligent personality.

### Methods

To achieve the set objectives in developing a modern functional structure for schools, the present study was divided into several stages:

1) Defining temporal and territorial boundaries. Due to the broad scope of the research, the authors initially established the temporal and territorial boundaries of this study. Considering that the internal functional structure of schools has evolved continuously and is based on regulatory documents, it was decided to study school structures beginning from 1960, marking the active phase of school construction in Astana. The diversity of school architecture — depending on the city's status, population size, climatic conditions, and other factors — prompted the authors to focus territorially on the capital of the Republic of Kazakhstan, Astana. Additionally, the research concentrated solely on public general education institutions rather than private schools, as public schools are designed based on governmental specifications and better reflect the social needs of the broader population.

2) Urban structure analysis. At the second stage, the urban planning structure of Astana was studied

to identify general education institutions relevant to the research. An optimal map of city routes was developed to enable rational field surveys.

3) Field surveys of educational institutions. A field survey method was applied to general education organizations. A total of 19 schools were studied. During the surveys, photographic documentation was conducted, including images of the school grounds, buildings, and evacuation plans located at entrances on each floor. The collected data were then systematized, allowing the identification of several types of "standard school models" that emerged as a result of the rapid population growth and shortage of educational institutions, leading to widespread replication of architectural designs and solutions. The field survey method is recognized as one of the key techniques in architectural and urban analysis, providing objective data on existing structures.

4) Collection and analysis of architectural documentation. At the fourth stage, architectural design documents for schools were collected and analyzed. The authors sent formal requests to relevant authorities (including LLP "AstanaGenPlan" Research Institute, the Department of Architecture, Urban Planning, and Land Relations of Astana, RSE "State Expertise", and RSE "State Urban Cadastre") and held meetings with project company executives. As a result, 11 sketch projects of standard schools and 3 detailed working projects for schools in Astana were obtained. Among them were typical designs for public educational institutions. Analysis of the architectural and planning solutions presented in these projects allowed for the formation of the existing functional model of general education institutions, primarily based on two most commonly implemented "standard" projects.

5) Review of theoretical foundations. The fifth stage focused on reviewing theoretical materials regarding the architectural and planning structure of schools and the factors influencing their transformation. Doctoral dissertations by T. A. Gvozdikova (2024), T. A. Kiseleva (2019), and along with scientific articles by S. Sh. Sadykova (2022), were analyzed. It was established that the growth of the student population and the adoption of new teaching methods aimed at developing well-rounded individuals are the main drivers of changes in the functional structure of schools. While the growth of the student body represents a quantitative factor leading to architectural replication of traditional spaces, the authors subsequently focused on qualitative factors: namely, types of intelligence. To this end, the theoretical works of renowned scholars were studied, including Howard Gardner (*Frames of Mind: The Theory of Multiple Intelligences*, 1983), Lev S. Vygotsky (*Mind in Society: The Development of Higher Psychological Processes*, Harvard University Press, 1978), Daniel Goleman (*Emotional Intelligence*,

Bantam Books, 1995), Raymond B. Cattell (Theory of Fluid and Crystallized Intelligence, Journal of Educational Psychology, 1963), Robert J. Sternberg (Beyond IQ: A Triarchic Theory of Human Intelligence, Cambridge University Press, 1985). Following this, common intelligence domains acknowledged by these authors were identified. In the article “Promoting Inclusive Education in Kazakhstan: Environmental and Architectural Aspects” by T. A. Gvozdikova and D. Amandykova (2024), the authors explore strategies for improving the spatial environments of educational institutions to promote inclusive education in Kazakhstan. They emphasize the importance of creating comfortable learning conditions for all students, including individuals with disabilities, and examine architectural and planning concepts that support this goal.

6) At the sixth stage, using the method of interaction (flow and synthesis), architectural spaces corresponding to different types of intelligence were developed. This approach enabled the assessment of the extent to which various types of intelligence are currently supported within existing schools, and allowed for projections regarding their future functional development.

7) At the seventh stage of the study, the authors conducted a sociological survey among teachers, students, and their parents. The objective of this method was to determine the social necessity of the proposed functional elements within the educational structure. A total of 495 participants were randomly selected for the survey. The survey included the following key questions: Are you satisfied with the range of educational spaces

currently available at your school? In your opinion, are the proposed spaces necessary within the school structure? (Participants were presented with a list of spaces identified by the authors). Subsequently, respondents were provided with a structured questionnaire where they were asked to rate the importance of each proposed space on a scale from 1 to 10, where 1 indicated “not important” and 10 indicated “extremely important”. Participants were also encouraged to leave comments or suggest their own answers for each question. The collected responses were systematized, enabling the identification of the direction and relevance of the study. Finally, using graphic modeling software, the authors demonstrated the scientific novelty of the research by visualizing the differences between the existing functional model of school buildings and the proposed model, which is based on the need to cultivate a multi-faceted individual and is supported by the results of the sociological survey.

#### Analysis

Field survey of 19 schools in Astana revealed the predominance of a standard architectural and planning model of educational institutions.

Standard schools of Type 1 (marked in red) include six facilities with a service radius of 500 meters, evenly distributed throughout the city territory, including residential neighborhoods and prospective development areas. Standard schools of Type 2 (marked in yellow) comprise 13 facilities with the same service radius, predominantly concentrated in the central and southern parts of the city (Fig. 1). Based on the analysis, a unified functional and planning model was identified across all types

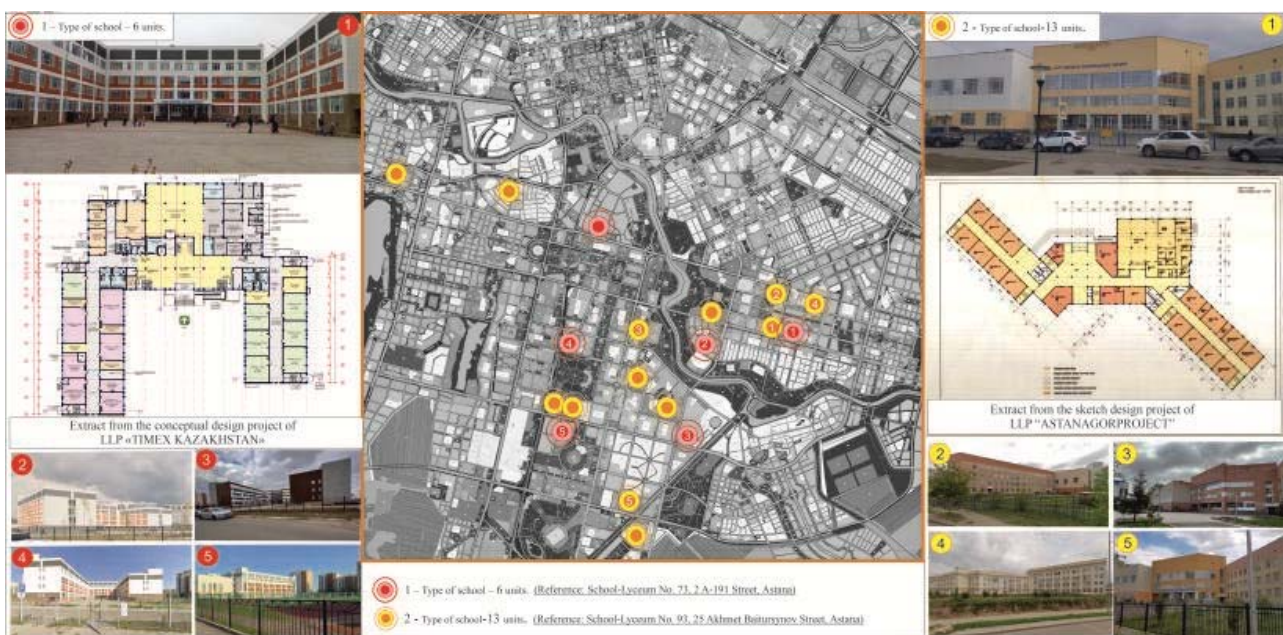


Fig. 1. Cartogram of the typological distribution of school buildings within the residential structure (Astana)

of schools. Consequently, for further in-depth study, two representative cases were selected: School-Lyceum No. 93, located at 25 Akhmet Baitursynov Street, Astana and School-Lyceum No. 73, located at 2 A-191 Street, Astana. Sociological Survey: To incorporate the perspectives of direct participants in the educational process, a sociological survey was conducted, covering 495 respondents (including approximately 40 teachers, 30 parents, and 425 students). The survey aimed to assess current perceptions of the school environment and to identify preferred directions for its development. The key quantitative findings are as follows: Approximately 70 % of teachers reported a shortage of specialized spaces for practical and creative activities (such as laboratories, studios, and project areas). Teachers emphasized that spatial limitations hinder the implementation of new educational methods – from project-based learning to interactive group work formats. 65 % of students expressed a desire for a greater variety of spaces beyond standard classrooms, including areas for socialization and relaxation, creative corners, and modern computer or

scientific laboratories. Additionally, 52 % of students directly stated that the current school environment does not sufficiently stimulate their interest in learning and personal development beyond the formal curriculum. Overall, the sociological survey revealed a consensus among teachers, parents, and students that the traditional school model is outdated and in need of transformation. The majority of respondents agreed with the statement that “a school should be a space for holistic development, not merely a place for knowledge transmission”.

**Results and Discussion**

These findings formed the basis for the proposed model of a school oriented towards the development of multiple types of intelligence. Formation of the Generalized Spatial Model: as a result of the analysis of prevalent standard school types, a generalized model of the spatial organization of existing schools was developed and is presented in the accompanying diagram (Fig. 2). It is important to note that this model is not an isolated case but reflects broader trends in mass school construction over the past decades. Conceptual Model of the

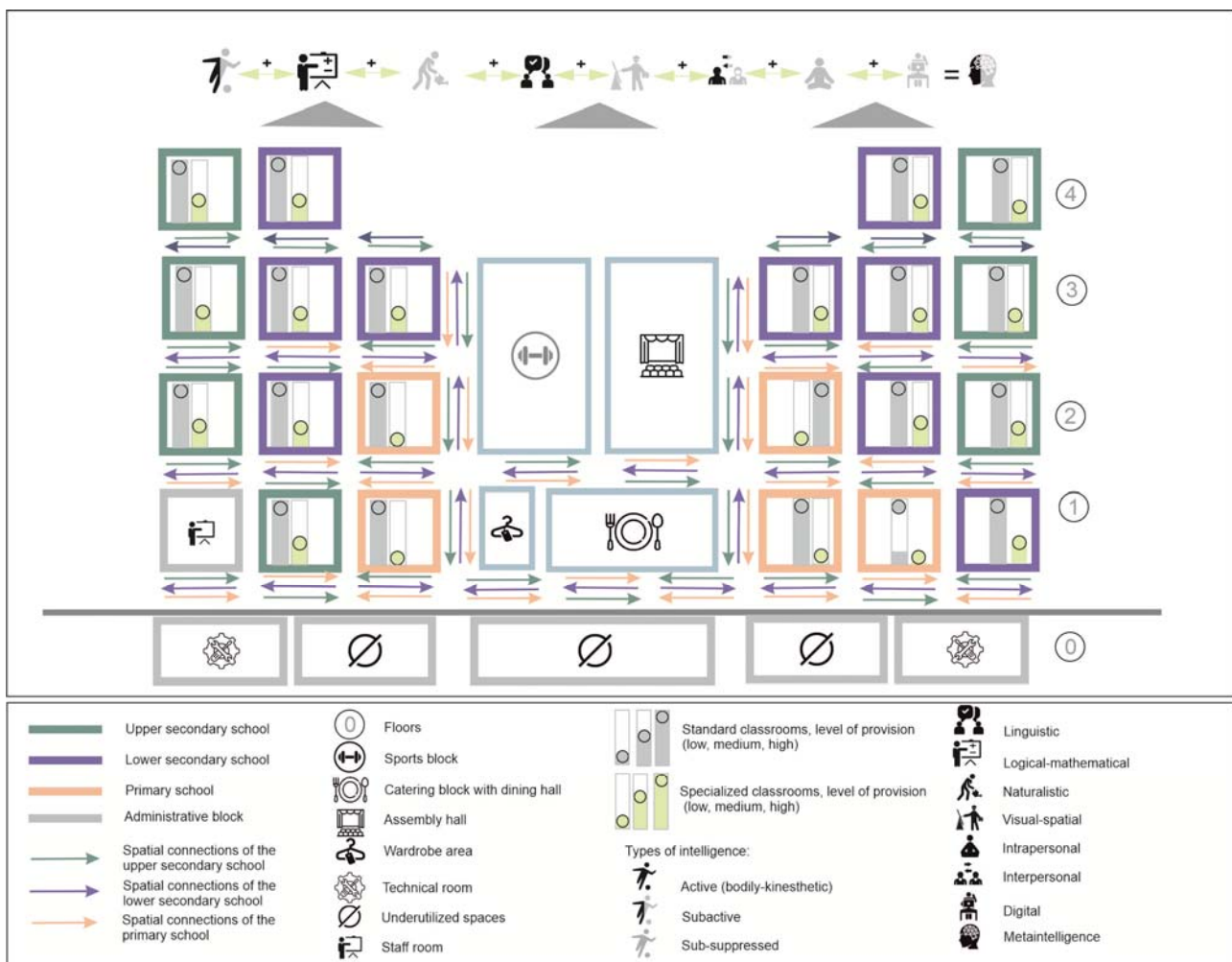


Fig. 2. Existing architectural and planning model of the school (Astana)

Functional-Planning Structure: the conceptual visualization is presented in the form of square blocks, representing the building's vertical structure (from ground floor to the fourth floor), with functional zoning of key school blocks: primary, middle, and high school areas; workshops; libraries; sports and administrative blocks; as well as medical facilities and an assembly hall. This model highlights the typical deficiencies in the organization of educational spaces characteristic of schools constructed under mass development programs in Astana.

The scheme presents a spatial-functional model of a modern school, structured by educational levels and corresponding types of intelligence. The diagram illustrates the interconnections between primary, middle, and high school blocks, emphasizing differentiated circulation routes, specialized facilities (sports, arts, administrative, dining, and assembly spaces), and zones that support the development of multiple intelligences — from linguistic and logical-mathematical to bodily-kinesthetic and digital.

As shown in the model, current school projects demonstrate a noticeable lack of specialized spaces designated for specific grade levels, resulting in the universal use of classrooms regardless of students' levels of preparedness. Specialized facilities (such as workshops, art rooms, and libraries) are located without consideration of age-specific student groups, leading to shared use by both younger and older students. This reduces the adaptability of the environment to the educational needs of different age groups and complicates the formation of coherent educational pathways. The placement of classrooms does not take age characteristics into account: for instance, middle and high school classrooms are often concentrated on the same floors, which causes intersecting student flows and disrupts the organization of the educational process. The spatial structure tends toward centralization, where shared areas become overloaded and serve as points of conflict between different traffic flows. Moreover, recreational spaces, which are particularly important for younger students, are largely absent, negatively impacting rest and recovery. Primary school blocks are fragmented across different floors, violating the principle of age-group isolation and complicating navigation within the building. In addition, primary grades are not equipped with specialized spaces such as workshops or laboratories, nor are there adapted zones that meet the specific developmental and educational needs of young students. Importantly, the layout of existing school architectural models enforces a regime of regulation and passivity—students sit in traditional frontal classroom arrangements, wait for bells, and move in narrow corridors under supervision. This structure presents a clear pedagogical disadvantage, as modern education values initiative, autonomy, and collaboration, and the physical environment should

support the development of these qualities rather than suppress them (Lackney, 1994). It is important to note the inefficiency of current architectural and urban planning solutions, which is reflected in the excessive size of school sites, the underutilization of basement levels, the inappropriate number of floors, and the presence of incomplete or irregular stories. All of these shortcomings negatively affect the formation of a comfortable and functional educational environment. The lack of professional functional zoning within such structures leads to the emergence of social “conflict points”, caused by the constant movement and intersection of student groups of different ages. This not only disrupts spatial organization but also reduces students' opportunities for rest and psychological recovery. The narrow range of functional spaces results in the creative and intellectual limitation of modern students, diminishing their opportunities for social interaction and communication. Furthermore, the reliance on average-age architectural standards in the design of learning spaces often leads to the creation of non-ergonomic environments that fail to meet the diverse physiological and psychological needs of students of different ages. According to a comprehensive literature review, Howard Gardner proposed the theory of multiple intelligences, recognizing the existence of several independent types of intelligence, each essential for successful human functioning. This theory integrates the analytical, creative, and practical intelligences studied by L. S. Vygotsky and R. Sternberg, as well as the emotional intelligence emphasized by D. Goleman. The concepts of fluid and crystallized intelligences, introduced by R. B. Cattell, also find their place within Gardner's framework, being interpreted through different forms of thinking and knowledge accumulation. Thus, Gardner's theory synthesizes the approaches of other scholars, offering a more holistic and flexible understanding of intelligence, making it particularly valuable for educational practices, including school architectural design. The proposed Architectural and Planning model consists of three autonomous blocks corresponding to different levels of education: the upper secondary school on the left, the primary school in the center, and the lower secondary school on the right. Color coding and individual directional arrows emphasize that each level has its own movement contour without intersecting with others. The planning structure is multi-core: within each block, a recurring module of “two classrooms+ + recreation area + specialized rooms” forms closed circuits around the main functional zones. Each wing includes a sports block, while the ground floor accommodates a catering unit with a dining hall and separate cloakrooms for each educational level, reducing counter-flows during breaks and lunch periods.

Administrative offices and teachers' co-working spaces are positioned along the façade, ensuring convenient visual supervision of student flows and quick access to the educational cores. Recreational and co-working areas (highlighted in green) are located inside the learning clusters rather than in corridor remnants, creating conditions for informal interaction, project work, and socialization. Standard and specialized classrooms are indicated by separate pictograms with levels of provision – low, medium, and high. At the bottom of the diagram, urban planning connections are shown: distinct entrance groups, links to the street network, and the possibility of phased operation, allowing school blocks, sports, and assembly halls to function autonomously and serve the local community beyond school hours (Fig. 3). In the proposed model, spatial organization is directly correlated with the types of intelligence identified by Gardner. For each area of development, the authors have identified corresponding school spaces: While all aspects are important for learning, particular emphasis is placed on the practical application of knowledge within mathematics classrooms, where students can solve complex problems and apply theoretical

concepts in practice. Additional spaces such as logic corners, robotics and programming laboratories, and mathematical project rooms can complement these core areas. According to the theory, the development of linguistic intelligence requires not only specific criteria but also specialized types of spaces that can stimulate this form of intelligence. Examples include language classrooms, literary corners, creative writing studios, spaces for linguistic games and problem-solving, literary discussion clubs, and recording studios. Bodily-kinesthetic intelligence is cultivated through physical activity, dance, games, coordination exercises, as well as practices of meditation and yoga. The corresponding spatial types include gyms, dance studios, interactive play zones, outdoor yoga and fitness areas, and studios for creative workshops. Naturalistic intelligence develops through experimentation and observation, as well as through the study of biology, geography, astronomy, chemistry, and physics, including field research, botany, and zoology. Specialized spaces such as astronomical observatories, zoological corners, winter gardens, and educational gardens play a key role in this process, as they immerse students in the natural environment



Fig. 3. Proposed architectural and planning model of the school (Astana)

and foster systemic ecological thinking. Intrapersonal intelligence evolves through self-awareness and reflection, emotional literacy, meditation and relaxation practices, independent research, and participation in discussion circles. Spaces that support these activities include psychological consultation rooms, centers for self-awareness, meditation rooms, and studios for creativity and self-expression. Digital intelligence is shaped through interaction with information and communication technologies, the development of digital literacy, programming, and critical thinking in media environments. Spatially, this manifests in IT laboratories, multimedia classrooms, VR and AR studios, digital fabrication labs, and cybersecurity zones, where students learn the principles of working with data and digital tools. Visual-spatial intelligence develops through visual arts, geometric constructions, three-dimensional modeling, virtual reality, and cartographic studies. Classrooms for graphic programming and design consultations, art studios, laboratories for 3D modeling and virtual environments, and spaces dedicated to geometry and cartography contribute significantly to this process. Interpersonal intelligence is enhanced through group projects and collaborative tasks, feedback training, communication workshops, and other forms of social interaction. Spaces designed for social games, teamwork, and collective exercises play an important role in nurturing interpersonal intelligence, extending students' opportunities for developing communication and cooperation skills. Furthermore, it should be noted that certain criteria for developing different types of intelligence can be effectively combined and balanced within a single educational space. For example, the use of interactive multimedia technologies in classrooms can simultaneously promote the development of both logical and visual-spatial intelligences. Such flexible environments contribute to a more holistic and comprehensive development of students, allowing them to acquire diverse skills and competencies within a unified educational context. All of the above-mentioned forms of intelligence collectively contribute to the formation of meta-intelligence – the human capacity to be aware of, integrate, and manage multiple cognitive abilities within a unified process of thinking and learning. Meta-intelligence (from Greek “meta” – “beyond” and Latin “intellectus” – “understanding”) refers to the ability of an individual to consciously analyze and direct their own cognitive processes, turning thinking into an intentional tool for self-development and adaptation to complex environments. It is precisely meta-intelligence that enables a modern person to maintain critical thinking, creative initiative, and emotional resilience in an era when analytical and routine functions are increasingly being delegated to artificial intelligence.

Spaces such as social gaming areas and team-building training rooms play a crucial role in supporting

the development of interpersonal skills and collaborative competencies (Pak et al., 2023). It is important to note that some spatial criteria for the development of multiple intelligences can be successfully combined within a single educational space. For instance, interactive multimedia classrooms can simultaneously support the development of both logical-mathematical and visual-spatial intelligences. Such flexible environments contribute to a more comprehensive and holistic student development by enabling diverse skills and abilities to be cultivated within a unified educational context. The spaces in the proposed model are designed to be transformable, adaptable to different learning scenarios, and inclusive by design. Unlike the standardized educational spaces found in Model 1, Model 2 integrates recreational areas directly into the learning environment, promoting informal interaction and a diversity of educational trajectories. This architectural approach not only extends the functionality of the school building but also fosters an environment that supports the realization of each student's individual potential. Thus, the developed model demonstrates improved performance across key aspects — zoning, organization of student flows, provision of specialized and recreational spaces, architectural flexibility, inclusivity, and alignment with current pedagogical approaches. Model 2 represents a new typology of educational space — adaptive, multifunctional, and oriented toward the cultivation of multiple forms of intelligence. Depending on the specific educational objectives and specialization of the institution, it is possible to enhance certain types of intelligence by adjusting the types of spaces. For example, a school that emphasizes creativity and visual-spatial thinking may increase the number of creative and artistic studios for maximum effect. As emphasized by previous research: “Effective learning environments integrate technology and provide learners with opportunities for collaboration, creativity, and critical thinking” (Sanoff, 2001). “The interaction between physical space and educational practice is complex, but designing environments that support diverse learning needs can enhance educational outcomes” (Woolner, 2010). It is crucial to recognize that while some educational spaces can comprehensively support the development of multiple intelligences, others may be tailored to specific intelligences. For instance, multifunctional areas such as libraries or media centers offer students the opportunity to simultaneously develop various aspects of intelligence through a diversity of resources and activities.

PhD in Architecture, Associate Professor S. Sh. Sadykova (2022), in her article “Innovative Trends in the Formation of Internal Educational Spaces of New Schools in Kazakhstan,” emphasizes that the principle of universality and adaptability is one of the priorities in the design of school buildings. Such an approach not only ensures flexibility in the

use of premises but also contributes to expanding the functional composition of the educational environment, allowing the integration of various forms of academic, project-based, and extracurricular activities. The results of the present study correlate with the conclusions of S. Sh. Sadykova, yet develop them further in a more practical and spatial-typological dimension. The proposed model goes beyond the mere universalization of spaces and focuses instead on structural diversity and functional specialization of educational blocks, which enables the implementation of Howard Gardner's theory of Multiple Intelligences within the architectural environment of the school. PhD in Architecture T. A. Kiseleva (2019), in her dissertation "Development of the Network of General Education Institutions in the Urban Structure of Astana in the 19<sup>th</sup>–21<sup>st</sup> Centuries", highlights the urgency of modernizing Kazakhstan's education system to meet the challenges of contemporary society. Her research identifies the absence of a clear theoretical classification of specialized educational institutions, which often leads to unsubstantiated placement of such schools within the urban structure. In response, the author proposes a conceptual model for developing the network of general education institutions at the city level, introducing a new concept of the "specialized school". Unlike the "specialized school" model proposed by T. A. Kiseleva, the present research does not confine itself to a single type of institution. Instead, it explores a universal, systemic model that can serve as a design tool for various general education schools within the urban framework. In dissertation "Architectural and Planning Organization of a School Building in the Context of the Information Society (on the Example of Samara)", PhD in Architecture S. V. Poznyak (2009) focuses on the changing role of information in society and the increasing need for its independent acquisition. According to the author, these factors create prerequisites for forming in schools a developed informational environment with open access. The findings of S. V. Poznyak's dissertation resonate with our research in recognizing the school as a dynamic information – spatial system that reflects ongoing social transformations. However, unlike Poznyak's emphasis on the development of the informational environment and digital infrastructure, the present study interprets the architectural model more broadly as a cognitive-spatial structure aimed not only at informational but also at intellectual and social integration within the learning environment.

### Conclusions

The conducted study revealed that the existing architectural and functional structure of schools

in Astana largely reproduces modern standardized models that do not meet the requirements of contemporary education. Despite certain attempts to introduce new spatial solutions, most schools remain oriented toward the traditional classroom-lesson system and fail to account for the diversity of students' intellectual abilities. The analysis established that population growth and new teaching methodologies — aimed at developing a well-rounded individual — serve as the main catalysts for the transformation of school functional structures.

The research demonstrated that the architectural and planning structure of a school is a crucial instrument in shaping the educational environment and fostering personal development. The analysis of existing schools in Astana showed that typical design models largely preserve outdated organizational principles, failing to provide the necessary flexibility, specialization, and psychological comfort. The model developed by the authors focuses on distributing student flows according to age and functional zones, which significantly reduces the intersection of movement paths and enhances the ergonomics of the educational process. The increase in the number of specialized classrooms, such as laboratories, creative studios, scientific and digital rooms, contributes to the development of multiple types of intelligence and the formation of individual educational trajectories. Special attention is given to the creation of recreation and co-working zones integrated into the overall spatial structure. These spaces form an environment for informal communication, collaborative creativity, and knowledge exchange among students, teachers, and parents. Collectively, these elements transform the school from a static building into a flexible educational ecosystem that supports self-development and cooperation. From an urban planning perspective, the proposed model promotes the rational use of territory, the inclusion of schools within residential block structures, and the formation of local educational clusters. From a socio-economic standpoint, it increases the efficiency of space utilization (including previously underused areas such as basements), reduces operational costs, and enhances the public value of educational facilities. At the cognitive level, the model aims to develop multiple intelligences and meta-intelligence, ensuring a transition from a traditional monofunctional structure to a system that stimulates conscious thinking, self-organization, and interdisciplinary interaction. Thus, the school of the future appears as the architecture of eight intelligences, where space becomes an active participant in the educational process and a catalyst for the holistic development of the individual.

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## ШКОЛА СОВРЕМЕННОСТИ: АРХИТЕКТУРА ВОСЬМИ ИНТЕЛЛЕКТОВ

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### Аннотация

**Введение.** Архитектура школьных зданий играет важную роль в формировании образовательной среды и влиянии на учебные процессы. **Цель исследования:** Изучить, как архитектурная и пространственная организация современных школьных зданий в Астане может быть согласована с теорией множественных интеллектов, с целью выявления принципов планирования и стратегий проектирования, поддерживающих всестороннее интеллектуальное развитие учащихся по всем восьми типам интеллекта. **Методы:** В исследовании определены временные и территориальные границы, проведен анализ городской структуры, использованы методы полевых исследований, сбор и анализ архитектурной документации, а также обзор теоретических основ. Дополнительное внимание уделено методам взаимодействия, интерпретируемым как архитектурно-пространственные типологии коммуникации и стилистика окружающей среды, поддерживающие различные способы обучения и вовлечения. **Результаты:** Анализ показал, что существующие типологии школьной архитектуры в Астане преимущественно поддерживают лингвистический и логико-математический интеллект посредством традиционной планировки классных комнат. Однако архитектурные элементы, способствующие развитию других типов интеллекта — такие как музыкальные классы, художественные студии, открытые учебные зоны и гибкие пространства для совместной работы — присутствуют непоследовательно и часто маргинализированы в пространственной иерархии. В исследовании выявлены архитектурные особенности, коррелирующие с активизацией различных типов интеллекта, включая амфитеатральные пространства для собраний (межличностный интеллект), зеленые внутренние двory (натуралистический интеллект), мастерские (телесно-кинестетический интеллект) и модульные классные помещения (внутриличностный интеллект). На основе полученных результатов авторы предлагают модель планирования школы, ориентированной на развитие нескольких типов интеллекта, в которой функциональные зоны организованы таким образом, чтобы обеспечить пространственные стимулы, соответствующие каждому типу интеллекта. Эта модель демонстрирует потенциальное направление для переосмысления школьной архитектуры как адаптивной и инклюзивной образовательной инфраструктуры.

**Ключевые слова:** школьная архитектура; образовательная система; типы интеллекта; книжно-фронтальный метод; система «класс-урок»; комфортная среда; архитектурно-планировочные методы.

# Restoration and reconstruction

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## DECORATIVE HERITAGE IN TRANSITION: A STUDY OF THE IMAMZADEH ABDULLAH AND NAEIN'S JAME' MOSQUE

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### Abstract

**Introduction.** Imamzadeh Abdullah is located in the village of Koudzar, about 30 km from Arak and approximately 270 km from Tehran, Iran. Located on a hill north of the village, the Imamzadeh dates back to the Seljuk and Ilkhanid periods. The building is constructed of brick with a stone foundation, and while the exterior lacks decoration, the interior features intricate ornamentation. **Methods.** This article explores the developments in stucco and decorative arts during a specific period, using Imamzadeh Abdullah and the Jame Mosque of Naein as case studies. It highlights key findings from a comparative analysis of the decorative and architectural features of both structures, examining regional changes and artistic innovations. Despite its historical and artistic significance, Imamzadeh Abdullah has suffered extensive structural and decorative damage over the years. The building has undergone three major restoration phases since 1967, yet further efforts are needed to preserve its intricate stucco decorations and architectural integrity. Careful documentation and analysis of its decorative elements, alongside comparisons with similar structures such as the Jame Mosque of Naein, are essential for deepening our understanding of its architectural and cultural importance. **Results.** Through a comparative analysis with the Jame Mosque of Naein, this research traces the evolution of architectural decorations in Imamzadeh Abdullah, highlighting key stylistic developments and regional artistic innovations.

**Keywords:** acrography; Imamzadeh Abdullah; decorative arts; Kufic script; Jame Mosque of Naein.

### Introduction

The Seljuk period in Iran (11<sup>th</sup> to 13<sup>th</sup> centuries AD) is known as a period of artistic and architectural achievements. Architectural spaces show many innovations in form and function. Architectural decorations, although having developed in a monochrome form, incorporated complex structural elements within them, and the combination of structure and decorations is one of the prominent features of this period. Among the famous buildings of this period, the Grand Mosque of Isfahan shows the architectural developments of the Seljuk period well and is even referred to as the museum of Iranian architecture. This building, with its diverse stucco decorations and its large-scale four-iwan (porch) architecture, is known as a landmark in Seljuk architecture (Blair et al., 1994). Therefore, the Grand Mosque of Isfahan is known as an influential and guiding model in the architecture of buildings after it, which simultaneously incorporates engineering knowledge and the beauties of Islamic architecture (O'Kane, 1995). This study focuses on a specific type of stucco decoration made of plaster known as acrography, which was particularly prevalent in West Asian and West Asian architecture

(Nezhad et al., 2021; Shahbazi et al., 2019). This type of decoration is known for its detailed designs that have both aesthetic and symbolic significance. Acrography was commonly used in mosques, tombs, and palaces and included floral motifs, Arabic inscriptions in Kufic or Thuluth script, and complex and combined decorations. These decorations typically conveyed religious and cultural concepts in an artistic and mystical language specific to that particular region.

In Islamic architecture, acrography played a central role during the Seljuk and Ilkhanid periods, and the craftsmen of this art combined mystical concepts with earthly beauties (Golombek and Wilber, 1988). The methods of creating these decorations include carving, embossing, moulding, and combining it with natural colours and painting. This decorative style is very common in the mihrabs of mosques and shrines in Iran (Shekofteh, 2025). What is noteworthy about this decorative style is that it not only added aesthetic and visual quality to the space, but also had an acoustic application in the halls of mosques and prayer rooms (Karbaf and Ezaan, 2025). The enduring legacy of this decorative style emphasizes its importance

as a vital element of the architectural heritage of West Asia, embodying the technical skill and creative vision of the masters.

The name “Koudzar” is derived from the term “Koud”, meaning a mass or heap, typically referring to organic matter used for fertility (manure), and “Zar”, which signifies land or a place and, on its own, denotes gold (Amid, 2000). This etymology suggests a historical connection to agriculture, highlighting the village’s reliance on its rich local resources for fertile land and its deep-rooted agricultural heritage.

In the following sections of this article, a detailed and accurate analysis of the acrography found in Imamzadeh Abdullah will be addressed. These stucco decorations have a strong relationship with the decorative styles of the Seljuk and Ilkhanid periods and have significant similarities and developments with the building of the Jame Mosque of Naein. Through a comparative analysis of Imamzadeh Abdullah and the Jame Mosque of Naein, this study aims to identify stylistic and regional differences while examining the distinct ways in which plant motifs are represented in each building.

The aim of this study is to introduce and highlight one of the lesser-known structures of the same period, the Imamzadeh of Abdullah in Koudzar. Despite its outstanding architectural features and special decorations, this building has been less studied and ignored in academic societies and scientific communities, probably due to its specific geographical location and distance from political events. Since architectural studies have been in urban centres such as Isfahan and Rey, rural buildings have not been considered, despite their unique contributions to regional developments in design and construction.

### Methods

To conduct a detailed analysis of architectural decoration in West Asia, a dual research approach combining case study and comparative analysis was employed. The case study method enables an in-depth examination of specific buildings, such as the Imamzadeh Abdullah in Koudzar, with a focus on unique decorative elements and their restoration processes. This approach is widely utilized in architectural research to uncover subtle connections between form, function, and artistic expression (Hillenbrand, 1994; O’Kane, 1995).

Comparative study is a reliable method (Tang et al., 2010) because it provides a systematic assessment of the similarities and differences between architectural structures, styles or construction methods. By contextualizing case studies among different trends, it provides deeper insight into regional, historical and cultural influences. The method establishes patterns and innovations and highlights the connection between localities and global trends. Its application comprehensively

confirms the development of architecture across space and time.

Further elaborating on this research method, a comparative study allows researchers to juxtapose the characteristics of the case study with similar structures, such as the Jame Mosque of Naein, to draw conclusions about regional variations and broader architectural trends (Blair et al., 1994; Necipoğlu, 1996).

Recent research in this area increasingly relies on qualitative and analytical approaches to examine decorative motifs, emphasizing their aesthetic, cultural, and religious roots (Al-Mosawi, 2016; Esfahani, 2015). For instance, Azami et al. (2014) employed a comparative framework to investigate stucco motifs in Iranian mosques, successfully linking these decorative elements to their historical and symbolic significance (Azami et al., 2014). By integrating archival studies, on-site surveys, and stylistic comparisons, this methodology effectively fills gaps in the existing literature — particularly the limited representation of regional monuments. In doing so, it not only broadens our understanding of West Asian architectural decoration but also establishes a solid foundation for situating individual structures within the wider context of Islamic art and architecture.

### Literature Review

Decoration has always been a defining feature of Iranian and Islamic architecture, conveying both aesthetic expression and philosophical, cultural, and religious ideas. The background of the present research combines key studies on the evolution, practices, and significance of architectural decoration in the Islamic world with an emphasis on Iranian contributions.

The roots of architectural decoration trace back to pre-Islamic cultures, notably during the Sassanian era when stone murals and elaborate stucco work were widespread. In *The Formation of Islamic Art*, Grabar (1987) illustrates how Islamic architecture has appropriated these ancient traditions by blending new Arabic forms, geometric designs, and calligraphic elements with the principles of abstract and spiritual art (Grabar, 1987).

In his 1994 work, *Islamic Architecture: Form, Function, and Meaning*, Hillenbrand emphasizes the evolution from the simplicity of the early Umayyad period to the intricate decorative styles of the Abbasid, Seljuk, and Ilkhanid eras. Iranian architecture, renowned for its exquisite stucco, tile, and brickwork, reached its zenith during the Seljuk and Safavid periods (Hillenbrand, 1994).

Numerous scholars have extensively studied the evolution of Islamic architectural decorations, highlighting the influence of artistic traditions, cultural contexts, and technological advances (Al-Obaid, 2005; Azzaari, 2021; Graves, 2018;

Shafiq, 2014). Scholars such as Necipoğlu (1996) and Pope (1964) have undertaken a more in-depth exploration of the symbolic dimensions inherent in Islamic architectural decoration. Notably, Necipoğlu offers a focused investigation into the ways in which geometric patterns embody the Islamic worldview, serving as representations of unity, infinity, and divine order. This research highlights the interplay between mathematical precision and mystical abstraction, a hallmark of Islamic architectural ornamentation (Necipoğlu, 1996; Pope et al., 1964). In his work *Islamic Architecture of Iran in the Ilkhanid Period* (1955), Donald Wilber offers a comprehensive examination of the materials and construction techniques employed in Iranian architecture. He highlights stucco as a prevalent medium for intricate decorative work, with notable examples found in the Alavian Dome in Hamedan and the Jame' Mosque of Isfahan — both of which exemplify the exceptional craftsmanship of Iranian artisans (Wilber, 1955). Blair and her colleagues (1994) also address the evolution of architectural decoration during the Islamic period, emphasizing the advancements in tilework. They particularly note the widespread use of multi-coloured tiles during the Timurid and Safavid eras, identifying this development as a significant artistic achievement in the architectural traditions of the time (Blair et al., 1994). Golombek and Wilber (1988) demonstrate how local cultural and environmental factors critically informed the development of architectural ornamentation over time (Golombek and Wilber, 1988). They identify the Timurid period's hallmark in its expressive deployment of colour and monumental scale within mosaic tilework. In contrast, the Safavid era is characterized by its cohesive aesthetic unity, sophisticated compositional integration, and the artful intertwining of calligraphic motifs with stylized plant forms.

Scholars of Islamic architecture continue to investigate the study, restoration, and reinterpretation of period-specific ornamental programs (Abdullahi and Embi, 2015; Ahani et al., 2018; Bier, 2015). O'Kane (1995) emphasizes the importance of safeguarding traditional construction techniques within contemporary restoration initiatives, while recent research into digital modelling and reproduction methods offers practical frameworks for implementing and analysing decorative designs (O'Kane, 1995).

Comparative studies — most notably Azami et al. (2014) — have scrutinized decorative stucco motifs in Iranian mosques, interrogating the interplay between indigenous traditions and broader Islamic artistic currents. The Jame Mosque of Naein, for instance, illustrates this synthesis: its austere ornamental vocabulary, characteristic of the early Islamic centuries, is interwoven with vegetal motifs

derived from Sasanian precedents, thereby charting the diachronic evolution of decorative paradigms across distinct periods and regions (Azami et al., 2014).

Despite extensive scholarship, certain facets of Islamic architectural ornamentation remain underexplored, particularly in less prominent edifices. Rural Iranian sites, for instance, often manifest decorative traditions that diverge markedly from those prevalent in urban centres such as Isfahan and Shiraz (Faraji and Masoumi, 2023). Although geographically peripheral, these structures offer invaluable local perspectives on wider artistic discourses and architectural trajectories. Analysing their distinctive motifs, construction methodologies, and adaptations to indigenous materials and environmental contexts can illuminate previously overlooked dimensions of Islamic-period decoration and contribute to more inclusive historiographies.

Despite a substantial body of scholarship on Islamic architecture, specific lacunae remain. In particular, they are:

- 1) a dearth of rigorous studies on rural and regionally peripheral monuments;
- 2) a shortage of comparative analyses that trace stylistic and chronological continuities between the early Islamic and Ilkhanid decorative patterns;
- 3) limited technical documentation of stucco manufacture and application;
- 4) insufficient interdisciplinary work that integrates archival evidence, material analysis, and digital recording.

This study addresses those gaps by undertaking a case study of Imamzadeh Abdullah in Koudzar, paired with a comparative analysis of the Jame Mosque of Naein. Using archival research, in-situ survey, stylistic comparison, and digital documentation, the research aims to:

- 1) provide technical and chronological documentation of stucco ornamentation;
- 2) clarify regional stylistic variation and transmission between the early Islamic and Ilkhanid contexts;
- 3) situate these findings within broader social, religious, and material networks. In doing so, the project seeks not only to enrich our understanding of Islamic architectural ornamentation but also to contribute a more inclusive and evidence-based historiography that incorporates understudied regional monuments.

## Results

### *The Imamzadeh Building and Its Specifications*

Koudzar is situated 38 km southeast of Arak, along the Arak-Khomein highway, at an elevation of approximately 1,718 m above sea level in a mountainous, cold-climate zone (Fig. 1). The region's aridity and low annual rainfall severely limit its agricultural potential. Although a small stream



Fig. 1. Red dot shows the location of Koudzar in Iran (Author)

courses through the village, its flow is insufficient to meet all irrigation requirements and local water demands (Tali et al., 2016).

The village's strategic location near the crossroads has made it a transit point throughout history, which has fostered socio-economic interaction between neighbouring regions, although it remains somewhat distant from major cultural centres such as Tehran or



Fig. 2. A landscape view of the Imamzadeh Abdullah building (Photo by A. Moghaddasi)

Isfahan. The frigid, mountainous climate of Koudzar has shaped not only local agricultural practices but also the vernacular architecture. As in many rural settlements across Iran's highlands, buildings here have responded to severe winters and chronic water shortages by employing indigenous materials — primarily stone and mudbrick (Hillenbrand, 1994). Although this geographic isolation poses significant challenges, it has simultaneously fostered the preservation of traditional architectural typologies and cultural customs, offering a singular window into rural life on Iran's central plateau.

#### *The Imamzadeh Structure*

The Imamzadeh stands at the northern edge of the village, atop a hill now consecrated as a cemetery (Fig. 2). Its plan is octagonal, and it originally supported a double-shelled dome; currently, only the inner shell remains (Fig. 3). Historical accounts suggest that the outer shell took the form of a conical dome (Rok), a typology characteristic of Islamic-Iranian dome construction. Chronologically, the structure dates to the Seljuk period (12<sup>th</sup> century CE), with subsequent modifications in the early Ilkhanid era. Architecturally, it closely parallels the Imamzadeh Jafar in Isfahan (Fig. 4).

Archaeological evidence suggests that the main edifice was erected during the Seljuk period, while its stucco ornamentation was applied some two centuries later in the Ilkhanid era. This chronological interval between structural construction and decorative overlay underscores the building's palimpsestic history. Moreover, the enduring evolution of Iranian architectural traditions demonstrates that edifices have been continually adapted and refined in response to functional requirements, shifting aesthetic paradigms, and evolving religious practices (O'Kane, 1995; Pope et al., 1964).

The use of octagonal structures and double-shell domes is a distinctive feature of Seljuk architecture, which consistently uses geometric forms to convey structural complexity and visual harmony (Blair et al., 1994). The similarity of this building to the Imamzadeh of Jafar in Isfahan is an expression of common architectural motifs and possibly the influences of regional styles that were prevalent in central Iran during the transition from Seljuk to Ilkhanid (Wilber, 1955).

The Imamzadeh's primary structural fabric comprises brick masonry laid atop a rubble-stone foundation — an assemblage characteristic of Seljuk and Ilkhanid architectural typologies. The edifice rises to a height of 10 m and presents a total circumference of 24 meters; each facet of its octagonal plan measures 2.6 m, with wall thicknesses reaching 1.7 m. These proportions not only attest to the building's inherent solidity but also demonstrate a sophisticated understanding of load distribution and structural stability (Fig. 5).

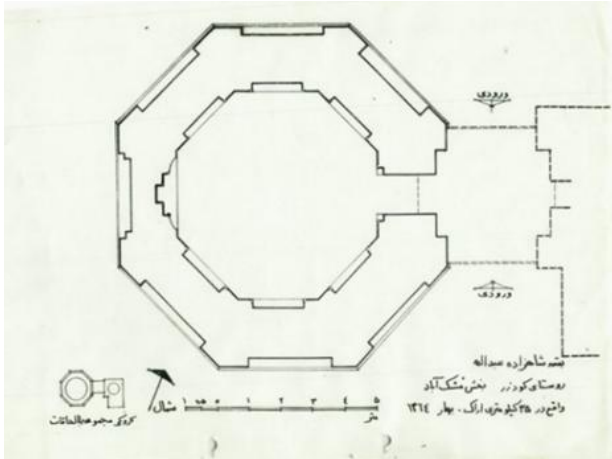


Fig. 3. Floor plan of the Imamzadeh Abdullah building (Source: Arak Cultural Heritage Documentation Center)

The selection of materials and construction techniques in the Imamzadeh structure reflects a strategic adaptation to local environmental conditions. Locally abundant brick was employed, its high thermal mass mitigating diurnal temperature extremes. Moreover, the foundation was reinforced

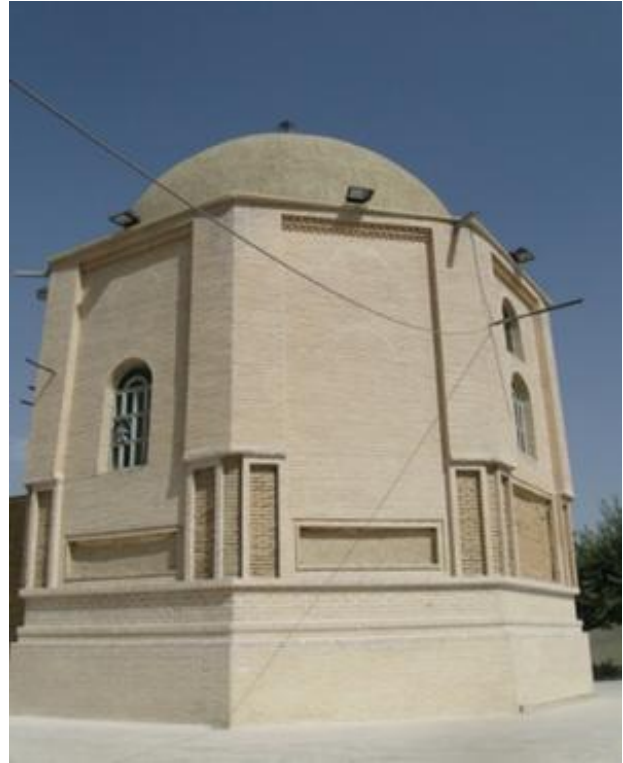


Fig. 5. Exterior view of the Imamzadeh (Photo by A. Moghaddasi)



Fig. 4. Imamzadeh Jafar in Isfahan (Photo by Ernst Emil Herzfeld)

with stone, a measure particularly suited to the region's cold, mountainous climate.

#### *Decorative Elements*

In contrast to the elaborate interior, the building's exterior brickwork is unadorned and austere. In 1967, local interventions applied a cement render to the facade, which further obscured original architectural details and compromised its historical authenticity. In contrast, the interior's stucco ornamentation remains exceptionally well preserved (Figs. 6 and 7). Regrettably, the exterior ornamentation has mostly succumbed to deterioration over time; however, the interior embellishments — emblematic of the Imamzadeh's artistic identity — remain intact.

A defining characteristic of Ilkhanid-period architecture is the extraordinary virtuosity exhibited in stucco craftsmanship. The prolific employment of diverse decorative techniques not only attests to the artisans' refined skill but also constitutes a central element of Islamic architectural aesthetics (Wilber, 1955).

The Imamzadeh's interior is adorned with elaborate stucco ornamentation — encompassing geometric configurations, floral motifs, and canonical Islamic iconography. These embellishments transcend mere decoration, functioning to elevate the spiritual ambiance, evoke a sense of transcendence, and foster a connection with the divine (Hillenbrand, 1994). The use of stucco here aligns with broader trends in Iranian architecture,



Fig. 6. Mihrab of the Imamzadeh Abdullah with Kufic script and Islimi designs (Photo by A. Moghaddasi)



Fig. 7. Islimi designs and geometric patterns on the wall of the building, with visible structural cracks. (Photo by A. Moghaddasi)

where ornamental programs serve as essential vehicles for communicating cultural narratives and religious affect.

Beyond their aesthetic function, the stucco ornamentation of this Imamzadeh offers critical insight into the intercultural artistic exchanges of the Ilkhanid era, a period marked by the intensification of Iranian, Mongol, and wider Islamic traditions (Grabar, 1987). The artistry and technical sophistication evident in these decorative elements reflect the presence of a vibrant artistic community, one that actively integrated diverse cultural influences into a unified and coherent architectural expression.

The Imamzadeh edifice functions not only as a landmark of architectural achievement but also as a tangible record of its era’s cultural heritage. Its robust masonry, coupled with the finely articulated interior stuccowork, attests to the site’s significance within the evolution of Iranian architectural practice. Continued scholarly inquiry, alongside targeted restoration and conservation initiatives, is essential both for safeguarding this invaluable resource and for deepening our appreciation of the artistic accomplishments of the Seljuk and Ilkhanid periods.

From a technical standpoint, the stucco ornamentation of this edifice is unrivalled in the region. Each interior surface is adorned with elaborate and

singular stucco reliefs, featuring complex geometric configurations and refined Islamic motifs that attest to the artisans’ exceptional skill and high degree of artistry. Moreover, the extensive deployment of stucco not only enhances the visual richness of the interior but also modulates its acoustic properties, fostering a serene environment conducive to contemplation and worship.

The most elaborately ornamented element of the structure is its mihrab, which serves as the building’s liturgical and visual focal point. This mihrab is adorned with delicate, flowing lines of ornamental Kufic script interwoven with stylized floral motifs, the precision of which attests to the artist’s mastery. Its intricate detailing invites comparison with celebrated examples such as the Oljeitu mihrab in the Jame’ Mosque of Isfahan. Beyond its decorative function, the mihrab embodies the symbolic nexus between the earthly and the divine, thereby enhancing both the sensory and spiritual experience of the worshippers.

*Analysis of Stucco Decorations: A Comparative Study of Geometric and Botanical Patterns in the Imamzadeh Abdullah and Jame’ Mosque of Naein*

In this section, we aim to conduct a detailed comparison of the stucco decorations in the Imamzadeh Abdullah building with the decorative patterns found in the Jame’ Mosque of Naein.

#### *Analysis of the Jame' Mosque of Naein*

In Fig. 8, captured by the author, the stucco decorations of the mihrab in the Jame' Mosque of Naein are characterized by distinctly Iranian motifs, infused with Sasanian influences. The stucco hemispheres at the center of the mihrab are notably substantial yet relatively simple. This decorative style later evolved during the Seljuk period and is often referred to as "high relief stucco work". An exemplary later manifestation of this can be seen in the dome of the Alavians in Hamedan, which traces its roots back to this period (Basiri, 2024). A noteworthy aspect of this mihrab is the absence of any inscriptions, and the arabesque designs have yet to achieve full maturity, with simple geometric forms, such as eight-pointed stars, prominently featured. The floral motifs visible in the upper section of the Figure represent a unique pattern within this architectural context (Fig. 8).

#### *Analysis of the Imamzadeh Abdullah*

Fig. 9 illustrates the mihrab of the Imamzadeh Abdullah in Koudzar. Here, the arabesques have reached a level of maturity, interwoven seamlessly with the mihrab, creating an inseparable visual and structural relationship. Notably, inscriptions have begun to find their place within the mihrab, with Kufic script merging harmoniously with the arabesque designs. Regarding the stucco hemispheres at the center of the mihrab, their volume and prominence

have diminished, yet their complexity and finishing have been enhanced, resulting in a more refined visual experience. The botanical forms also exhibit a more symmetrical arrangement, offering a balanced aesthetic.

#### *Geometric Patterns*

In Fig. 10, which depicts the geometric patterns on a column, a soft, circular movement can be observed, yet the floral motifs do not demonstrate the deep, complementary connection seen in later periods. This suggests the architect's intent during this era to merge geometric shapes, typical of Islamic design, with botanical motifs. Given that this building belongs to the early centuries of mosque construction, the lack of extensive practical experience in executing such designs likely means that the originality of the floral motifs largely retains its pre-Islamic characteristics.

#### *Advancements in Geometric Designs*

As shown in Fig. 11, the geometric patterns have reached a pinnacle, with a distinct differentiation observable among the geometric shapes. The circles maintain their original characteristics, and the polygons (star shapes) also reflect this. In contrast to the Jame' Mosque of Naein, soft movements within the geometric patterns are absent, suggesting that both the circular forms and the geometric designs have become firmly established in their



Fig. 8. Mihrab of the Jameh Mosque of Naein (Photo by A. Moghaddasi)



Fig. 9. Mihrab of the Imamzadeh Abdullah of Koudzar (Photo by A. Moghaddasi)



Fig. 10. A landscape view of the mihrab and decorations of the Jameh Mosque of Naein (Photo by A. Moghaddasi)



Fig. 11. Decorative patterns on the wall of the Imamzadeh Abdullah building (Photo by A. Moghaddasi)

respective placements. The floral motifs are so intricately intertwined with the geometric forms that each botanical element seems specifically tailored to a portion of this comprehensive pattern.

*Use of Inscriptions*

In Figs. 12 and 13, inscriptions appear in areas beyond the mihrab within this religious structure, predominantly situated above the arches and distinct from the geometric decorations. An additional point to note about these inscriptions is that the Kufic script used is embellished, making it quite challenging to read.

*Incorporation of New Scripts*

Finally, in Figs. 14 and 15, we observe that, in addition to the traditional Kufic script — long prevalent in Islamic architectural designs — the Thuluth script has also been introduced into the decorative elements of this period. This incorporation reflects an evolution in decorative practices and a broader exploration of calligraphy within architectural ornamentation.

**Discussion**

Although foundational scholarship has elucidated the historical, formal, and symbolic dimensions of Islamic ornamentation (Grabar, 1987; Hillenbrand, 1994; Necipoğlu, 1996) and comparative work has addressed prominent stucco motifs (Azami et al., 2014; Wilber, 1955), key gaps persist. Empirical reviews indicate that rural and regionally peripheral



Fig. 12. Decorative details of the Jameh Mosque of Naein (Photo by A. Moghaddasi)

monuments remain inadequately documented (Faraji and Masoumi, 2023); comparative, diachronic studies tracing stylistic continuities from the early Islamic through the Ilkhanid periods are limited; technical documentation of stucco manufacture and application is sparse; and interdisciplinary approaches that combine archival evidence, material analysis, and digital recording have been insufficiently applied (Al-Obaid, 2005; O’Kane, 1995). The present study addresses these deficits by pairing a focused case study of Imamzadeh Abdullah (Koudzar) with a comparative analysis of the Jame



Fig. 13. Folded Kufic inscriptions above the arches of the Jameh Mosque of Naein (Photo by A. Moghaddasi)

Mosque of Naein, employing archival research, systematic in-situ survey, stylistic comparison, and digital documentation. This combined methodology aims to produce technical and chronological records of stucco ornamentation, clarify regional patterns of stylistic transmission between early Islamic and Ilkhanid contexts, and situate decorative programs within broader social, religious, and material networks — thereby supplying empirical data and methodological precedent needed to broaden and substantiate the historiography of Iranian Islamic architectural decoration.

In addition, this study extended existing scholarship by demonstrating how focused regional analyses could reshape broader understandings of Islamic architectural ornamentation. By concentrating on an understudied rural monument and situating it within a comparative framework, the research highlighted patterns and relationships that had remained largely absent from mainstream architectural narratives. The findings showed that the decorative programme of Imamzadeh Abdullah not only reflected local craftsmanship and material constraints but also preserved stylistic transitions that were less visible in major urban monuments. This reinforced the argument that rural structures — despite their modest scale — offered critical evidence for tracing the diffusion, adaptation, and persistence of artistic forms across time.

### Conclusion

The study demonstrated that the stucco program of Imamzadeh Abdullah represents a distinct and technically sophisticated phase within the regional decorative repertoire: a coherent integration of geometric systems, vegetal motifs (notably grapevine foliage), and Kufic epigraphy that is concentrated and most fully realized in the mihrab. Close reading of stylistic, compositional, and technical features indicates that these decorative



Fig. 14. Thuluth script used in the mihrab of the Imamzadeh Abdullah of Koudzar (Photo by A. Moghaddasi)



Fig. 15. Flourished Kufic script in the mihrab of the Imamzadeh Abdullah of Koudzar (Photo by A. Moghaddasi)

interventions postdate the primary Seljuk structure and reflect a later, more mature decorative agenda consistent with Ilkhanid-period practice.

Comparative analysis with the Jame Mosque of Nain clarified the local trajectories of motif adoption and adaptation: while Nain preserves explicit continuities with Sasanian-derived vegetal forms (palm and grapevine), Imamzadeh Abdullah manifests a more advanced synthesis in which vegetal and geometric vocabularies are deliberately reconciled into unified compositions. This pattern supports a model of regional transmission in which peripheral monuments both conserve older iconographic stocks and serve as loci for stylistic elaboration. Crucially, these observations permit more secure relative dating of decorative phases

and underscore the importance of examining non-urban sites for reconstructing chronological and stylistic sequences.

Practically, the findings identify the mihrab and associated stucco panels as primary targets for conservation and further technical study. Material and microstructural analyses, together with expanded comparative sampling of rural monuments, would refine understanding of manufacture, chronology, and workshop practice. More broadly, the case of Imamzadeh Abdullah argues for the inclusion of regionally peripheral monuments in historiographic accounts of Iranian Islamic ornamentation, thereby enriching — and where necessary revising — established narratives derived predominantly from major urban ensembles.

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## ДЕКОРАТИВНОЕ НАСЛЕДИЕ В ПЕРЕХОДНЫЙ ПЕРИОД: ИССЛЕДОВАНИЕ ИМАМЗАДЕ АБДУЛЛЫ И МЕЧЕТИ ДЖАМЕ В НАЙНЕ

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### Аннотация

**Введение.** Имамзаде Абдулла находится в деревне Кудзар, примерно в 30 км от Арака и приблизительно в 270 км от Тегерана, Иран. Расположенная на холме к северу от деревни, Имамзаде относится к периодам Сельджуков и Ильханидов. Здание построено из кирпича с каменным фундаментом, и хотя снаружи отсутствует декор, внутри оно отличается замысловатым орнаментом. **Методы.** В этой статье рассматриваются изменения в лепнине и декоративно-прикладном искусстве в определенный период на примере мечети Имамзаде Абдуллы и мечети Джаме в Найне. В ней освещаются ключевые результаты сравнительного анализа декоративных и архитектурных особенностей обоих сооружений, рассматриваются региональные изменения и художественные новшества. Несмотря на свою историческую и художественную значимость, мечеть Имамзаде Абдуллы за эти годы сильно пострадала от структурных и декоративных повреждений. С 1967 года здание пережило три крупных этапа реставрации, однако необходимы дальнейшие усилия для сохранения его замысловатых лепных украшений и архитектурной целостности. Тщательная документация и анализ его декоративных элементов, а также сравнение с аналогичными сооружениями, такими как мечеть Джаме в Найне, необходимы для углубления нашего понимания его архитектурной и культурной значимости. **Результаты.** В данном исследовании, на основе сравнительного анализа с мечетью Джаме в Найне, прослеживается эволюция архитектурного убранства мечети Имамзаде Абдуллы, освещаются ключевые стилистические тенденции и региональные художественные новшества.

**Ключевые слова:** акрография; Имамзаде Абдулла; декоративно-прикладное искусство; куфическое письмо; мечеть Джаме в Найне.

## BALANCING THERMAL AND VISUAL COMFORT THROUGH MULTI-OBJECTIVE PARAMETRIC FORM OPTIMIZATION: A CASE FROM YAZD, IRAN

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### Abstract

**Introduction.** Building form plays a critical role in determining energy efficiency and occupant comfort, particularly in hot-arid climates such as Yazd, Iran. **This study proposes** a passive design strategy that leverages parametric modeling and simulation to optimize residential building forms for both thermal and visual comfort. **Methods.** A multi-objective genetic algorithm was employed to identify optimal geometric configurations across four different floor area scenarios (250, 350, 450, and 650 m<sup>2</sup>). Four primary form typologies — cubic, L-shaped, U-shaped, and O-shaped — were parametrically generated and evaluated using thermal performance metrics and daylight indicators. **The results** demonstrate that a rectangular cuboid with a shape factor of approximately 1.8, oriented along the north-south axis, consistently provides superior thermal comfort compared to other forms. Energy analysis revealed that the optimized configurations can reduce total energy consumption by up to 38.6 % while maintaining acceptable indoor environmental quality. This methodology supports data-driven decision-making in the early conceptual design phase, facilitating the development of context-sensitive, energy-efficient housing solutions in arid regions.

**Keywords:** multi-objective optimization; parametric form; thermal comfort; visual comfort; genetic algorithm; sustainable design; energy efficiency.

### Introduction

Buildings are fundamental to human life, serving as physical environments for a wide range of activities. However, the environmental footprint of the modern construction industry poses serious ecological concerns (Zou et al., 2021). As global efforts intensify to minimize the negative impact of buildings and enhance their benefits, energy efficiency has become a key objective for architects and urban planners. The energy crisis has been a focal point of scientific inquiry for decades, particularly because buildings account for approximately 36 % of final global energy consumption and 39 % of energy-related CO<sub>2</sub> emissions (Si et al., 2019). These figures underline the necessity of integrating energy-efficient strategies during the design process. Among all design stages, the conceptual design phase is the most critical, as it determines the majority of architectural decisions and holds the greatest potential for energy-saving outcomes (Fang and Cho, 2019).

Despite the growing implementation of active and passive energy strategies, these are often introduced after the initial design concept is developed (Feng et al., 2021). To achieve meaningful energy reductions, the form and geometry of buildings must be carefully

addressed early on through passive strategies, which can reduce the need for later active systems and significantly decrease operational energy consumption. Optimizing form during the conceptual phase not only enhances energy performance but can also significantly reduce annual energy use, particularly during peak demand periods.

The growing construction activities in hot-arid regions like Yazd have created unprecedented environmental challenges and energy demands (Moulaii et al. 2011). In hot-arid climates, passive cooling strategies are particularly crucial for sustainable thermal comfort. The vernacular architecture of Iran's hot-dry regions offers valuable insights into effective passive design principles. Studies of traditional buildings in cities such as Yazd, Kashan, and Isfahan have identified sophisticated passive cooling systems that work in harmony with the local climate (Izadpanahi et al., 2021). These include strategic shading through tall courtyard walls, earth coupling via deep basements, natural ventilation systems utilizing wind catchers, evaporative cooling through courtyard pools, and the strategic use of thermally massive materials like adobe. These integrated approaches created comfortable microclimates while minimizing energy

consumption (Foruzanmehr, 2015). Particularly in Dezful, underground spaces known as Shavadans demonstrate remarkable thermal performance, maintaining stable temperatures around 23–25 °C despite extreme outdoor conditions reaching 45–50 °C (Sadooghi et al., 2019).

Numerous studies have examined the influence of building geometry on energy consumption. For instance, Hemsath and Bandhosseini (2015) demonstrated that variations in building form can impact energy use as much as changes in material selection. With the advancement of computational tools, artificial intelligence, and optimization algorithms, designers are now able to generate and assess parametric design alternatives using performance-based criteria (Østergaard et al., 2016; Wortmann and Nannicini, 2017). This shift enables more informed decision-making in early design stages. The role of climate-responsive design becomes even more critical in hot-arid regions, where building performance is tightly linked to occupant comfort and energy demand. The city of Yazd, Iran, serves as an exemplary case due to its long-standing vernacular tradition in adapting to extreme climate conditions (Jamalpour and Arbaban, 2016). Historic courtyard houses in Yazd utilized compact, inward-focused forms to mitigate harsh solar exposure and high temperatures (Zarei and Mirdehghan, 2015). In contrast, many modern residential developments disregard these passive strategies, resulting in built environments that perform poorly in terms of thermal comfort and energy efficiency (Jamalpour and Arbaban, 2016).

The objective of the present study is to address this gap by investigating how parametric geometric configuration optimization, grounded in these proven passive design principles, can support the development of climate-adapted residential buildings in Yazd with enhanced energy performance. By combining environmental simulation with multi-objective optimization, the research seeks to propose high-performance building forms that balance thermal and visual comfort while respecting the unique climatic and cultural context of the region.

This research builds upon a previous study conducted in Persian, which explored the conceptual design of energy-efficient buildings in Yazd using passive strategies (Moulaii and Younesi, 2025). The current study expands that work by integrating a multi-objective optimization approach, considering both thermal comfort and daylight performance, to generate a set of optimal design solutions. By applying adaptive thermal comfort models and daylight simulation indices (UDI), the study aims to assist decision-making in the early stages of architectural design, providing a foundation for further passive strategies such as window sizing, shading, and thermal mass considerations. Furthermore, the study quantifies

the energy-saving implications of these geometric optimizations, providing economic justification for implementing passive design strategies.

## **Materials and Methods**

### ***Research Framework and Objectives***

A considerable body of research has focused on optimizing building form for enhanced energy performance and occupant comfort. In a 2020 study, an intelligent control algorithm was employed to design and simulate an optimized HVAC system using Fanger's comfort model and a genetic algorithm (Mohammed et al., 2020). A 2016 study introduced a novel performance-based optimization framework for passive design strategies during early architectural phases, targeting parameters such as daylighting, solar control, and natural ventilation (Konis et al., 2016). Similarly, 2021 research utilized a simulation-optimization approach to minimize energy consumption in residential buildings using RIUSKA simulation software (Feng et al., 2021).

However, these studies often focus on specific systems or later design stages. A significant research gap remains in the comprehensive optimization of the initial building form and orientation — the very foundation of passive design — particularly for hot-arid climates. This research addresses this gap by developing an integrated methodology for optimizing vernacular residential buildings in Yazd's hot-arid climate, aiming to generate optimal building forms that balance thermal and visual comfort while providing foundational solutions for subsequent passive strategies.

### *Literature Review and Theoretical Foundation*

#### *Passive Design and Climate-Responsive Architecture*

Recent systematic reviews have demonstrated that integrating traditional wisdom with modern technology offers the greatest potential for achieving sustainable thermal comfort (Manshour and Lehmann, 2025). Studies of vernacular architecture in various Iranian climates, including mountainous regions (Bahramifar et al., 2021) and hot-humid areas (Mohammadia et al., 2018), confirm that passive strategies such as compact urban fabric, proper orientation, semi-open spaces, and high thermal mass materials can reduce cooling energy consumption by 26–46 % and decrease discomfort hours by 12–34 %.

Traditional Iranian architecture, based on five principles of “Introversion”, “Autonomy”, “Human-conformity”, “Structure and Modulation”, and “Purposefulness” (Shahamat, 2014), shows complete conformity with sustainable architecture principles. Passive design strategies tailored to specific climatic contexts have been extensively optimized, as demonstrated by a 2020 case study in Morocco that applied Pareto front optimization to enhance thermal insulation and building mass

using local bioclimatic charts (Ameur et al., 2020). In China, a 2017 study optimized passive design features for hot summers and cold winters using NSGA-II and Artificial Neural Networks to explore 37 design variables (Gou et al., 2017).

#### *Parametric and Multi-Objective Optimization*

The integration of parametric design with multi-objective optimization has been widely explored. The H.D.S. Beagle prototype platform combined computational parametric modeling with performance-based analysis for iterative design exploration (Gerber and Lin, 2013). Parametric tools like Grasshopper and its Octopus plugin have been employed to balance daylight and thermal performance through strategic skylight placement (Shahbazi et al., 2019). Other studies have optimized building form, envelope, and shading systems using EnergyPlus and GenOpt with Particle Swarm Optimization (Lu et al., 2017).

Advanced optimization frameworks have demonstrated that parametric optimization processes can explore extensive design alternatives, automatically identify optimal solutions, and significantly improve building performance across different climate zones. Multi-objective optimization methods have proven superior to single-objective approaches in building performance optimization. Research showed that while multi-objective optimization might increase total energy consumption by 2.9–11.3 %, it can dramatically reduce thermal discomfort (PPD) by 49.1–56.8 % (Delgarm et al., 2016). This multi-objective approach enables the identification of design solutions that not only enhance occupant comfort but also optimize energy performance — a critical factor in design decision-making. Similarly, studies optimizing windows and shading systems have demonstrated that proper configuration can reduce total energy consumption by up to 26.7 % while improving thermal comfort (Sun et al., 2021). Building on this foundation, the current study extends energy performance optimization to the fundamental level of building form and geometry, examining how these primary design decisions can achieve even greater energy savings through integrated passive strategies.

#### *Daylight and Thermal Comfort Optimization*

Optimizing daylight and thermal comfort simultaneously has attracted significant attention. A 2019 simulation-based study in Tehran assessed optimal window-to-wall ratios, finding that 25–35 % on southern façades provided the best balance between daylight access and thermal load (Motazedian, 2019). Further studies explored automated window control systems and intelligent thermal comfort prediction algorithms for enhanced energy performance (Stazi et al., 2017, Tang and Wang, 2019).

The present study leverages these findings by establishing an optimized building form and

orientation as a foundational step, which subsequently informs and constrains the design parameters for elements such as windows and shading, which are explored in later stages of the design process.

### **Methodology**

#### *Overall Research Framework*

The optimization framework for a single-story residential building was developed through the following three main phases:

1) **Parametric Modeling.** A parametric model of the building was constructed, where key design variables — such as aspect ratio, courtyard placement, and orientation — were defined, and their ranges were determined based on the local climatic conditions and design constraints.

2) **Energy and Daylight Simulation.** Energy performance and daylight availability were simulated under the hot and dry climate of Yazd.

3) The operative temperature during the summer was calculated using the Adaptive Thermal Comfort Model, assuming no mechanical ventilation.

4) The Useful Daylight Illuminance (UDI) was computed to evaluate daylight performance throughout the year.

5) The objective in this phase was to minimize the average operative temperature during the summer and to maximize the annual average UDI.

6) **Multi-objective Optimization.** The design variables and performance metrics were integrated into a genetic algorithm-based multi-objective optimization process. The goal was to identify optimal building forms that enhance both thermal and visual comfort. The overall process of the optimization workflow is illustrated in Fig. 1.

#### *Parametric Form Modeling*

Parametric modeling was employed using Grasshopper (within Rhinoceros 3D) to generate a set of cube-based architectural forms (Fig. 2). This approach supports exploration of multiple configurations prior to final design selection (Lucarelli et al., 2020).

Cubic geometries were selected due to their prevalence in global architecture (Steadman, 2006) and vernacular residential structures in Yazd (Zarei and Mirdehghan, 2015). Each form was created by subtracting a movable smaller cube from a fixed-volume base, with variable dimensions and orientation relative to geographic north (Fig. 3).

Four typologies — Cubic, L-shaped, U-shaped, and O-shaped — were developed while maintaining constant horizontal cross-sectional area across four floor area categories (250, 350, 450, and 650 m<sup>2</sup>), based on local housing data. To eliminate impractical designs, constraints were applied regarding aspect ratio (0.25–4), minimum external wall distances ( $\geq 3$  m), and a fixed height of 3.5 m. Due to differing parametric inputs, models were executed independently for each form type. Table 1

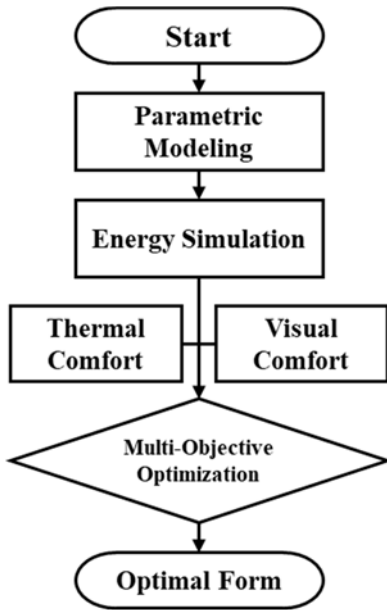


Fig. 1. The workflow for identifying the optimal configuration

and Table 2 illustrate representative forms and parameter sets, and the modeling workflow is shown in Fig. 4.

*Building Energy Simulation*

Building geometry plays a crucial role in optimizing energy consumption (Omrani and Marsono, 2015). This study employs energy simulation using Honeybee and Ladybug plugins (version 1.5.0) to evaluate the impact of architectural

form variables on heating and cooling demand. The key variables used in this study are briefly described in Table 3.

The simulations utilized the ‘HB Construction Set by Climate’ component, which automatically assigns building envelope properties based on climate zone and building vintage according to ASHRAE 90.1 standards, ensuring reproducibility and compliance with industry norms. The specific settings used were as follows:

- Climate Zone: Climate Zone 2B (Hot - Dry);
- Building Vintage: ASHRAE 90.1 - 2019 and IECC 2021;
- Construction Type: Steel Framed.

Based on these inputs, the Honeybee engine automatically assigns a complete set of constructions for all envelope components, including insulated walls and double-glazed windows with low solar heat gain coefficients appropriate for hot climates. This configuration ensures envelope properties — such as wall U-values (~0.332 W/m<sup>2</sup>K), window U-values (~3.24 W/m<sup>2</sup>K), and solar heat gain coefficients (SHGC ≤ 0.25) — comply with ASHRAE 90.1–2019 requirements for Climate Zone 2B, representing typical energy-efficient construction for hot-dry climates. The simulation incorporates zoning, climate

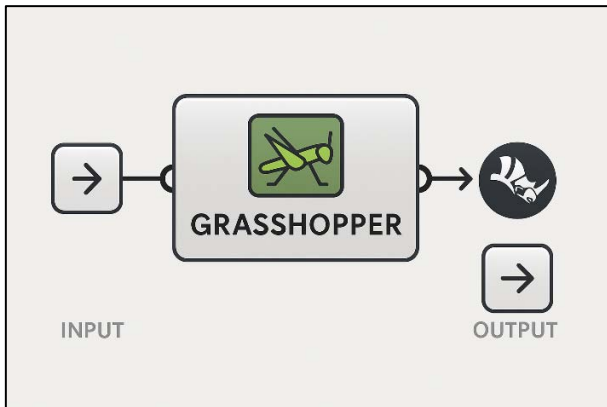


Fig. 2. Software used for computational parametric modeling approach

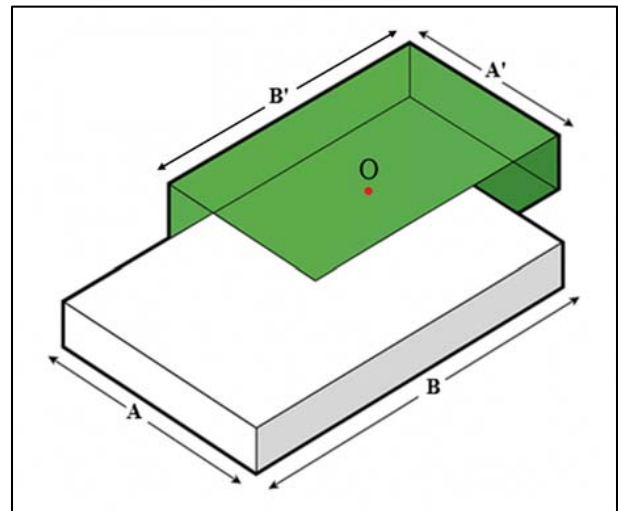


Fig. 3. Sample parametric form: A = width of the main cube, B = length of the main cube, A' = width of the subtracted cube, B' = length of the subtracted cube, O = center point of the subtracted volume in the plan

Table 1. Examples of general form types achievable through computational parametric modeling approach

Cube	L-Shape	U-Shape	O-Shape

Table 2. Required parameters for each form category

Form Type	Orientation (°)	Main Cube Length (m)	Subtracted Cube Length (m)	Subtracted Cube Width (m)	Sub cube Center X (m)	Sub cube Center Y (m)
Cube	✓	✓	—	—	—	—
L-Shape	✓	✓	—	—	✓	✓
U-Shape	✓	✓	—	✓	✓	✓
O-Shape	✓	✓	✓	✓	✓	✓

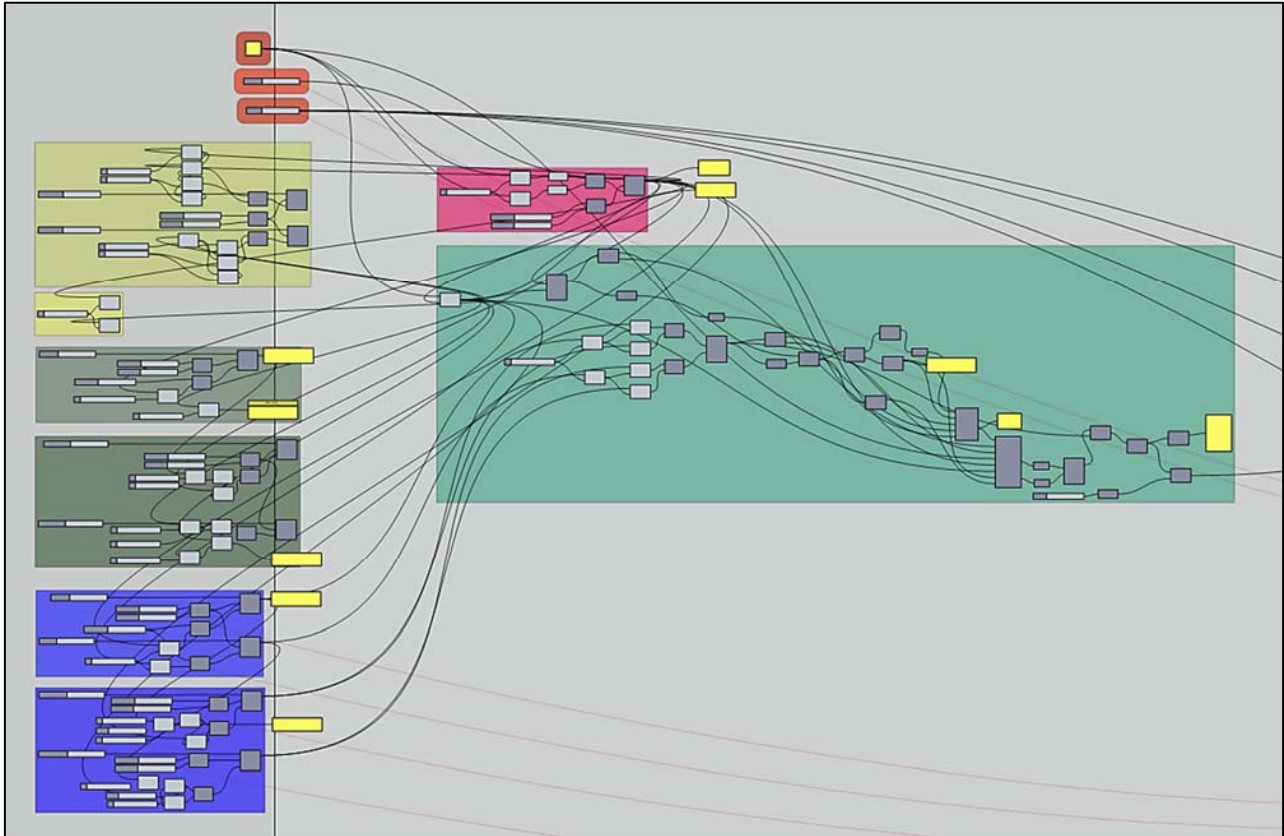


Fig. 4. General schematic of the computational parametric modeling approach process

Table 3. Form and shape-related variables used in the study

Variable	Definition	Example of Application
<b>Compactness Index</b>	Ratio of a building's volume to its exterior surface area	Bekkouche et al. (2013) examined the impact of compactness on thermal behavior in hot-arid climates. Their findings showed that increased compactness improves indoor thermal comfort.
<b>Shape Factor</b>	Ratio of building length to width	Aksoy and Inalli (2006) showed that optimizing shape and orientation can reduce heating energy demand by up to 36 %. Mingfang (2002) studied how variations in length, depth, and width influence solar gains in tubular buildings.
<b>Building Orientation</b>	Angle between the building's transverse axis and geographic north	Faizi et al. (2011) analyzed orientation effects using Ecotect software and found that a 0° alignment provides optimal solar exposure in Tehran

settings, and window configurations, with the building type set as “apartment” — representing a standalone residential unit. The analysis utilizes ASHRAE 90.1 2019 and IECC 2021 data for accurate assessment. The results from the building envelope energy modeling serve as key inputs for thermal and visual

comfort simulations. This configuration ensures high-performance assemblies typical for hot climates, including insulated walls and double-glazed windows with low solar heat gain coefficients. An overview of the building envelope energy simulation process in Grasshopper software is presented in Fig. 5.

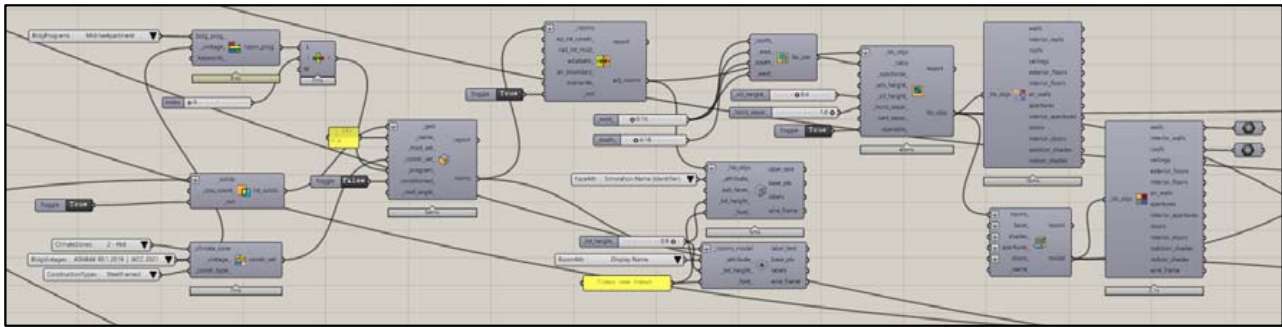


Fig. 5. Building energy simulation section

Considering that climatic data for Yazd is essential for the simulation section of this study, a brief description of the studied climate is provided here. Climate Context — Yazd, Iran: Given that energy simulations in this study are tailored to the local conditions of Yazd, a concise understanding of its climate is essential. Yazd is located in central Iran (latitude:  $\sim 32^\circ \text{N}$ , elevation: 1220 m above sea level), classified as BWh (hot desert climate) according to the Koppen system (Jahanbakhsh and Esmaeelpour, 2004). The region is characterized by low annual precipitation (average  $\sim 56 \text{ mm}$ ), high evaporation rates, and very low relative humidity, particularly in the summer months, where it falls below 15%. The mean annual temperature is approximately  $20.5^\circ \text{C}$ , with summer highs exceeding  $40^\circ \text{C}$  and winter lows occasionally falling below freezing, resulting in an average of 33 frost days per year. Yazd also experiences over 3400 hours of sunshine annually, making solar radiation a significant factor in building energy performance. Seasonal rainfall occurs mostly in winter and early spring, while summer is extremely dry (Fallahpour, 2015). The dominant wind directions are from the west, northwest, and southeast, with an average annual wind speed of 2.4 m/s. In line with Jahan-Bakhsh and Esmaeelpour (Jahanbakhsh and Esmaeelpour, 2004), window-to-wall ratios (WWR) were set at 15% in energy simulation models, reflecting vernacular design strategies for hot arid climates, where minimal window area helps reduce cooling loads. Yazd's extreme climate conditions emphasize the importance of passive design elements, making it a relevant testbed for this study's parametric simulations.

#### *Thermal Comfort*

According to the study by Orosa and Oliveira (2011), in naturally ventilated buildings, the Adaptive Model provides a more accurate prediction of thermal comfort compared to the PMV (Predicted Mean Vote) index, which is more suitable for buildings equipped with HVAC systems. Given that the present study considers only natural ventilation, the Adaptive Model was employed to evaluate indoor thermal comfort. Humphreys and Nicol (1988)

investigated human thermal neutrality, defining it as the temperature at which individuals feel thermally neutral or "comfortable". Their findings, based on laboratory and field studies, led to the development of the Adaptive Model through regression analysis.

In this study, thermal comfort was calculated using the Adaptive Comfort component within the Honeybee and Ladybug plugins for Grasshopper, linked to the building energy simulation outputs. Sensors were distributed across a 1-meter grid, positioned 20 centimeters above the floor level, to collect operative temperature data for optimization purposes. Thermal comfort conditions in Yazd were evaluated based on the study by Jahanbakhsh and Esmaeelpour (2004). At night, thermal comfort is typically achieved only during June, July, and August, while other months are characterized by cool or cold nighttime conditions. During daytime, April and October offer comfortable conditions, whereas the summer months (June to August) present extreme heat. Regarding building orientation, Fallahpour (2015) found that the majority of residential complexes in Yazd are oriented either north-south or northwest-southeast. North-south oriented buildings are less exposed to strong seasonal winds but receive higher solar radiation during the hot season, while northwest-southeast orientations provide a balanced solar exposure but are more influenced by prevailing winds. Based on meteorological data from Shahid Sadoughi Airport, the hottest week of the year typically occurs between July 3 and July 9, and the coldest week between January 11 and January 17. Therefore, thermal comfort simulations in this study focused on daytime hours (8:00 a.m. to 6:00 p.m.) during the hottest week of the year to represent critical thermal stress periods. Fig. 6 illustrates the thermal comfort simulation framework implemented in Grasshopper.

#### *Visual Comfort*

Visual comfort is defined as a mental response to the quantity and quality of light in a given space. In this study, Useful Daylight Illuminance (UDI) was utilized as the primary metric for visual comfort evaluation. UDI calculates the annual occupied hours during which daylight levels fall within the

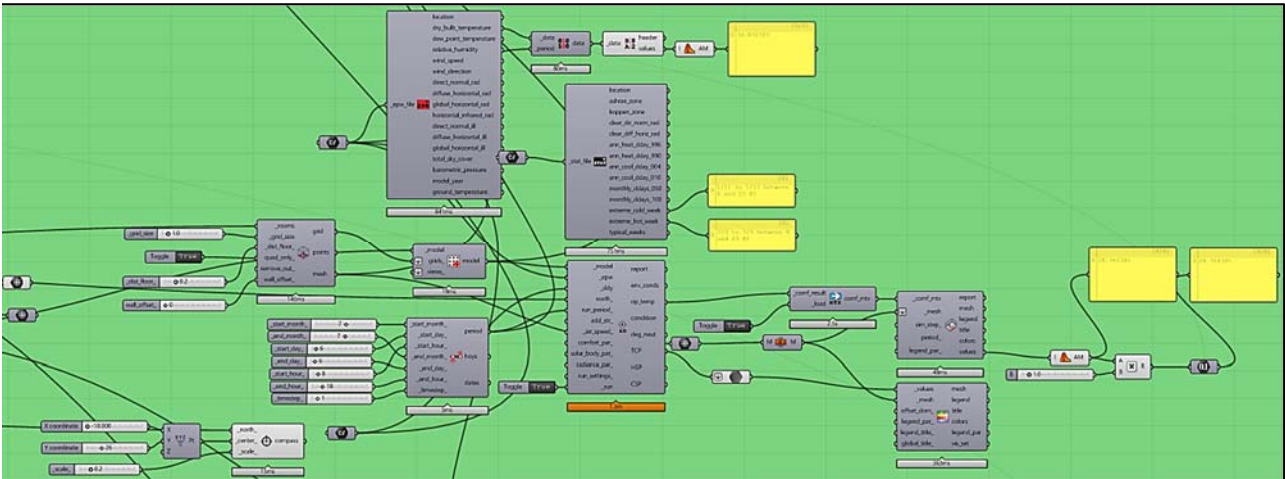


Fig. 6. Thermal comfort section

range of 300-3000 lux, ensuring optimal lighting and preventing visual discomfort (Rana et al., 2021). The calculations were conducted using the Annual Daylight component of the Honeybee Radiance plugin, integrated with building energy simulation outputs (Shafavi Moghaddam et al., 2019). The assessment timeframe included all days of the year between 8 a.m. and 6 p.m., with the goal of maximizing UDI to optimize daylight utilization and reduce energy consumption. Fig. 7 illustrates the thermal comfort simulation framework implemented in Grasshopper.

Table 4 presents the average operative temperature and UDI values, along with thermal and daylight visualizations on the floor plan, for 10 randomly generated L-shaped plan samples with varying parameters. These samples are based on the climate of Yazd and a total floor area of 650 m<sup>2</sup>. The average values obtained from these random samples are used as a reference for comparison with the optimal configurations derived from the optimization process.

#### Optimization

Optimization for four primary forms was carried out individually using a genetic algorithm through the Octopus plugin in Grasshopper software. Octopus is a Grasshopper plugin used

for optimization processes. It employs genetic algorithms for single or multi-objective optimization and enables users to select diverse parameters, enhancing the search space for solutions. In addition to allowing users to define population size and the maximum number of generations prior to optimization, it prevents process interruptions when encountering infeasible solutions by moving to the next solution after reaching a maximum runtime (Lucarelli et al., 2020). The tool generates a Pareto front of optimized points at the end of the process, from which users can select the most suitable solutions based on their requirements. In this study, the Octopus plugin was used to optimize the form of a single-story residential villa. The mean annual UDI (Useful Daylight Illuminance) and mean operative temperature were defined as objectives, while the design parameters described in the parametric section (Table 2) were assigned as genes. The goal was to achieve dual-objective optimization: minimizing operative temperature and maximizing UDI for the four selected forms across various building footprint sizes, considering the hot and arid climate of Yazd. The endpoints of the Pareto optimization graph represent the minimum operative temperature during the hottest week of the year and the maximum annual UDI (Fig. 8).

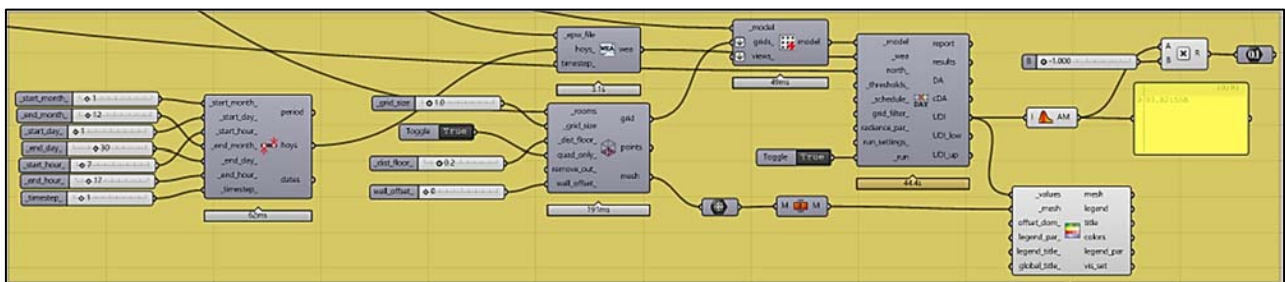
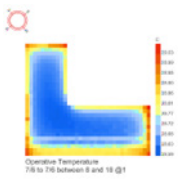
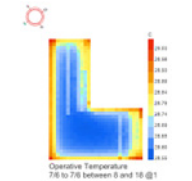
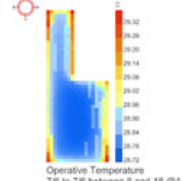
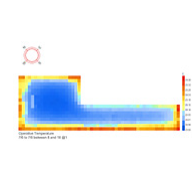
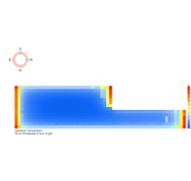
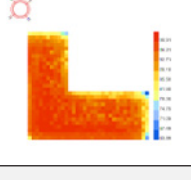
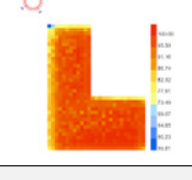
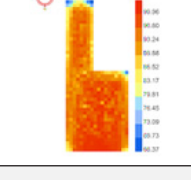
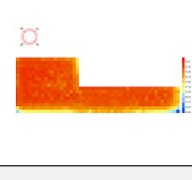
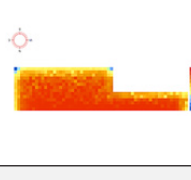
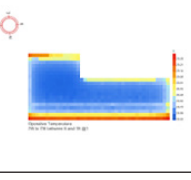
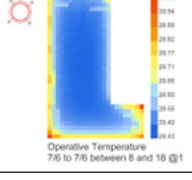
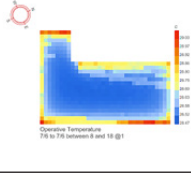
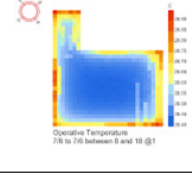
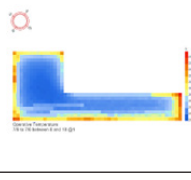
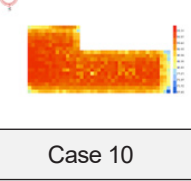
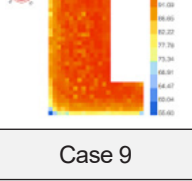
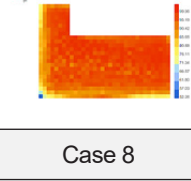
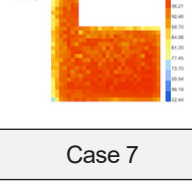
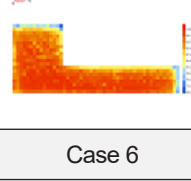


Fig. 7. Visual comfort section

Table 4. Operative temperature and UDI averages for 10 random L-shaped plans in Yazd Climate

					Operative Temperature
					UDI
Case 5	Case 4	Case 3	Case 2	Case 1	Case Description
Average Op. Temp.: 28.8 Average UDI: 94.2	Average Op. Temp.: 28.8 Average UDI: 93.4	Average Op. Temp.: 28.9 Average UDI: 93.3	Average Op. Temp.: 29.1 Average UDI: 92.8	Average Op. Temp.: 28.6 Average UDI: 93.7	
					Operative Temperature
					UDI
Case 10	Case 9	Case 8	Case 7	Case 6	Case Description
Average Op. Temp.: 28.8 Average UDI: 93.8	Average Op. Temp.: 28.5 Average UDI: 93.5	Average Op. Temp.: 28.6 Average UDI: 93.5	Average Op. Temp.: 28.6 Average UDI: 94	Average Op. Temp.: 29.1 Average UDI: 93.9	

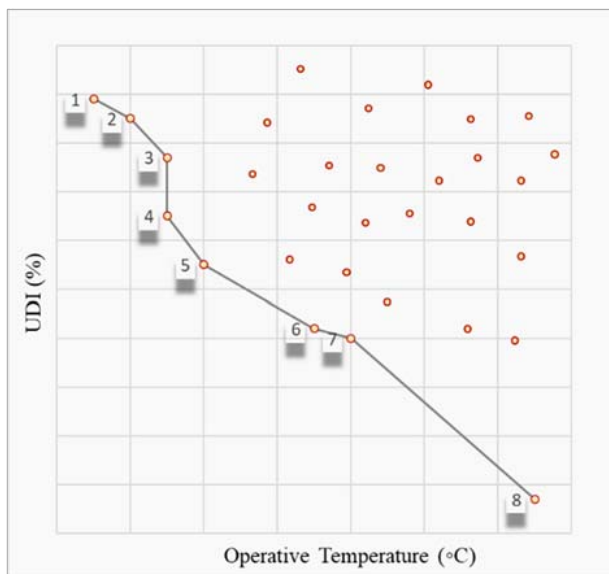


Fig. 8. An example of a Pareto front diagram and its extreme points generated by the Octopus plugin (Point 1: the start of the Pareto curve indicating the minimum operative temperature; Point 8: the end of the Pareto curve indicating the maximum UDI)

Optimization parameters:

- Initial population size: 85;
- Termination condition: 5 generations;
- 50 % elitism selection;
- 30 % mutation probability;
- 80 % mutation rate (to ensure extensive evaluation of solutions);
- 80 % crossover rate.

Results

Multi-objective optimization was performed to minimize the average indoor operative temperature during the hottest week of the year and to maximize the annual average UDI for four different floor areas (250, 350, 450, and 650 m<sup>2</sup>) in Yazd’s hot-arid climate. Considering four base form) cube, L, U, and O (the optimal points at both ends of the Pareto front (representing minimum operative temperature and maximum UDI) are reported in Tables 5, 6, 7, and 8. These tables present detailed geometric parameters, performance metrics, and derived indicators including compactness index and shape factor values. For energy performance analysis comparing all optimized configurations

Table 5. Optimization results for cubic form

Area (m <sup>2</sup> )		Pareto Points	Average Op. Temp (°C)	UDI (%)	Building Orientation (0° to 360°)	A(m)	B(m)	Compactness Index	Shape Factor
250	Start	29.07	92.86	178	11.96	20.89	3.802	1.764	
	End	29.42	93.13	132.8	19.13	13.06	3.880	0.682	
350	Start	28.66	93.66	178	13.82	25.31	4.469	1.831	
	End	28.94	93.87	220	17.97	19.47	4.672	1.083	
450	Start	28.37	93.92	180.3	15.59	28.86	5.061	1.851	
	End	28.38	94.08	176.8	15.85	28.37	5.084	1.789	
650	Start	27.99	94.31	179.3	18.94	34.31	6.101	1.811	
	End	27.99	94.31	179.3	18.94	34.31	6.101	1.811	

Table 6. Optimization results for L-shaped form

Area (m <sup>2</sup> )		Pareto Points	Average Op. Temp (°C)	UDI (%)	Building Orientation (0° to 360°)	A (m)	B (m)	C (m)	D (m)	Compactness Index
250	Start	29.15	93.23	180.3	12.71	15.84	3.71	5.37	3.681	
	End	29.56	93.62	205.8	11.28	12.58	3.24	13.42	3.351	
350	Start	28.69	93.61	182	14.77	19.28	3.36	5.70	4.400	
	End	28.81	94.43	194	15.78	8.85	3.00	16.46	4.259	
450	Start	28.43	93.88	178.8	16.19	23.09	3.42	5.95	4.972	
	End	28.56	94.58	194.3	17.86	10.82	3.12	17.40	4.489	
650	Start	28.02	94.37	181.5	19.68	28.82	3.96	5.25	6.045	
	End	28.29	94.78	206.9	17.04	28.71	3.19	11.59	5.665	

Table 7. Optimization results for U-shaped form

Area (m <sup>2</sup> )		Pareto Points	Aver. Op. Temp (°C)	UDI (%)	Building Orientation (0° to 360°)	A (m)	B (m)	C (m)	D (m)	E (m)	F (m)	Compactness Index
250	Start	29.42	92.10	81.8	22.09	4.47	4.41	4.73	4.41	3.05	3.224	
	End	29.55	92.94	186.3	14.65	3.10	4.48	3.03	4.48	11.84	3.368	
350	Start	28.94	93.57	180	12.80	10.34	3.66	5.71	3.66	12.89	3.851	
	End	29.13	94.08	195	16.06	6.63	4.20	14.76	4.20	4.24	3.810	
450	Start	28.575	93.79	265.3	32.20	4.69	4.06	4.23	4.06	5.58	4.429	
	End	28.816	93.92	205	16.49	12.72	4.08	3.93	4.08	11.58	4.607	
650	Start	28.143	94.05	86.6	32.20	6.05	4.16	4.74	4.16	9.99	5.684	
	End	28.451	94.63	172.5	15.52	11.21	3.58	34.78	3.58	3.90	4.710	

against a suboptimal baseline, see Table 11 in the Discussion.

### Discussion

#### Thermal and Visual Performance Analysis

As previously mentioned, the ambient temperature during the hottest week of the year in Yazd reaches

approximately 35 °C. Table 9 presents a selection of suboptimal O-shaped configurations for a 650 m<sup>2</sup> floor area. While not representing the worst-performing cases, these examples illustrate the effectiveness of the optimization process. Compared to these cases, the optimized forms achieved

Table 8. Optimization results for O-shaped form

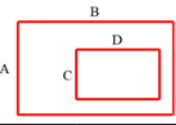


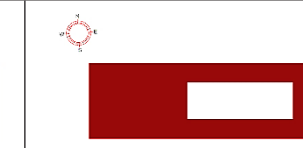

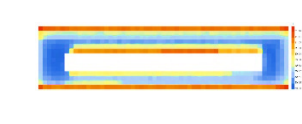


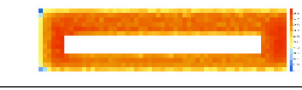
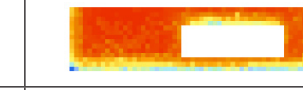
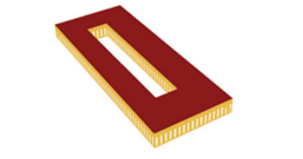
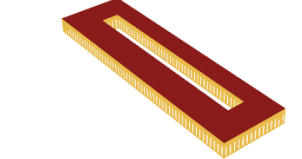
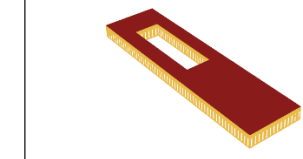
		O-Shaped Form									
Area (m <sup>2</sup> )	Pareto Points	Aver. Op. Temp (°C)	UDI (%)	Building Orientation (0° to 360°)	A (m)	B (m)	C (m)	D (m)	X-axis Coordinate of the Subtracted Cube Center (m)	Y-axis Coordinate of the Subtracted Cube Center (m)	Compactness Index
250	Start	29.53	91.18	98.2	22.63	11.46	3.13	3.05	5.37	15.67	3.101
	End	29.60	92.45	174.8	9.99	26.24	3.20	3.86	12.09	4.86	2.885
350	Start	29.02	93.01	186	13.74	26.25	3.21	3.38	18.50	8.87	3.755
	End	29.32	93.58	209	18.92	19.27	4.07	3.64	4.98	9.62	3.810
450	Start	28.66	93.51	273.6	29.15	15.74	3.00	3.00	10.66	15.07	4.419
	End	28.69	93.72	176.3	15.74	29.34	3.59	3.35	14.82	8.65	4.323
650	Start	28.30	93.89	169.2	17.31	38.24	3.27	3.75	18.63	9.17	5.191
	End	28.52	94.15	210	17.35	38.32	3.27	4.58	20.17	9.17	5.115

Table 9. Selected examples of suboptimal building form configurations designed for the hot-arid climate of Yazd, used for comparative analysis against the optimized models

			Top View of the Form
			Operative Temperature
			UDI
			3D View of the Form
Operative Temperature: 31 Useful Daylight Illuminance: 91.5	Operative Temperature: 30.4 Useful Daylight Illuminance: 91	Operative Temperature: 29.14 Useful Daylight Illuminance: 91.2	Configuration Details

reductions of approximately 2–3 °C in operative temperature and a 3–4 % increase in annual UDI, confirming the tangible benefits of the proposed optimization strategy.

Before discussing the results, it is essential to note that the validity of the findings was verified through three approaches:

1) Reference: Bekkouche et al. (2013), which provides a validated analysis framework for the city of Yazd and supports the quality of this study's outcome;

2) A comparative check against 10 randomly generated L-shaped forms with a floor area of 650 m<sup>2</sup> (as shown in Table 4), none of which yielded a lower operative temperature or higher UDI than the Pareto-optimal points derived through the optimization process;

3) Consistency with the findings reported in Reference (Fallahpour, 2015), which are further elaborated in the section discussing orientation results.

Fig. 9 illustrates the lowest operative temperatures achieved through the optimization of various building forms across different floor areas.

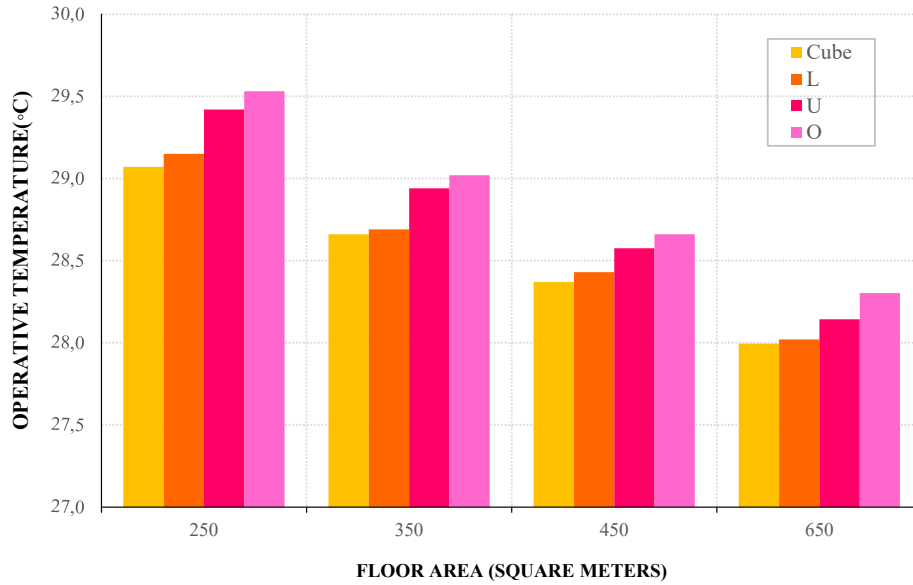


Fig. 9. Minimum operative temperatures from optimized forms across different floor areas in Yazd

This chart illustrates that, for each floor area category, the lowest operative temperature is achieved by the cube form, followed by the L, U, and O forms, respectively. It also demonstrates a consistent trend across all form types: as floor area increases, the minimum operative temperature achieved through optimization decreases. This indicates improved thermal comfort in single-story residential buildings with larger floor areas, with the cube form being the most effective in enhancing thermal comfort. Fig. 10 presents the compactness index of the forms with the highest thermal comfort for each floor area category, based on form type.

It can be observed that the highest compactness index for each floor area category corresponds to the cube form. Following that, the L, U, and O forms

respectively exhibit the next highest compactness values across all floor area categories. Moreover, there is a general trend showing that as the building floor area increases, the compactness index also increases. By comparing the results in Fig. 9 with those in Fig. 10, a meaningful relationship between the compactness index and thermal comfort in Yazd can be identified. Specifically, higher compactness values are associated with improved thermal comfort performance. This correlation was previously demonstrated by Bekkouche et al. (2013), who found a direct relationship between form compactness and thermal comfort in hot-dry climates. The findings of the current study are consistent with those results. Additionally, Fig. 11 illustrates the average compactness index of all Pareto-optimal

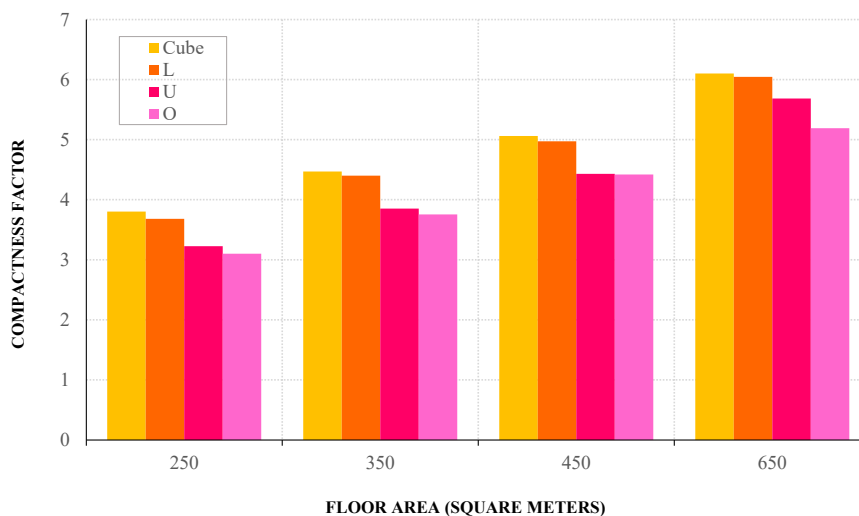


Fig. 10. Compactness index of optimized building forms achieving the highest thermal comfort for each floor area category in a hot-arid climate

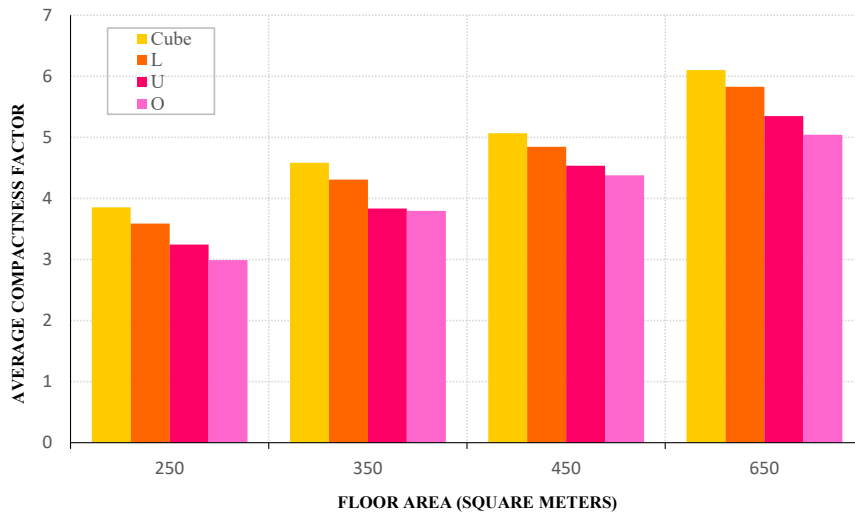


Fig. 11. The average compactness index of all Pareto-optimal solutions for each floor area-form type category

points obtained from the multi-objective optimization process, categorized by floor area and form type.

This chart also illustrates the average compactness index of all Pareto-optimal solutions for each floor area-form type combination. The highest average compactness values correspond to the cube form across all considered floor areas. This is followed, in descending order, by the L, U, and O forms. Fig. 12 presents the maximum UDI values obtained through the optimization process for each form type across the different floor area categories.

This chart shows that the highest UDI values – used in this study as an indicator of visual comfort – are consistently associated with the L-shaped form across all floor area categories. For the 250 m² category, the next highest UDI values after the L form are observed in the cube, U, and O forms,

respectively. In the 350 m² category, following the L form, the order is U, cube, and O. For the 450 m² floor area, the sequence after the L form is cube, U, and O. Similarly, in the 650 m² category, the highest UDI values after the L form belong to the U, cube, and O forms in that order. It should be noted that no meaningful correlation was found between the maximum UDI values and the compactness index of the optimized forms. Fig. 13 illustrates the shape factor values of the optimized forms for each input floor area. Since the shape factor is derived from the building’s length-to-width ratio, this metric is only valid for the cube form.

Fig. 13 includes two curves: the yellow line represents the variation of the shape factor for the thermally optimal form (i.e., with the minimum operative temperature) across each input floor area, while the red line shows the shape factor corresponding to the

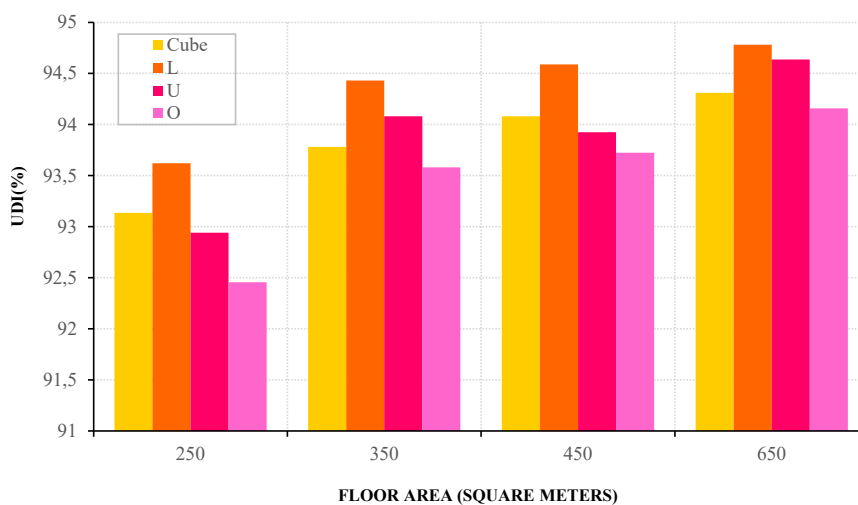


Fig. 12. Maximum UDI values resulting from the optimization of different building forms across various floor areas

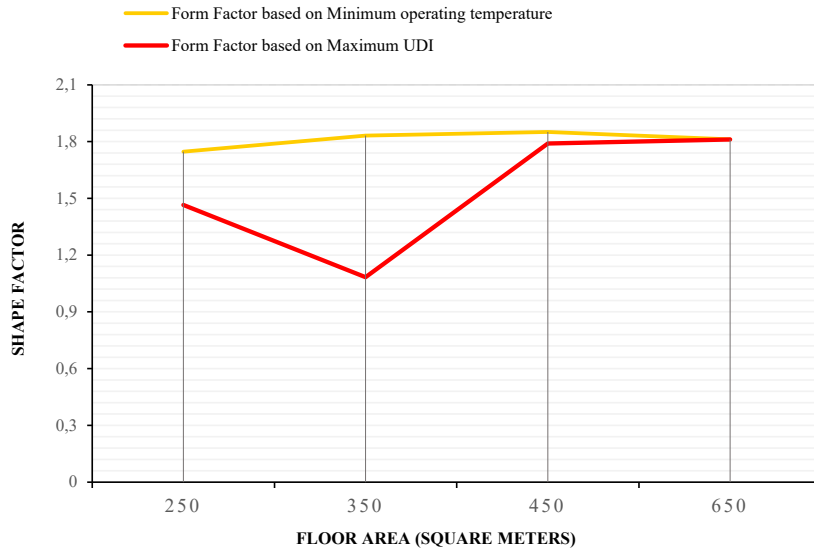


Fig. 13. Shape factor of optimized forms for each input floor area category

visually optimal form (i.e., with the maximum UDI) for each floor area category. The relatively stable trend observed in the shape factor of thermally optimal forms suggests that, for improved thermal comfort, the ideal cube form should maintain a shape factor of approximately 1.8, regardless of floor area. In contrast, no meaningful relationship is observed between the shape factor and floor area when maximizing UDI. Since previous results have shown that the cube form yields the highest thermal comfort across all tested floor areas within Yazd's hot-arid environmental conditions, it can be concluded that a cube form with a shape factor of approximately 1.8 is the thermally optimal configuration for single-story buildings up to 650 m<sup>2</sup> in this region. For a detailed analysis of building orientation in Yazd, refer to Fig. 14.

For the evaluation of building orientation, only the cube form was utilized to isolate the impact of orientation, as the orientation input for other forms — due to their asymmetry — interacts directly with form variation during optimization. In this chart, the optimal orientation of the cube form is shown based on the minimum operative temperature (yellow line) and the maximum UDI (red line). The results indicate that the orientation yielding minimum operative temperature remains nearly constant across varying longitudinal floor area inputs. Therefore, considering thermal comfort optimization during the hottest week of the year, it can be concluded that for floor areas up to 650 m<sup>2</sup>, the optimal orientation is independent of floor area. The best-performing orientations for thermal comfort in Yazd are approximately 0°

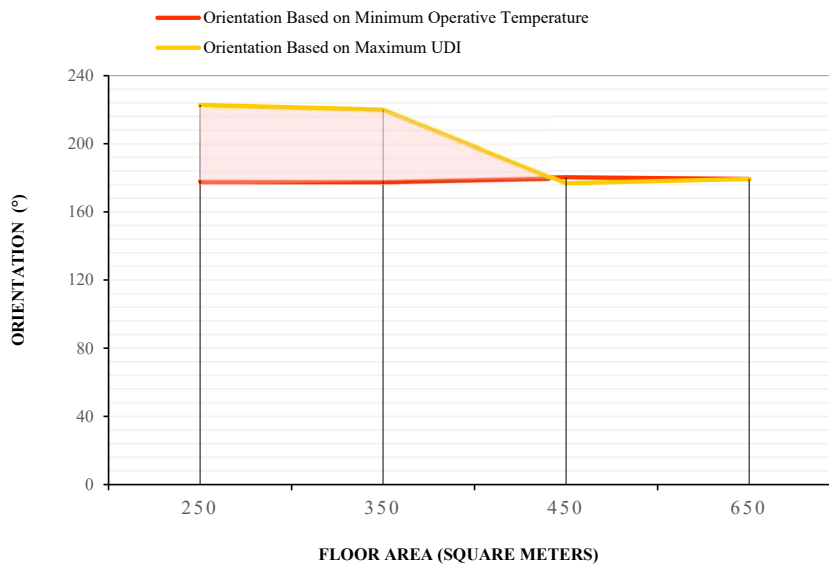


Fig. 14. Optimal building orientation chart for the City of Yazd

or 180°, owing to the symmetry of the cube. It is also noteworthy that the optimal orientations of the remaining Pareto points (excluding the endpoints shown in the chart) generally fall between the two plotted curves. This suggests that for floor areas of 250 and 350 m<sup>2</sup>, optimal orientations range between 180° (north-south) and 220° (northwest-southeast), while for floor areas of 450 and 650 m<sup>2</sup>, the preferred orientation is around 180° or 0° (north-south). In contrast, optimal orientation based on visual comfort (UDI) varies more noticeably with changing floor area. It is important to note that the findings of this study are consistent with those reported by Fallahpour (2015), who identified the optimal building orientation in Yazd's hot-arid climate as ranging between the north-south and northwest-southeast axes.

*Energy Performance Analysis*

Beyond comfort metrics, the energy implications of form optimization were quantified to assess economic viability. The total cooling and lighting energy consumption of all optimized configurations with a 650 m<sup>2</sup> floor area was calculated and compared against a suboptimal O-shaped reference case from Table 9 (Case #3). This reference case, characterized by a UDI of 91.5 % and an operative temperature of 31 °C, represents a conventional design without optimization. Table 10 presents the comparative energy analysis in kilowatt-hours (kWh).

The results demonstrate that the optimized cubic form achieves the highest energy performance with a 38.6 % reduction in total energy consumption compared to the suboptimal reference. Notably, even the least efficient optimized configuration (O-shaped End point) still yields a substantial 32.4 % energy saving. This clear hierarchy in energy performance — Cubic > L-shaped > U-shaped > O-shaped — directly correlates with the thermal comfort results, confirming that form optimization for thermal comfort simultaneously delivers significant energy efficiency gains.

The 6.2 % performance gap between cubic and O-shaped forms (38.6 % vs 32.4 %) underscores

the significant impact of form selection on energy efficiency. This translates to approximately [2000–2500] kWh annual energy savings for a typical residential building in Yazd.

*Convergence Phenomenon and Design Implications*

The identical results for both Pareto endpoints in the cubic form indicate a unique convergence where a single configuration simultaneously minimizes operative temperature and maximizes daylight availability for the 650 m<sup>2</sup> floor area. This convergence phenomenon in the cubic form represents an exceptional finding in multi-objective optimization, where typically competing objectives are simultaneously satisfied by a single configuration. This convergence suggests that for this specific scale in Yazd's climate, the cubic form achieves an ideal balance between thermal and visual comfort objectives, presenting designers with an unambiguous optimal solution. In contrast, the other form typologies exhibit the expected trade-off between the two objectives, requiring designers to select between thermal-driven (Start point) or daylight-driven (End point) configurations based on project priorities.

*Integration with Building Control Systems*

Building upon these geometric and orientational optimizations, this study has primarily targeted the building form as a fundamental passive strategy. The collective results demonstrate that geometric parameters — especially the compact cube form with north-south orientation — establish a significant passive thermal baseline. However, in a dynamically changing climate, achieving consistent year-round comfort requires combining this passive foundation with low-energy control mechanisms. The identified optimal orientation and window-to-wall ratios in optimized forms create an ideal platform for implementing adaptive shading systems. As demonstrated in the vernacular architecture of the region, fixed shading elements have long been employed for solar control (Izadpanahi et al., 2021). Modern interpretations could incorporate

**Table 10. Energy consumption comparison between optimized configurations and the suboptimal reference case (650 m<sup>2</sup>)**

FORM TYPE	PARETO FRONTS	TEMP. REDUCTION (°C)	UDI INCREASE (%)	COOLING ENERGY SAVING (KWH)	LIGHTING ENERGY SAVING (KWH)	TOTAL ENERGY SAVING (%)
<b>CUBIC</b>	Start	3.01	2.81	2071.4	418.5	<b>38.6</b>
	End	3.01	2.81	2071.4	418.5	<b>38.6</b>
<b>L-SHAPED</b>	Start	2.98	2.87	2050.1	431.3	<b>38.4</b>
	End	2.71	3.28	1864.3	518.8	<b>36.9</b>
<b>U-SHAPED</b>	Start	2.85	2.55	1965.5	362.9	<b>36.1</b>
	End	2.54	3.13	1753.6	486.8	<b>34.7</b>
<b>O-SHAPED</b>	Start	2.7	2.39	1857.4	328.8	<b>33.9</b>
	End	2.48	2.65	1706.1	384.3	<b>32.4</b>

automated or manually controlled external louvers that maximize solar heat rejection in summer while allowing beneficial passive heating in winter, thereby enhancing the thermal performance achieved through form optimization alone. Furthermore, the L-shaped forms' superior daylighting performance, evidenced by their higher UDI values, presents significant potential for integration with daylight-responsive lighting controls. This approach aligns with the optimization goals in early design stages, where form parameters are determined before specific system selections (Feng et al., 2021). In such an integrated setup, the building's inherent daylight distribution capacity would be complemented by dimmable artificial lighting, maintaining visual comfort while reducing electricity consumption — an important consideration beyond the current simulation scope but logically connected to the visual comfort findings. Therefore, the optimized configurations identified in this research should be regarded not as complete solutions but as a robust passive framework. Subsequent design development can build upon this foundation by incorporating adaptive control systems for solar gain management, ventilation, and artificial lighting.

This integrated approach — where passive form establishes the performance foundation and active controls provide fine-tuning for diurnal and seasonal variations — represents not merely an optimization strategy but a fundamental shift toward resilient, low-energy architectural practice in hot-arid regions.

### **Conclusion**

This study highlights the critical importance of energy consumption considerations in the architectural and design processes of buildings. With the advancement of simulation and modeling technologies in the built environment, the practical application of these tools has gained traction as a means to optimize building performance — striving to reduce energy consumption while enhancing occupant comfort. The energy analysis revealed that form optimization can yield 32.4–38.6 % energy savings, with cubic forms demonstrating both superior thermal comfort and energy performance. The unique convergence observed in cubic forms provides designers with unambiguous optimal solutions for the 650 m<sup>2</sup> scale in Yazd's climate. In this context, and with an emphasis on optimized design approaches, the research focused on minimizing energy use through the optimization of building form within Yazd's hot-arid environmental conditions — an approach historically embedded in the city's architectural heritage. Unlike passive

analyses alone, this study employed a performance-based design strategy to identify optimal forms under natural ventilation conditions. The resulting configurations can serve as foundational references for architects prioritizing energy efficiency in the early stages of design in climates similar to Yazd. By integrating geometric configuration optimization into the conceptual design phase, the proposed framework enables not only passive but also active strategies to be developed on a sound basis — ultimately contributing to the realization of ideal, high-performance buildings suited to Yazd's environmental context.

Thermal comfort during the hot season and visual comfort were selected as the two primary objectives for multi-objective optimization. The results were presented in the form of Pareto fronts for each area-form combination (across four base geometries: compact cube, L-shaped, U-shaped, and O-shaped). Owing to the multi-objective nature of the analysis, a spectrum of optimal solutions was generated for each scenario. However, this study primarily analyzed the extreme ends of the Pareto front — those representing the minimum operative temperature during the hottest week of the year, and the maximum annual Useful Daylight Illuminance (UDI). To validate the optimization outcomes, the optimal forms were compared with randomly generated samples of the same form type, floor area, and climate zone. Additionally, comparative findings from two peer-reviewed studies were used to further verify the credibility of the results, which confirmed the robustness of the optimization outputs. The multi-objective optimization for Yazd's climate indicated that, when prioritizing thermal comfort during the hot season, the most efficient solution is a compact cubic form with a shape factor of 1.8 and an orientation of 0 degrees. In contrast, when visual comfort is given higher priority, the optimal configuration is an L-shaped form, with dimensions provided in results. In general, building orientations ranging from 180° (north-south axis) to 220° (northwest-southeast) are preferable for vernacular architecture in Yazd. Furthermore, the results revealed that increasing the floor area of the buildings correlates positively with improved thermal and visual comfort during the hot season. It is worth noting that all design solutions presented in the results tables are valid optimized outcomes for dual objectives and can be readily applied by designers. Future studies are encouraged to explore winter season optimization to further refine design strategies for year-round performance in Yazd's climate.

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## БАЛАНСИРОВАНИЕ ТЕПЛООВОГО И ВИЗУАЛЬНОГО КОМФОРТА ПОСРЕДСТВОМ МНОГОЦЕЛЕВОЙ ПАРАМЕТРИЧЕСКОЙ ОПТИМИЗАЦИИ ФОРМЫ: ПРИМЕР ИЗ ЯЗДА, ИРАН

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### Аннотация

**Введение.** Форма здания играет решающую роль в определении энергоэффективности и комфорта жильцов, особенно в жарком засушливом климате, таком как Язд, Иран. **В этом исследовании предлагается** стратегия пассивного проектирования, которая использует параметрическое моделирование и симуляцию для оптимизации форм жилых зданий с точки зрения теплового и визуального комфорта. **Методы.** Для определения оптимальных геометрических конфигураций в четырех различных сценариях площади помещений (250, 350, 450 и 650 м<sup>2</sup>) был использован многоцелевой генетический алгоритм. Были параметрически сгенерированы и оценены четыре основных типа форм — кубическая, L-образная, U-образная и O-образная — с использованием показателей тепловых характеристик и индикаторов дневного света. **Результаты** показывают, что прямоугольный параллелепипед с коэффициентом формы приблизительно 1,8, ориентированный вдоль оси север-юг, обеспечивает неизменно более высокий уровень теплового комфорта по сравнению с другими формами. Энергетический анализ показал, что оптимизированные конфигурации могут снизить общее энергопотребление до 38,6 % при сохранении приемлемого качества внутренней среды. Эта методология поддерживает принятие решений на основе данных на ранней стадии концептуального проектирования, способствуя разработке контекстно-чувствительных, энергоэффективных решений для жилья в засушливых регионах.

**Ключевые слова:** многоцелевая оптимизация; параметрическая форма; тепловой комфорт; визуальный комфорт; генетический алгоритм; устойчивое проектирование; энергоэффективность.

## MODERN TRENDS IN THE CHEMICAL MODIFICATION OF “GREEN” BUILDING MATERIALS

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### Abstract

**Research objective** is to conduct a comprehensive theoretical analysis of modern methods for modifying lignocellulosic building materials (LCBM), including wood, non-wood plant raw materials, and composites based on them. The main focus is on overcoming the natural limitations of LCBM use, such as hygroscopicity, biodegradability, and low fire resistance, through chemical modification with organoelement compounds (OEC). **Methods** include analysis and synthesis of traditional modification methods; detailed systematic analysis of the mechanisms of action of organoelement modifiers; comparative assessment of the effectiveness of various methods and compounds. **Results:** traditional methods (impregnation with preservatives, fire retardants, water repellents), polymer impregnation and thermal treatment, as well as innovative approaches using nanotechnologies are considered. The mechanisms of action of OECs, classified by key elements: organosilicon compounds (OSC), organophosphorus compounds (OPC), organoboron compounds (OBC), organometallic systems (OMS), and multicomponent compositions, are analyzed in detail. It is shown that OSCs primarily provide hydrophobization and geometric stabilization, OPCs and OBCs address fire protection and biostability challenges, while polyfunctional systems (P-Si-B-N) combine comprehensive protection with minimal impact on mechanical properties. Special emphasis is placed on the environmental benefits and durability of modified materials that align with the principles of “green building.” The review presents recent advances in this subject area, highlighting the promise of OECs for creating competitive, environmentally friendly, and safe next-generation building materials.

**Keywords:** lignocellulosic building materials; wood modification; organoelement compounds; organosilicon compounds; organophosphorus compounds; organoboron compounds; fire protection; hydrophobization; biostability; thermal modification.

### Introduction

Lignocellulosic building materials (LCBM), which include wood of various species, non-wood plant raw materials, and composite materials based on them, represent a renewable resource for the construction industry. Their distinctive features include environmental friendliness: the production of LCBM typically requires less energy than the production of steel, concrete, or plastics (Nässén et al., 2012; Alekseeva and Valeeva, 2023). Furthermore, many LCBMs are recyclable, compostable, or can be used for energy recovery at the end of their life cycle (Wojnowska-Baryła et al., 2020). LCBMs can regulate indoor humidity, creating a comfortable environment (Alapieti et al., 2020) and are energy-efficient as they have excellent thermal insulation properties reducing the need for heating/cooling (Wu et al., 2025). Moreover, they are lightweight: the lower weight of LCBM structures compared to concrete / brick reduces foundation costs and possess high strength-to-

weight ratio: despite its relatively low density, wood exhibits high bending, compressive, and tensile strength, allowing its use for load-bearing structures subjected to significant loads (Niemz et al., 2023). Besides, high construction speed is an advantage as prefabrication of structural elements (especially CLT, Glulam) and ease of assembly accelerate the process (Ilgin et al., 2023). High thermal and acoustic insulation properties of LCBM reduce the need for additional materials (Krestyaninova and Yuminova, 2017), and vapor permeability of LCBM contributes to a healthy microclimate and prevents moisture accumulation indoors (Shams et al., 2024). The last but not the least is seismic resistance as LCBM structures possess good flexibility and ability to absorb earthquake energy (Ugalde et al., 2019).

However, the natural characteristics of LCBM (hygroscopicity, biodegradability, low fire resistance) necessitate modification. The main methods for modifying LCBM are as follows. Impregnation involves introducing chemicals into the pores and cell

walls of wood under pressure or without it (Groshikov and Ovsyannikov, 2014; Usikov et al., 2016).

### Methods

The following research methods were used in this work. Analysis and generalization of traditional modification methods. This stage is fundamental and belongs to the category of theoretical research methods. Its goal is to form a coherent picture of the current state of scientific development in the field of material modification.

Detailed systemic analysis of the mechanisms of action of organoelement modifiers. This is a key theoretical-experimental method aimed at uncovering the essence of the processes that occur when modifiers are introduced into a material. Systemic analysis implies considering the object not in isolation, but as a complex of interconnected components.

Comparative assessment of the effectiveness of various methods and compounds. This is an analytical stage that often concludes a study or a major part of it. It allows for a transition from scattered data to specific conclusions and practical recommendations. It includes elements of qualimetry (the science of quality measurement).

### Results

The following *types of modifiers* are used:

– *Preservatives (biocides)*: copper, chromium, arsenic, ammonium salts, boron compounds. The purpose of preservation is protection against fungi and wood-boring insects. The effectiveness of preservatives is quite high, but they pose environmental problems when biocides leach from the protected material (Mazanik, 2011).

– *Fire retardants*: phosphorus, nitrogen, boron salts; intumescent coatings that expand when heated, forming a thick layer of foam or char residue. The purpose of using fire retardants is to reduce flammability and slow flame spread. Fire retardants introduced into LCBM by impregnation demonstrate high efficiency but can leach out and reduce the strength of the substrate (Luneva and Petrovskaya, 2011).

– *Water repellents*: waxes, oils, silanes, siloxanes reduce water absorption and prevent swelling (Braekemaier et al., 2015). They are highly effective for protection against liquid water but do not prevent equilibrium moisture content.

The advantages of impregnation are its relative simplicity, well-established technologies (especially for preservatives and fire retardants), and the possibility of deep impregnation. However, leachability of many compositions, potential toxicity and environmental risks, possible deterioration of mechanical properties, and changes in appearance highlight the disadvantages of this method. Polymer impregnation involves filling cell cavities (lumina) with monomers followed by their polymerization inside the wood. Monomers used include styrene, methyl

methacrylate (MMA), furan resins, and vinyls. This method achieves a significant increase in hardness, wear resistance, compressive strength, dimensional stability (due to pores “plugging”), biostability, and reduced water absorption of LCBM (Gulyaev et al., 2023). However, this method is characterized by high cost, significant increase in wood density, complexity of the process (requiring vacuum / pressure, polymerization initiators), possible deterioration of workability, and toxicity of some monomers. This method does not solve the problem of flammability (some polymers are flammable) (Kuzmin et al., 2022).

Thermal modification of wood involves heating wood to 160–240 °C in an oxygen-free environment for several hours. This leads to the degradation of hemicelluloses (the main source of hygroscopicity), partial restructuring of lignin and cellulose (Hill et al., 2021), resulting in a significant reduction in hygroscopicity and equilibrium moisture content; improved dimensional stability (less swelling / shrinkage); increased biostability (resistance to decay fungi); color change (wood acquires darker shades). However, this also results in a decrease in bending strength / impact toughness, increased brittleness of the wood, and practically no reduction in flammability (Sokolov, 2023).

The advantages of the thermal modification method are its environmental friendliness, excellent dimensional stability of thermally modified wood, high biostability, and aesthetic appearance. The disadvantages of this method include the energy intensity of the process and limitations on treatment thickness (Sokolov, 2023).

Nanotechnologies in LCBM modification involve using nanomaterials (e.g., nanoparticles of metals and oxides, nanocellulose, carbon nanotubes, nanoclays) for impregnation with nanoparticle dispersions, incorporation into composites (particleboard, fiberboard), and application of nanocoatings (Shamaev et al., 2022). This provides biocidal properties for LCBM (using Ag, Cu, ZnO nanoparticles); UV protection (using TiO<sub>2</sub>, ZnO nanoparticles); fire protection (using nanoclays, metal hydroxide nanoparticles); hydrophobicity (using SiO<sub>2</sub> nanoparticles (Kilyusheva et al., 2020) and silanes); strengthening (using nanocellulose and carbon nanotubes) (Shamaev et al., 2022). Advantages of this modification method include high efficiency at low concentrations of components used and multifunctionality. However, disadvantages such as the high cost of nanomaterials, difficulty of uniform distribution and fixation in wood, safety concerns, and ecotoxicity of nanoparticles require further research in this direction.

Chemical (reactive) modification of LCBM is based on the chemical interaction of a modifier (including nanoscale) with the hydroxyl groups (-OH) of cellulose, hemicelluloses, and lignin,

forming covalent bonds. Significant advantages of this method are deep and stable modification of LCBM properties, environmental friendliness of many reaction products, high biostability, dimensional stability, and reduced flammability of LCBM (Bazarnov et al., 2004). The use of organoelement systems as modifiers, combining inorganic elements (Si, P, B, N) with organic compounds, enables unique mechanisms for controlling LCBM properties due to high affinity for the substrate (Pokrovskaya, 2009). This review analyzes recent advances in this area, focusing on Russian and international research.

The wide range of organoelement compounds (OECs), whose use can influence the structure of wood and thereby modify its properties to varying degrees, ensures increased interest from researchers in finding ways to develop rational formulation and technological solutions for creating various types of modifiers.

Based on the key element in the organoelement modifiers (OEMs), they can be divided into the following enlarged groups (Figure):

- organosilicon compounds (OSCs);
- organophosphorus compounds (OPCs);
- organoboron compounds (OBCs);
- OEMs based on other elements (Sn, Cu, Zn);
- multicomponent systems.

**Organosilicon compounds (OSCs).** Their mechanism of action involves the formation of hydrophobic siloxane (Si-O-Si) networks on the surface or in the pores of LCBM, or covalent bonding of OH groups of cellulose / lignin / hemicelluloses via silane coupling agents. Thus, OSCs provide hydrophobization of the substrate, increased dimensional stability, improved weather resistance, and moderate increase in thermal stability. For example, alkylalkoxysilanes (particularly methyltrimethoxysilane, MTMS) penetrate and polymerize in cell walls; siloxanes (silicone oils / resins) form water-repellent films; silazanes, which contain nitrogen atoms, possess high penetrating ability and not only hydrophobize the LCBM surface but also increase bio- and fire resistance (Hill, 2006).

The features of the composition, properties, and mechanism of action of OSCs ensure increased interest in these types of compounds for use as modifiers to improve the performance properties of building materials and products based on wood, which is confirmed by the analysis of publications on research results from leading scientific schools working in this direction.

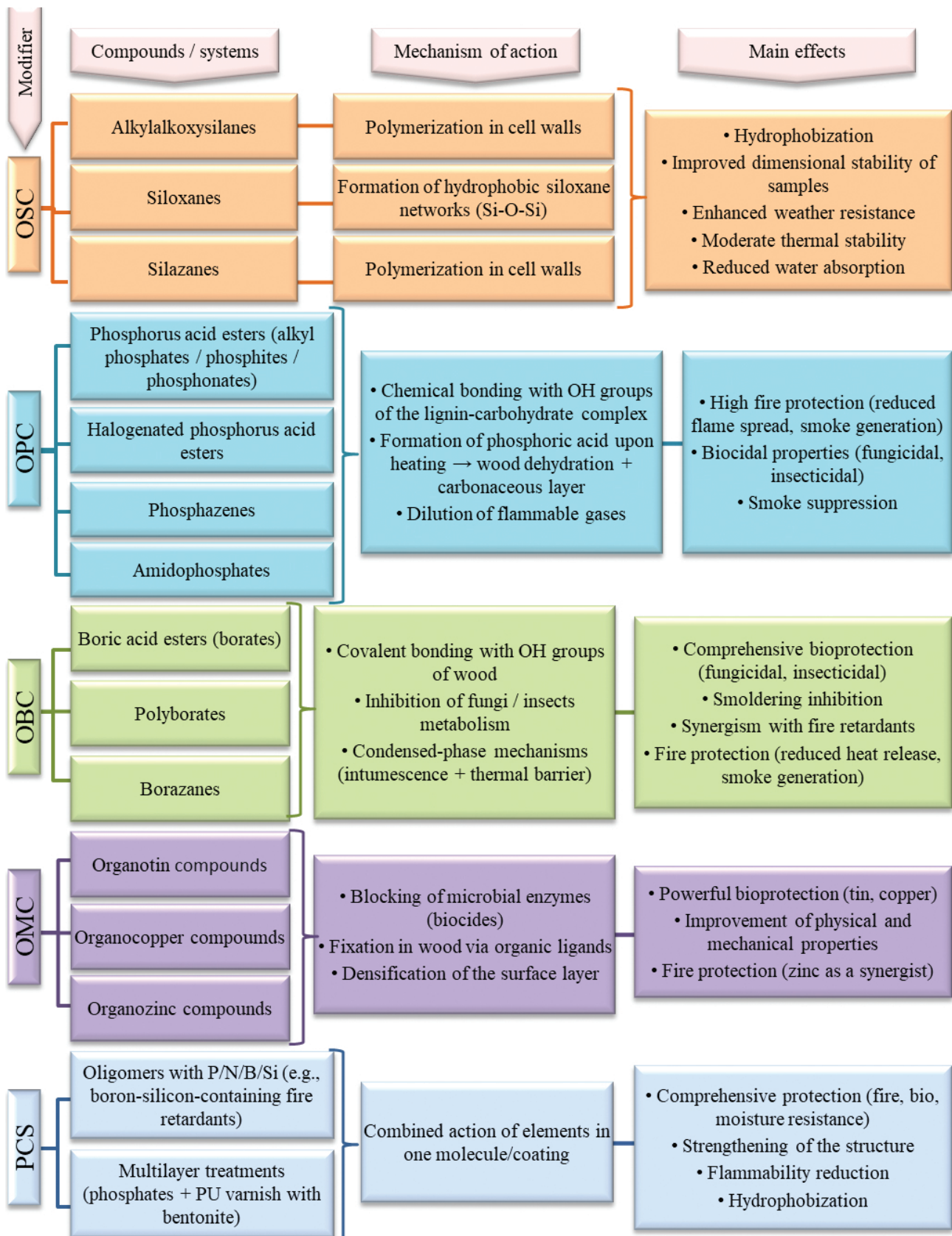
For instance, the work (Lisyatnikov et al., 2021) examined the interaction of one-component polyurethane and an organosilicon compound from the alkoxysilane group – tetrapropoxysilane. The composition is intended for obtaining a hydrophobic coating with improved performance properties to protect building structures made of LCBM from

the effects of technogenic and natural factors. The interaction mechanisms of one-component polyurethane with tetrapropoxysilane were studied using spectroscopy.

The product of the interaction between the polymer and tetrapropoxysilane is a three-dimensionally crosslinked polymer in which polyurethane macromolecules are crosslinked by organosilicon molecules. The chemical reaction is based on the interaction mechanism of isocyanate groups with reactive groups of alkoxysilane. The effect of the modifier on the surface structure of the cured coating was studied using a microscope. The contact angle of the modified and unmodified composition was determined, as well as the concentration of tetrapropoxysilane at which the coating acquires hydrophobic properties. The effect of tetrapropoxysilane on the adhesive characteristics of the polymer composition, as well as the change in hardness of the composition at various alkoxysilane concentrations were studied. Chemical modification of polyurethane allows its properties to be varied in the desired direction without deteriorating its other characteristics (Lisyatnikov et al., 2021).

The work (Sèbe and Jéso, 2000) investigated the dimensional stabilization of maritime pine sapwood through chemical modification with hydrophobic organosilicon compounds. Modification was carried out by esterification, using various chemically synthesized models containing trimethylsilyl groups: 3-trimethylsilylpropanoic anhydride (I), 2-trimethylsilylmethylglutaric anhydride (II), and trimethylsilylethenone (III). Grafting was confirmed by infrared spectroscopy and  $^{13}\text{C}$  and  $^{29}\text{Si}$  CP MAS NMR analysis; corresponding elements were detected in the wood cell walls. Dimensional stabilization induced by groups I and II proved stable over three cycles of oven drying followed by water soaking and surpassed stabilization induced by acetylation. However, the graft from group III was found to gradually hydrolyze to an acetyl group via a metallotropic rearrangement. Further investigation of the hygroscopicity and swelling of wood modified with groups I and II showed that dimensional stabilization is due to a bulking effect, not a change in substrate hygroscopicity. Specifically, the bulky grafts of groups I and II are believed to swell locally in the wood cell wall, revealing regions with new hydroxyl groups accessible to water (Sèbe and Jéso, 2000).

The work (Mai and Militz, 2004) described a wide variety of organosilicon compounds for application to wood. Some compounds, such as organofunctional silanes, mainly applied in combination with tetraalkoxysilanes (sol-gel process), as well as chlorosilanes and trimethylsilyl derivatives, have been proposed for full impregnation treatments of wood. Additionally, other systems such as plasma coating with hexamethyldisiloxane and



Classification of organoelement modifiers for lignocellulosic building materials

microemulsions containing mainly silane and siloxane mixtures have been developed for wood surface treatment. The effects associated with the different types of treatment range from increased dimensional stability, durability, and fire resistance to enhanced wood hydrophobization. In cases of decay and fire resistance, combining silicon-based systems with other chemicals is required to obtain satisfactory results. Due to the excellent water-repellent properties and weather resistance of some treatment types, it is recommended to apply silicon-modified wood in hazard class III conditions (EN 335, above ground exposure) (Mai and Militz, 2004).

In the work (Proshina et al., 2013), comparative studies were conducted on the impregnation process of wood with solutions of organosilicon compounds, using gamma-aminopropyltriethoxysilane and hexamethylsilane (solutions in hexane and white spirit), as well as urea-formaldehyde copolymer and machine oil, followed by drying. It was shown that impregnating wood with gamma-aminopropyltriethoxysilane improves the characteristics of products made from natural wood (Proshina et al., 2013).

The work (Azarov et al., 2012) investigated the effect of nanodispersions of organoelement compounds on the strength properties of mycologically degraded wood. As chemical modifiers, the authors proposed using organoelement compounds, primarily organosilicon nanodispersions in aqueous media, namely polyorganosiloxanes. The main physical and mechanical properties of these polymers are associated with the high flexibility of their macromolecules and relatively low intermolecular interaction. Preliminary studies show that upon interaction of samples with polyorganosiloxanes, an increase in physical and mechanical properties is observed. Moreover, compressive strength increases by 16 %, and static bending strength increases by 18 %. During the interaction of polyorganosiloxane and cellulose, a process of interaction between the hydroxyl groups of cellulose and the hydroxyls of the organosilicon composition, possessing the greatest activity, is observed (Azarov et al., 2012).

When treating wood with hexamethyldisilazane, only trace amounts of silicon were found in the substrate composition (Pokrovskaya, 2009). This indicates the low reactivity of silazanes towards components of the lignin-carbohydrate complex of wood cell walls, leading the author to the necessity of preliminary phosphorylation of the substrate to increase the degree of silylation. Organophosphorus compounds were used for this purpose (Pokrovskaya, 2009).

**Organophosphorus compounds (OPCs)** are capable of forming multifunctional protection systems through chemical modification of wood. They provide a complex effect: fire protection, hydrophobization, strengthening, and bioprotection,

making them indispensable in construction and restoration. The protective mechanism of these types of organoelement compounds manifests upon heating and is associated with the formation of phosphoric acid, dehydration of wood, and formation of a carbon layer. This is accompanied by dilution of combustible gases with non-combustible ones. Due to the presence of functional groups in their composition, OPCs can chemically bond with OH groups of the components of the lignin-carbohydrate complex (LCC) of LCBM cell walls. Consequently, OPCs provide a high level of fire protection (leading to reduced flame spread rate and decreased smoke generation). Furthermore, OPCs typically possess bioprotective properties (exhibiting fungicidal and insecticidal effects). Examples of such compounds include alkyl phosphates / phosphonates (dimethyl methylphosphonate – DMMP), which are effective fire retardants; halogenated phosphates (e.g., tris(chloropropyl)phosphate – TCP), which have increased effectiveness due to P and Cl synergy but are environmentally unsafe; phosphazenes, which are non-halogenated, thermally stable fire retardants; amidophosphates/phosphoramidates, which can chemically bond with wood (Lowden and Hull, 2013).

The work (Portnov and Mikhaleva, 2020) analyzed the influence of phosphorus-containing organic materials on the fire hazard of wood. A correlation was identified between thermodynamic criteria (Gibbs free energy) and the physicochemical properties of modified wood (Portnov and Mikhaleva, 2020).

The study (Pokrovskaya and Portnov, 2017) examined the process of modifying wood with phosphorous acid esters to reduce fire hazard properties. Thermodynamic parameters of the modified wood surface were determined. High values of free surface energy were substantiated when studying the surface structure and surface layer of modified wood. The relationship between the energy characteristics of the modified wood surface, the effectiveness of surface layer modifiers, the surface layer structure, and the fire hazard characteristics of wood was shown. Based on the obtained data, the possibility of optimizing modifiers when creating protective compositions according to thermodynamic criteria was demonstrated (Pokrovskaya and Portnov, 2017).

The work (Pokrovskaya and Portnov, 2015) presented results examining the influence of surface treatment of wood with compositions based on alkyl esters of phosphorous acids on fire hazard characteristics such as fire-retardant efficiency group, flammability and ignitability index, flame spread index, and smoke-producing ability. Additionally, the bioprotective effectiveness of the modifiers used was studied. It was concluded that the most effective protective compositions for wood

are esters of phosphorous acid, particularly diethyl phosphite, which is an effective smoke suppressant. Based on the obtained data, a fire-bioprotective composition for wood was developed (Pokrovskaya and Portnov, 2015).

The study (Afanasyev and Korotkov, 2012) examined the effectiveness of impregnating amidophosphates for fire protection of wood materials. Using the highly informative method of NMR spectroscopy, the processes occurring during the synthesis of the base product OSA-1 were studied. A mechanism for the fire-retardant action of this composition was proposed. The warranty period for fire protection of wood under atmospheric exposure conditions was calculated (Afanasyev and Korotkov, 2012).

The article (Pokrovskaya, 2018) describes the strengthening of partially destroyed wood samples from an Anglican church through surface modification. The first layer of the multilayer coating is nitrilotrimethylphosphonic acid, which forms covalent bonds with the substrate, partially strengthening the wood. The second layer is an epoxy resin solution, forming covalent bonds with the first layer coating, with the hydroxyl groups of the first layer participating in the curing of the second layer. A two-layer coating is formed, whereby the strength of the wood increases by 2–2.5 times, water absorption decreases by 3 times, and mass loss during combustion does not exceed 9 % according to GOST 27484-87 (Pokrovskaya, 2018).

**Organoboron compounds (OBCs).** This type of compound exhibits complex protective action: biocidal – disrupting the metabolism of fungi / insects; inhibiting smoldering and showing synergy with other fire retardants. They are often introduced as boric acids / esters. Examples include boric acid esters with glycols / glycerol, which improve boron fixation and leachability; N-alkyl borates (bis(N-cyclohexyldiazoniumdioxo)borane) – “Kholil” are used as antiseptics and fire retardants; borazanes (boron-nitrogen rings) antisepticize and act as fire retardants for LCBM (Kartal et al., 2004; Leonovich and Politov, 2021).

In the study (Namyslo and Kaufmann, 2009), a new type of chemical wood modification for its permanent functionalization with organoboron compounds was developed and applied. This is achieved by covalent attachment of metalloids substituents to wood hydroxyl groups via benzotriazolyl-activated benzoic acid. Thus, standard modification procedures in wood chemistry, such as acetylation, are improved by avoiding the loss of half the reagent in the case of acid anhydrides or the release of corrosive hydrochloric acid in the case of carboxylic acid chlorides. In this case, the boron atom could contribute to solving a long-standing problem in the field of wood protection: the chemical fixation of an organoboron compound

through a well-defined covalent bond. Accordingly, this avoids the insufficient long-term availability of traditionally common boron compounds as wood preservatives caused by leaching. The study was also extended to arylsilyl compounds as a second type of organometallic substance that could potentially be used for subsequent chemical reactions via ipso-substitution. The presented wood modification reactions yielded weight percentage gains ranging from 14 to 31 % on beech wood, spruce wood, and pine sapwood sawdust (approx. 500 µm in diameter) or pine sapwood veneer chips (Namyslo and Kaufmann, 2009).

To reduce flammability, oriented strand boards (OSB) were coated with a polyelectrolyte complex (PEC) consisting of sodium polyborate (SPB) and polyethyleneimine (PEI) using a simple two-step process (Rodriguez-Melendez et al., 2024). This PEC treatment imparts self-extinguishing behavior to OSB during combustion and reduces total heat release by 21 % and total smoke release by 79 %, increasing time to ignition by 18 % compared to untreated OSB. Furthermore, the PEI / SPB coating adds virtually no weight (5.8 wt.%) to the OSB, preserving visual aesthetics and mechanical properties. The main fire-retardant effect is achieved through condensed phase action via a combination of intumescence and thermal barrier mechanisms (Rodriguez-Melendez et al., 2024).

**Modifiers based on organometallic compounds (OMCs),** which include: organotin, organocopper, organozinc compounds. Organotin compounds (e.g., tributyltin oxide (TBTO)) are potent biocides but are highly toxic, so their use is restricted by the international convention – ROTEX. Organocopper compounds – components of modern preservatives like ACQ (Alkaline Copper Quaternary) and Cu-HDO (Bis-(N-cyclohexyldiazoniumdioxo)-copper) – provide fungicidal action; the organic substituent (often quaternary ammonium or a nitrogen complex) improves copper fixation in wood and provides additional biocidal effect (Freeman and McIntyre, 2008). Organozinc compounds are sometimes used as co-biocides or in combinations for fire protection (synergists).

Within the framework of the study (Belyaev et al., 2021), a multifunctional protective composition for wood based on arabinogalactan and mechanically activated polymineral sand was developed, capable of enhancing its physical and mechanical properties. Surface modification of wood with organomineral compositions leads to an increase in its density, hardness, and strength. The hardness of treated wood is 24 % higher, and compressive strength along the grain is 20 % higher than that of untreated wood. After treatment, the wood surface darkened and slightly yellowed, which does not preclude its use in building construction and renovation. Results

of measuring color coordinates of the surface of modified samples indicate the stability and durability of the developed protective coating even after 4 months of exposure to atmospheric conditions. Based on the slight return of color coordinates of treated wood to the values of original wood, it can be concluded that there is partial leaching of the composition (Belyaev et al., 2021).

**Multicomponent monomers/oligomers** are compounds containing simultaneously phosphorus (fire protection) and / or nitrogen (fire retardant synergist, biocide) and / or silicon (water repellent, thermal stabilizer) and / or boron (biocide and fire retardant) in one molecule, ensuring their polyfunctional action.

In the study (Kurbanova and Ismailov, 2015), a boron- and silicon-containing oligomeric fire retardant based on sodium metasilicate with sodium tetraborate was developed, having an initial oxidation temperature above 350 °C. It can be used as a fire retardant in the production of paints, varnishes, and enamels to improve the appearance and protect objects (including those based on LCBM) from corrosion and high-temperature exposure. The maximum yield of the oligomeric fire retardant in the temperature range of 70-80 °C, the recommended application concentration in production of 6–7 %, and the simplicity of the production technology ensure economic efficiency. Boron- and organosilicon resins, due to their excellent qualities, find diverse applications (Kurbanova and Ismailov, 2015).

To develop a comprehensive approach to ensuring the durability of wooden structures, the work (Mikhaleva et al., 2021) proposed a multilayer treatment with compositions of dimethyl phosphite and polyurethane (PU) varnish with nanosized bentonite particles. The basis is phosphorylation, i.e., surface application of the most effective phosphorus-containing fire retardants to wood samples, which, in combination with bentonite-modified PU varnish, provides polyfunctional protective properties. As a result of this multilayer treatment, the material becomes classified as low-flammability (mass loss less than 20 %), while acquiring high moisture and biostability. Achieving fire, bio, and moisture resistance and increasing the strength of partially destroyed wood provides polyfunctional protection, making it possible today to preserve and extend the service life of many wooden structures, including monuments of wooden architecture (Mikhaleva et al., 2021).

As a result of research conducted at the Moscow State University of Civil Engineering (National Research University) under the guidance of Professor E.N. Pokrovskaya (Pokrovskaya and Koteneva, 2003; Pokrovskaya et al., 2004; Sidorov and Koteneva, 2008), it was established that organophosphorus compounds, being effective fire retardants and biocides, can surface-modify wood

under "mild" conditions. This suggested the possibility of creating an impregnating composition based on phosphorus- and organosilicon compounds, considering the occurrence of chemical interaction between them and the wood surface layer, which would possess a long-term complex protective effect. Based on the analysis of the ability of various classes of phosphorus- and organosilicon compounds individually to undergo chemical interaction with the wood surface layer, components were selected for the development of a multicomponent fire-bio-moisture protective composition (Pokrovskaya and Koteneva, 2003; Pokrovskaya et al., 2004; Sidorov and Koteneva, 2008).

The works (Koteneva et al., 2010; Koteneva, 2011; Stepina et al., 2014) demonstrated the high effectiveness of boron-nitrogen compounds as antiseptics and fire retardants for LCBM, due to the synergistic effect of boron and nitrogen atoms in their composition. Moreover, the chemical bonds formed between the molecules of boron-nitrogen modifiers and the components of the lignin-carbohydrate complex of plant raw material cell walls are resistant to hydrolysis due to the boron-amine coordination within the modifier, which excludes nucleophilic attack by water molecules. This ensures long-term protection of LCBM against biocorrosion and ignition.

Systematizing the presented material, the main mechanisms of action of OEMs and the resulting effects and properties of the LCBM surface can be identified (Fig.). OSCs act through the formation of hydrophobic siloxane networks (Si-O-Si) and covalent bonding with OH groups of cellulose / lignin / hemicelluloses, polymerization in cell walls, and formation of water-repellent films. This ensures hydrophobization of the substrate (main effect), increased dimensional stability, improved weather resistance, moderate thermal stability, and reduced water absorption. OPCs participate in forming chemical bonds with OH groups of wood components. Upon heating, they form phosphoric acid, causing wood dehydration and formation of a carbon layer, while diluting combustible gases, thereby providing high fire protection for LCBM (reduced flame spread, smoke generation), biocidal properties (fungicidal, insecticidal), and smoke suppression. Boron-nitrogen compounds (BNCs), through covalent bonding with OH groups of wood components, become firmly fixed in the substrate composition, inhibiting the metabolism of fungi / insects and providing condensed-phase mechanisms (intumescence + thermal barrier) for fire protection. OMCs are fixed in wood via organic ligands, blocking microbial enzymes, densifying the surface layer, and providing fire protection for the substrate. Multicomponent systems combine the action of elements (P and / or N and / or Si

and / or B) in one molecule / coating, providing comprehensive protection for LCBM (fire, bio, moisture resistance).

### **Conclusions**

Chemical modification of lignocellulosic materials with organoelement systems is a strategic direction for creating next-generation building materials that align with the ideology of “green building”. Modern research confirms that:

- OSCs are indispensable for hydrophobization and geometric stabilization, but their potential is fully realized in hybrid systems;

- OPCs and BNCs address the issues of fire protection and biodegradation, with boron-containing complexes showing high potential in preventing their leaching from wood products;

- polyfunctional compositions (P-Si-B-N) are a key trend, providing comprehensive protection with minimal impact on the mechanical properties of wood.

Thus, the modification of lignocellulosic materials with organoelement compounds creates prerequisites for positioning wood as a competitive, environmentally friendly, and durable building material consistent with the principles of sustainable development.

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## СОВРЕМЕННЫЕ ТЕНДЕНЦИИ В ХИМИЧЕСКОМ МОДИФИЦИРОВАНИИ «ЗЕЛЕННЫХ» СТРОИТЕЛЬНЫХ МАТЕРИАЛОВ

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### Аннотация

**Цель исследования:** проведение комплексного теоретического анализа современных методов модифицирования лигноцеллюлозных строительных материалов (ЛЦСМ), включая древесину, недревесное растительное сырье и композиты на их основе. Основное внимание уделено преодолению природных ограничений использования ЛЦСМ, таких как гигроскопичность, биоразлагаемость и низкая огнестойкость, посредством химического модифицирования элементарноорганическими соединениями (ЭОС). **Методы:** анализ и обобщение традиционных методов модифицирования; детальный системный анализ механизмов действия элементарноорганических модификаторов; сравнительная оценка эффективности различных методов и соединений. **Результаты:** рассмотрены традиционные методы (импрегнация консервантами, антипиренами, гидрофобизаторами), полимерная пропитка и термическая обработка, а также инновационные подходы с использованием нанотехнологий. Детально проанализированы механизмы действия ЭОС, классифицированных по ключевому элементу: кремнийорганические (КОС), фосфорорганические (ФОС), борорганические (БОС) соединения, металлоорганические системы (МОС) и поликомпонентные композиции. Показано, что КОС обеспечивают преимущественно гидрофобизацию и стабилизацию геометрии, ФОС и БОС — решают задачи огнезащиты и биостойкости, а полифункциональные системы (P-Si-B-N) сочетают комплексную защиту с минимальным влиянием на механические свойства. Особый акцент сделан на экологических преимуществах и долговечности модифицированных материалов, соответствующих принципам «зеленого строительства». В обзоре представлены последние достижения в рассматриваемой предметной области, подчеркивая перспективность ЭОС для создания конкурентоспособных, экологичных и безопасных строительных материалов нового поколения.

**Ключевые слова:** лигноцеллюлозные строительные материалы; модифицирование древесины; элементарноорганические соединения; кремнийорганические соединения; фосфорорганические соединения; борорганические соединения; огнезащита; гидрофобизация; биостойкость; термическое модифицирование.

# INVESTIGATION OF THE TRIGGER MECHANISM OF SELF-HEALING OF CONCRETE BY MICROGRANULES

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## Abstract

**Introduction.** Concrete, as a traditional building material, was first developed by the British civil engineer John Smeaton in the 18<sup>th</sup> century. In 1894, the Frenchman Joseph Monier first injected concrete into molds with steel bars, giving birth to reinforced concrete structures. Since then, concrete has been used to protect steel bars and improve the load-bearing capacity and safety of structures. However, concrete has a fatal flaw in its resistance to tension, so the repair of concrete as a branch of concrete materials has received widespread attention from both academic and engineering communities in the past decade. **Methods.** The addition of encapsulated millimeter particle units during the concrete mixing phase has been proven to be an effective implementation of autonomous concrete repair. In the development of self-healing concrete, the encapsulation unit and trigger design are important factors that determine the work performance of self-healing units and the overall repair efficiency of concrete. **Results.** This article describes the passive and active trigger in two directions, further explaining the main triggering mechanism of concrete self-healing and the corresponding repair mechanism, as well as compares and analyzes the technical characteristics and application range of various self-healing triggering mechanisms, providing a reference for future product development.

**Keywords:** microgranules; self-healing mechanism; trigger mechanism.

## Introduction

Concrete is widely used in the construction industry worldwide due to its high bearing capacity, compressive strength, durability, and low production cost. However, the low tensile strength and cracking issues are two inherent defects that are difficult to avoid in concrete materials. The tensile strength of concrete can be effectively enhanced by adding reinforcement, but there is currently no fundamental method to inhibit crack formation. Although crack formation and development are the only signs of damage and failure in concrete structures, the causes of concrete cracking are complex, with common factors including plastic shrinkage, thermal stress, settlement, drying shrinkage, weathering, rebar corrosion, and load application (S and S, 2023). If these cracks are not effectively prevented and repaired, they may cause durability and reliability issues in concrete structures (Sun et al., 2020). Therefore, necessary repair measures are of great significance in extending the service life of concrete structures. Traditional repair methods for concrete cracking, such as filling and sealing, and low-pressure grouting, although have a certain positive effect on extending the service life of concrete, also have many shortcomings. Firstly, the service life of the filling material is usually limited and requires regular inspections and maintenance. Secondly, the timeliness of manual repairs may pose safety hazards for the use of concrete structures. In addition, from an economic

perspective, the inspection and maintenance of concrete buildings or structures also consume a large amount of manpower and resources, and the related maintenance costs increase significantly with the extension of service life.

In response to the cracking issues of concrete materials, researchers have explored the use of additives in the cement matrix to delay concrete cracking (Sakir et al., 2020) and started using supplementary cementitious materials such as silica fume, granulated blast furnace slag, fly ash, metakaolin, limestone powder, and rice husk ash to replace part of the cement matrix, thereby reducing early-age cracking in concrete. In recent years, nanomaterials such as carbon nanotubes have also been used to improve the performance of concrete. Carbon nanotubes can bridge micro-cracks in concrete and strengthen the interface transition zone between aggregate and cement paste, to some extent delaying the development of micro-cracks (Lan et al., 2022). However, these modified methods still cannot fundamentally address the issue of reduced durability and safety of concrete structures after cracking. Therefore, endowing concrete with the ability to autonomously detect and heal cracks from a material design perspective undoubtedly has important scientific and social value in enhancing the durability and structural toughness of concrete materials.

In the past twenty years, the innovative concept of self-healing concrete has been the subject of in-

depth research, with experts and scholars in the relevant field having conducted extensive work on the design of self-healing methods and self-healing units applicable to concrete (Van Tittelboom and De Belie, 2013). In fact, concrete itself has the ability to self-heal cracks, as unhydrated cement particles further hydrate and repair microcracks under the combined action of water and carbon dioxide (Van Tittelboom et al., 2012). However, natural healing is only effective in microcracks of limited scale, and has minimal effect on cracks wider than 200 microns. In order to enhance the self-healing capacity of concrete, researchers have developed autonomous repair techniques based on externally added self-healing units (Wu et al., 2012).

According to whether the self-healing process is based on the chemical reaction of concrete's own binder or on the release of repair substances from externally added self-healing units, researchers generally classify concrete self-healing methods into two categories: autogenous self-healing and autonomous self-healing. The self-healing of concrete cracks mainly depends on one or more of the following mechanisms:

- 1) the formation of calcium carbonate precipitation from calcium hydroxide in cement;
- 2) settling of debris and loose cement particles caused by water flow;
- 3) rehydration of unhydrated cementitious particles;
- 4) further swelling of hydrated cementitious matrix.

It can be seen that the main triggering conditions for self-healing are the presence of special environments containing water and air. Researchers have also attempted to promote the speed and efficiency of autogenous self-healing through various additives. For example, the use of superabsorbent polymers (SAP) (Lee et al., 2010; Snoeck et al., 2012; Park and Choi, 2018; Wu et al., 2021a) or other internal water-retaining substances (Qian et al., 2010) to provide a water source for unhydrated binders, thereby promoting the further hydration and precipitation of unhydrated products to repair cracks, or by directly adding related minerals to the cement matrix to accelerate secondary hydration and recrystallization (Sisomphon et al., 2013; Marchon et al., 2018; Vehmas et al., 2018; Chandra Sekhara Reddy and Ravitheja, 2019). Compared to autogenous self-healing, autonomous self-healing of concrete cracks mainly relies on adding self-healing units containing repair substances such as biological, organic or inorganic materials to the cement matrix, and based on certain triggering mechanisms, controlled release of repair substances in the self-healing units to achieve active repair of concrete cracks. In order to improve the triggering efficiency and repair efficiency of self-healing units, researchers have designed

a series of self-healing units with different triggering mechanisms according to various factors and environmental variables associated with concrete degradation. In addition to using concrete cracking as the triggering mechanism for self-healing units, special ions, pH values, light energy, heat energy, and other environmental factors have also been used as triggering mechanisms to design functional units for concrete self-healing (Mauser et al., 2004; Bédard et al., 2010; Broaders et al., 2011; Kost and Langer, 2001; Kim et al., 2013; Dong et al., 2015). For example, in the marine environment, concrete is susceptible to chloride ion damage, leading to rebar corrosion, so researchers have used chloride ion concentration as a triggering mechanism to guide the repair of concrete degradation problems by self-healing units (Xiong et al., 2015; Liang et al., 2018). Recently, emerging triggering mechanisms such as magnetic fields, electric fields, microwaves, and ultrasonic waves have also been designed and used to control the release of repair functions in self-healing units (Dubinsky et al., 2008; Klibanov et al., 2010; Yim et al., 2012; Wan et al., 2021).

The self-healing ability of concrete is not generated out of thin air, and even the occurrence of self-healing in concrete itself requires environmental factors such as water and carbon dioxide as triggering conditions. When designing repair units suitable for self-healing concrete, the design of the self-healing triggering mechanism will directly affect the actual effect of its repair function and the overall repair efficiency of the concrete, due to the different types of repair agents, the physicochemical environment within the concrete, and the repair targets. Therefore, the selection of the self-healing unit triggering mechanism is a crucial part of the self-healing concrete system. Although there are many different design methods and corresponding triggering mechanism types for existing self-healing units, there is a lack of overall understanding and systematic comparative research on the triggering performance of various self-healing units under different triggering mechanisms and the repair efficiency of concrete, which greatly affects the systematic advancement of self-healing concrete research and hinders the practical application of self-healing concrete in engineering. In response to these issues, this paper systematically summarizes the main types of existing self-healing concrete and the basic principles of the corresponding triggering mechanisms; compares the differences in triggering efficiency and triggering conditions among various triggering mechanisms; and summarizes the repair effects of different triggering mechanisms, repair agent types, and repair conditions on concrete cracks. Based on the comparison, this paper also discusses in detail the evaluation methods for the applicability and efficiency of self-healing triggering

mechanisms, with the aim of providing guidance for future research on self-healing concrete and the design of its self-healing mechanism.

## Methods

### Self-repair triggering methods

The internal deterioration characteristics of concrete (e.g. matrix cracking, pH, ion concentration) as well as external service environment changes (e.g. loading, temperature, light, magnetic field, microwave and ultrasonic waves) are often used by researchers as triggering conditions for self-healing concrete repair units. Depending on whether the triggering of the self-repair behavior of concrete requires human control and intervention, the triggering mechanisms for self-healing concrete can be divided into passive triggering and active triggering. The following is an introduction to these two types of triggering mechanisms, respectively.

Passive triggering mechanisms mainly include crack triggering, environmental triggering, ion triggering, and other triggering methods. The working mechanism is that when negative factors affecting the stability or durability of concrete structures reach the design threshold, the factor will act as a trigger to activate the repair function of self-repair units in the concrete, and the repair agent in the self-repair unit will subsequently repair the concrete.

The working mechanism of crack-triggered self-healing concrete can be summarized as follows: the stress at the crack tip caused by the expansion of micro-cracks damages the repair agent carrier and provides a release channel for the repair material. Since the release of the repair agent occurs almost simultaneously with the crack propagation, the repair behavior under the crack triggering mechanism responds very quickly to deteriorating factors, and the curing action of the repair agent can quickly stop the further expansion of the crack. Although the principle of the crack trigger mechanism is simple, the triggering efficiency of this mechanism is influenced by many factors, including: crack width; bond strength between the repair unit and the concrete matrix; material properties of the repair unit, etc.

Previous studies have shown that crack width greatly affects the repair results (Van Tittelboom et al., 2016). A crack width exceeding the repair threshold

value will significantly weaken the repair effect, while a width which is too narrow may fail to trigger the self-repair behavior (Sinha et al., 2022). In addition, the properties of the repair agent carrier (self-repair unit) are closely related to the triggering efficiency of crack triggering. The morphology and surface physical characteristics (roughness) and chemical characteristics (chemical functional groups) of the repair unit are important factors affecting the bond strength between the encapsulant and the concrete matrix (Apolinário de Oliveira et al., 2021). Fig. 1 shows the triggering situation of two different-shaped self-repair units in the concrete matrix. To increase the surface roughness of the encapsulant, Araújo et al. (2018) prepared five different surface roughness capsules through polishing, the addition of a sand layer, and other methods. Compared with the untreated group, the capsules after surface treatment had a higher triggering rate when passing through cracks. Feng et al. (2020) successfully ruptured microcapsules containing repairing agent powder as the cracks passed by, by encapsulating the capsules with quartz sand particles to increase their surface roughness.

Shape memory alloys (SMAs) are metallic materials that can “remember” their original shape. The shape memory effect and superelasticity are the two main properties of SMAs, and they are also the theoretical basis for the application of SMAs in self-healing concrete structures (Wool, 2008). The working mechanism of SMA in self-healing concrete can be summarized as follows: SMA, with pre-stress applied, generates compressive stress on the crack surface when triggered by external stress on the concrete, forcing the crack to close and inhibiting its propagation, restoring the deflection and deformation of the concrete structure components. There are two common methods for applying SMAs to self-healing concrete. One method is to externally reinforce SMA materials onto concrete components, and the other is to incorporate SMA materials as self-healing units into concrete structures, as shown in Fig. 2.

In existing research, the feasibility of using SMAs for self-healing concrete has been thoroughly demonstrated. Sakai et al. (2003) tested SMAs to reinforce concrete beams and found that small

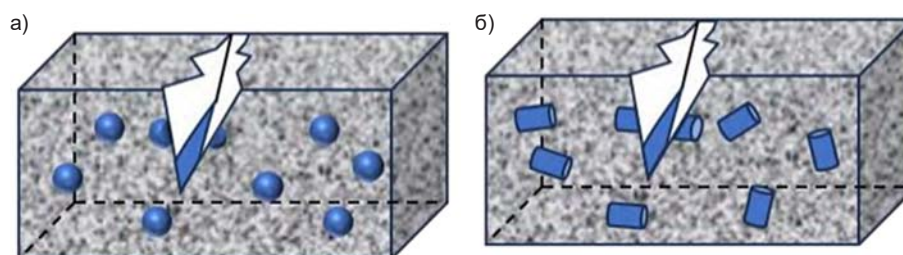
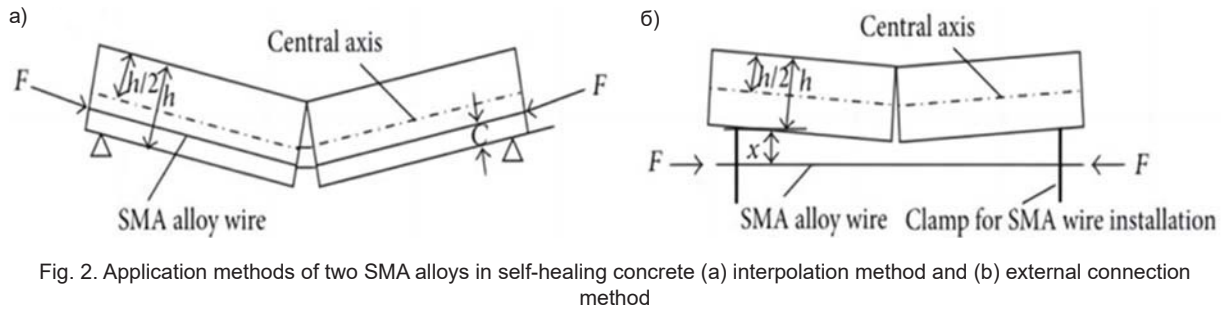


Fig. 1. Cracking induced autonomous self-healing in (a) concrete spherical capsules; (b) cylindrical capsules. (Apolinário de Oliveira et al., 2021)



cracks almost completely closed after unloading. Sun et al. (2013) embedded SMAs into concrete beams and effectively repaired cracks with widths of up to 0.4 mm. However, due to the uneven distribution of SMAs, not all cracks can be effectively repaired by SMAs alone, leading to uneven repair areas. To address this, researchers have combined SMAs with other self-healing materials to design a new composite material consisting of Engineered Cementitious Composite (ECC) and SMA fibers to address this issue. Experimental results showed that, compared to concrete specimens, SMA-ECC specimens not only had significantly improved strength and ductility, but also effectively reduced the number and width of cracks, demonstrating promising crack repair capabilities. Bonilla et al. (2018) evaluated the self-healing effect of concrete beams reinforced with calcium nitrate microcapsules and SMAs. The experimental results showed that the addition of microcapsules significantly enhanced the self-healing capacity in the presence of SMAs. The ionic trigger method is mainly used in capsule-type self-healing units, often using ions harmful to concrete structures as the trigger for the self-healing unit. By setting up an ion-sensitive trigger unit inside the encapsulated repair agent shell (capsule), it can react with the corresponding harmful ions after they enter the concrete, creating a channel for the internal repair agent to be released from the encapsulated shell, achieving the active repair of concrete degradation.

It is generally believed that the corrosion of steel reinforcement is the main cause of durability problems in reinforced concrete structures, and chloride ions are one of the factors causing premature corrosion of steel reinforcement. Chloride ions ( $\text{Cl}^-$ ) can reach the transition zone between steel and concrete through micro / nano channels in the concrete matrix. When the  $\text{Cl}^-$  concentration exceeds a threshold, the protective passivation layer on the steel surface will be destroyed, leading to corrosion. Since chloride ion erosion of concrete has already occurred before cracks appear and may cause a certain degree of damage to the structural durability, using crack triggering alone as the trigger mechanism for self-healing has a certain lag. The

advantage of the ion trigger mechanism is that the trigger unit can respond to concrete degradation issues before cracks develop, avoiding damage to the structural stability during the cracking period of concrete components.

Researchers have been exploring the use of  $\text{Cl}^-$  as a trigger for self-healing mechanism design and its application in the self-healing of concrete in marine environments. Liang et al. (2018) synthesized microcapsules with an ion-responsive shell consisting of multiple ionic liquids (Cpil). Fig. 3 shows the mechanism of action of this ion-triggered microcapsule. In water containing  $\text{Cl}^-$ , the  $\text{PF}_6^-$  functional group in the capsule shell can exchange with  $\text{Cl}^-$ , transforming the hydrophobic polymeric ionic liquid (PIL) on the outer shell of the microcapsule into a hydrophilic channel. At this time, the  $\text{Ca}(\text{OH})_2$  healing agent encapsulated in the capsule can be released through the hydrophilic channel, chemically binding with  $\text{Cl}^-$  to effectively reduce chloride ion erosion. Another research approach is to use response materials containing metal ions (such as  $\text{Ag}^+$ ,  $\text{Pb}^{2+}$ ) on the self-healing unit, which can react with  $\text{Cl}^-$  upon encountering it to produce precipitation, providing a pathway for the overflow of the repair agent inside the capsule. Xiong

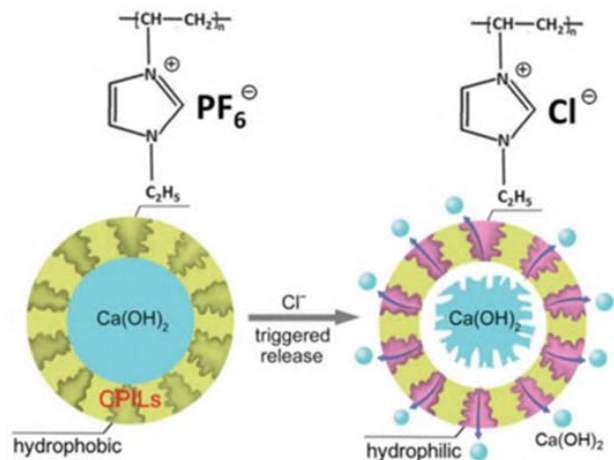


Fig. 3. Schematic diagram of  $\text{Ca}(\text{OH})_2$  release from  $\text{Cl}^-$  induced microcapsules (Liang et al., 2018)

et al. (2015) developed a novel capsule-based self-repair system that intelligently responds to chloride ions. The system uses silver alginate hydrogel as the matrix material for the capsule, epoxy resin as the repair agent, and the concentration of chloride ions as the trigger for self-repair. When the silver alginate hydrogel comes into contact with dissolved chloride ions, the silver ions can quickly react with the chloride ions to form silver chloride precipitation, leading to the rupture of the capsule and the release of the repair agent inside.

During the service life of concrete, the internal temperature, humidity, and pH value will continue to change with age, and these changes are closely related to issues such as concrete cracking, rebar corrosion, and strength degradation. Therefore, researchers have attempted to use these environmental factors as triggering conditions for self-healing, in the design of self-healing triggering mechanisms.

The pH trigger uses changes in the concrete's internal pH as the triggering condition for self-healing (Matsuda et al., 2019). The pH trigger is mainly applied in encapsulated self-healing materials, where the encapsulation shell contains a large amount of weak alkali or weak polyacid. When cracking or aging issues cause a change in the pH inside the cement, the weak alkali or weak polyacid undergo protonation or deprotonation under the influence of pH. This process causes the charged groups to repel each other, leading to the expansion and rupture of the encapsulation shell. Commonly used pH-sensitive polymers include polyacrylic acid (PAA), polyvinyl alcohol (PVA), polymethacrylic acid (PMAA), poly-N-vinylpyrrolidone (PVP), polyallylamine hydrochloride (PAH), polycaprolactone (PCL), and polyethylene glycol (PEG) (Snoeck and N, 2016). Matsuda et al. (2016) synthesized pH-triggered microcapsules with ester chains as the shell, which have the ability to hydrolyze under alkaline and acidic conditions and form an oxide layer on steel substrates. He et al. (2015) prepared ethyl cellulose (EC) / calcium hydroxide microcapsules. The EC shell of the microcapsule is pH-sensitive and can be triggered by the changing pH value inside the concrete and release calcium hydroxide to adjust the environmental pH. Dong et al. (2015) prepared a microcapsule system with polystyrene resin (PS) / sodium monofluorophosphate ( $\text{Na}_2\text{PO}_3\text{F}$ , MFP), and found that the triggering efficiency increases as the environmental pH decreases, as shown in Fig. 4, which displays microcapsules under different pH conditions. Kim et al. (2020) synthesized pH-sensitive microcapsules containing  $\text{NaNO}_2$  corrosion inhibitor using the water-in-oil-in-water (W/O/W) double-emulsion method. They placed the synthesized pH-sensitive capsules in deionized water (pH 6.8), carbonate / bicarbonate buffer

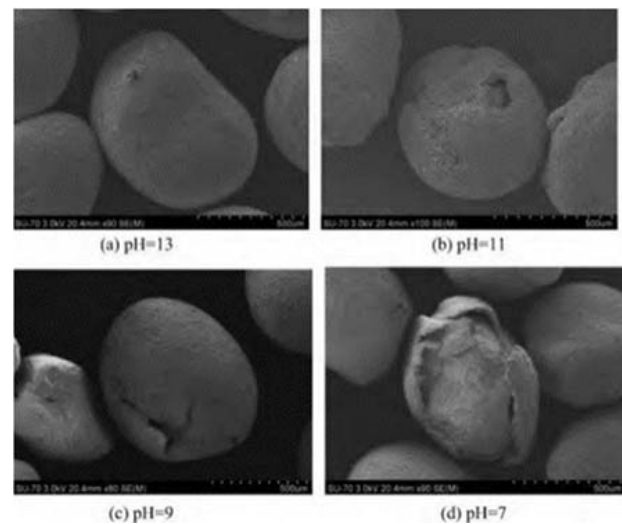


Fig. 4. Scanning electron microscope image of microcapsules after soaking in different pH solutions for the same time (Dong et al., 2015)

solution (CBS, pH 9.1), and simulated concrete pore solution (SCPS, pH 12.6) and observed the release process. The results show that the higher the pH, the faster the release rate of the self-healing capsules.

Ultrasonic waves have the characteristics of directional accuracy, strong penetration, and concentrated energy, and are widely used as a non-destructive testing method in the fields of medicine, biology, and engineering. Previously, Klibanov et al. (2010) used the unique cavitation and acoustic streaming effects of ultrasonic waves to trigger and target the delivery of drug-carrying microbubbles, laying a scientific and technological foundation for using ultrasonic waves as the triggering mechanism for self-healing concrete. The mature application of ultrasonic transducers in non-destructive testing of concrete structures also proving the harmlessness of ultrasonic waves to concrete structures (Yim et al., 2012). As a non-destructive triggering method, ultrasonic triggering can achieve the goal of targeted self-healing of concrete by stimulating the self-healing units before significant deterioration of the concrete occurs.

The mechanism of ultrasonic triggering is as follows (Nodehi et al., 2022): Under the mechanical vibration caused by the propagation and reflection of ultrasonic waves, the gas enclosed in the capsules of the repair agent or the environmental medium (i.e., the pore solution of the cementitious material) constantly escapes outward and generates microbubbles. Under the action of mechanical vibration, these microbubbles undergo a series of dynamic processes such as movement, expansion, and rupture. The instantaneous high pressure of up to about 100 MPa generated after the rupture of the bubbles will cause damage to the microcapsule wall, thereby releasing the repair agent (Fig. 5). Compared to traditional



Fig. 5. Mechanism of ultrasound-induced rupture of microcapsules (Xu et al., 2018)

mechanical triggering methods, ultrasonic triggering not only has higher triggering efficiency but is also controllable, reducing the impact of defects such as cracks on concrete to a minimum. Xu et al. (2018) demonstrated through experiments that ultrasonic waves can effectively improve the triggering and release efficiency of UF / E microcapsules in cement mortars. In contrast, the efficiency of traditional crack triggering is generally lower, with only a small percentage of microcapsules rupturing.

Among the available self-healing triggering mechanisms, magnetic field triggering offers the possibility of precise control and on-demand release, and therefore has particular advantages. During the triggering process, the magnetic particles in the healing unit will shake, flip or gather under the low-frequency magnetic field, thereby disrupting the surrounding material structure and releasing the healing components in the healing unit. In addition, the heat generated by the magnetic and metallic materials under the action of high-frequency magnetic fields, through magnetic and inductive heating effects, can also cause the self-healing units to rupture and trigger the healing behavior. The electromagnetic controlled release microcapsules designed by Li et al. (2020) were prepared by melt-polycondensation method, and under the electromagnetic field, the mortar containing microcapsules could recover to 91.4 % of its initial compressive strength, nearly twice as high as under room temperature conditions. The main mechanism is that under the electromagnetic field environment, nano- $\text{Fe}_3\text{O}_4$  induces temperature rise, causing the paraffin to melt, leading to the release of the encapsulated healing agent toluene diisocyanate (TDI).

It is worth noting that water in concrete will evaporate and diffuse at temperatures exceeding  $100\text{ }^\circ\text{C}$ , and at temperatures exceeding  $180\text{ }^\circ\text{C}$ , concrete will undergo micro-scale dehydration and collapse (Hager, 2013). Prolonged action of the magnetic field trigger will cause the overall temperature of the concrete structure to rise, affecting the durability of the concrete specimens over the long term. In order to better utilize the magnetic triggering mechanism without compromising the overall stability of the concrete structure, Loiseau et al. (2016) proposed a magnetic triggering encapsulation system (Explosive Raspberries). This system consists of an induction heating core and temperature-sensitive bursting microcapsules, which can release their contents in a matter of seconds without causing global heating of the main structure. Fig. 6 shows the complete triggering process of this system. One of the main advantages of the Explosive Raspberries concept, compared to traditional thermal triggering encapsulation systems, is the spatial control of the heat generation process. When a high-frequency alternating magnetic field is applied, heat is generated only in the vicinity of the cast steel particles. Induction heat is not applied to the entire matrix, but directly to the microcapsules in close contact with the heat source, thus having the potential to be applied as a magnetic field-triggered self-healing unit in concrete.

Microwave radiation heating is the result of the interaction between polar molecules in the material and the microwave electromagnetic field. It is widely used due to its non-contact, selectivity, and cleanliness. Gorin et al. (2006) previously confirmed that nanosilver particles can be used to improve

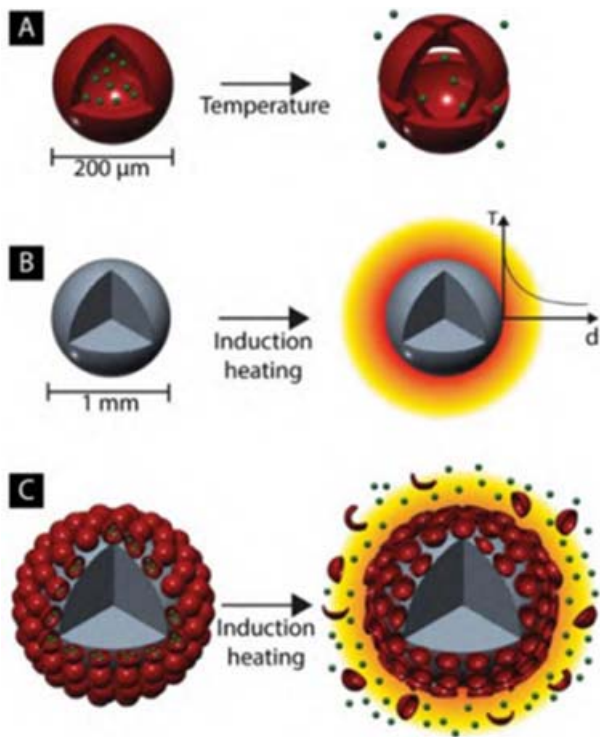


Fig. 6. Working principle of magnetic trigger blasting system (Loiseau et al., 2016)

the efficiency of microwave radiation damage. Nowadays, various microwave sensitizers, such as Au, Ag, and Fe<sub>2</sub>O<sub>3</sub>NPs, as well as MoS<sub>2</sub> nanosheets and nanodiamonds, have been used for remote microwave-induced drug release. The working mechanism is that microwave-sensitive particles embedded in the capsule shell will cause local heating damage to the outer shell under microwave radiation. Table 1 summarizes the advantages and disadvantages of the various triggering methods mentioned above.

*Trigger efficiency evaluation method*

The self-healing trigger efficiency is one of the important factors determining the self-healing performance of concrete. Below is the summary and introduction of existing evaluation methods for self-healing trigger efficiency.

The methods for evaluating the trigger efficiency of self-healing in experiments can be divided into two categories: direct observation and indirect evaluation. The direct observation method uses optical microscopy, scanning electron microscopy (SEM), environmental scanning electron microscopy (ESEM), and other micro-imaging technologies to evaluate the triggering of self-healing units by observing the profile or fracture of the sample,

Table 1. Self-repair trigger mechanism

Trigger Mechanism	Trigger Methods	Advantages	Disadvantages	Reference
Passive Trigger	Crack Triggering	The triggering method is simple and direct, able to react quickly to cracks and promptly repair them. It has relatively low application requirements for concrete environments and can function in complex conditions.	The triggering efficiency is low, and it cannot prevent the generation of cracks, only take remedial measures for existing cracks.	(Van Tittelboom et al., 2016; Araújo et al., 2018; Feng et al., 2020; Apolinário de Oliveira et al., 2021; Sinha et al., 2022)
	Stress Triggering	It responds positively to the destructive load and can improve the concrete's resistance to tensile damage.	The repair behavior is not repeatable, and the repair effect is limited.	(Sakai et al., 2003; Wool, 2008; Sun et al., 2013; Bonilla et al., 2018)
	Ion Triggering	Ions can diffuse through micro-nano voids in the concrete matrix and trigger self-healing function without needing to go through concrete cracks, making the triggering method more intelligent.	Special ions are usually only present in specific environments, so their use as a triggering mechanism is limited.	(Xiong et al., 2015; Liang et al. 2018)
	pH Triggering	It can self-adjust trigger based on the internal environment of the concrete, able to actively repair extremely small micro-cracks in concrete.	pH triggering is based on changes in the pH value of the concrete matrix, with a single triggering condition, and is easily influenced by additives.	(He et al., 2015; Matsuda et al., 2016; Snoeck and N, 2016; Matsuda et al., 2019; Kim et al., 2020)
Active Trigger	Ultrasound Triggering	Accurate direction, strong penetration, concentrated energy	May increase the porosity of the structure, with adverse effects on durability.	(Klibanov et al., 2010; Yim et al., 2012; Xu et al., 2018; Nodehi et al., 2022)
	Magnetic Field Triggering	Efficient, and triggering does not adversely affect the concrete substrate	Triggering equipment is complex and expensive.	(Hager, 2013; Loiseau et al., 2016; Li et al., 2020)
	Microwave Triggering	High triggering efficiency, low cost, can be manually controlled and environmentally friendly	May cause overheating of repair units or the substrate, with adverse effects on structural stability.	(Gorin et al., 2006)

which is the most direct experimental observation method. Hu et al. (2018) judged the trigger efficiency by directly observing the rupture of macrocapsules after pre-compression of the test block. For microcapsules at the micron or even nanometer level, their rupture cannot be directly observed by the naked eye, so the morphology of the microcapsules within the crack surface can be analyzed by observing them under a microscope to determine the triggering situation. Xu et al. (2021) proposed to judge the triggering situation based on changes in microcapsule morphology. The specific method is to observe the SEM image of the area where the microcapsules are located in the cement paste, as shown in Fig. 7. If the core material of the microcapsule is completely released but the shell is still embedded in the cement paste, it indicates complete triggering and good bonding between the microcapsule shell and the cementitious material. Lv et al. (2020) used ESEM to study the crack surface of the microcapsules embedded in the cement paste, observed the fracture of the microcapsules in the cement paste specimen, and judged their trigger efficiency based on the morphological appearance of the encapsulant.

New imaging technologies have been widely used in the detection of trigger efficiency of self-healing materials, and the visualization of the release process of the repair agent using imaging technology has also been proven feasible. The main techniques involved include X-ray computed

tomography imaging technology, neutron computed tomography imaging technology, and digital image correlation technology. Mihashi et al. (2000) used X-ray imaging technology to characterize the self-healing ability of intelligent concrete containing urea-formaldehyde resin microcapsules (UFF) developed by them.

Direct observation method has certain limitations. When the volume of repair units is small and the quantity is large (Dong et al., 2016), it is difficult to accurately characterize the triggering of repair units through direct observation. The degree of crack healing, mechanical property restoration rate, durability characteristics, and other performance recovery of self-healing concrete are closely related to the triggering efficiency of the repair units. Therefore, for micro-nano-level self-healing triggering units, their triggering efficiency can be indirectly characterized by the degree of concrete performance recovery after their triggering.

Due to the large number and small volume of self-healing units in self-healing concrete, it is often difficult to statistically record the triggering of all self-healing units using experimental observation and counting methods. Compared to experimental verification, using numerical simulation to evaluate and analyze the triggering of self-healing is often more comprehensive and accurate (Jefferson et al., 2018). Research on the triggering efficiency of self-healing using computer simulation analysis mainly falls into two categories: direct and indirect methods. The direct method involves modeling to directly study the response probability of the repair agent encapsulant under the triggering mechanism. The indirect method characterizes the triggering efficiency by simulating the recovery of concrete performance after repair.

#### *Selection of Triggering Mechanisms*

Given the complex application environment of concrete and the different performance recovery requirements after deterioration, selecting suitable and efficient self-healing triggering mechanisms for self-healing concrete is particularly important. Due to the lack of systematic summary and evaluation of existing self-healing triggering mechanisms in current research, this paper has identified three criteria for selecting self-healing triggering mechanisms: triggering efficiency, repair objectives, and constraints. Based on these criteria, Table 2 compares the triggering rates of triggering units under different triggering mechanisms and clarifies the applicability and limitations of each triggering mechanism, providing a reference for relevant researchers.

The effectiveness of self-healing in concrete largely depends on the triggering of self-healing units. The response of triggering units to triggering conditions, or triggering efficiency, is the basis for evaluating the triggering situation.

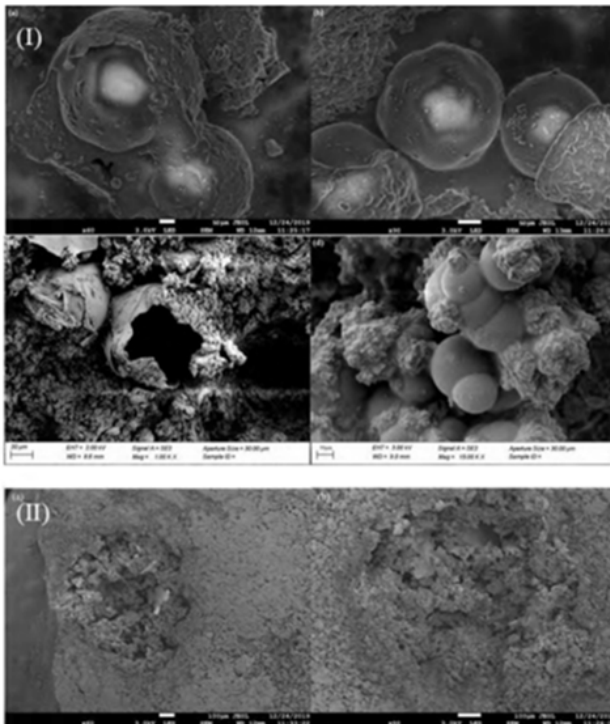


Fig. 7. SEM images of microcapsules after crack triggering, and ultrasonic triggering (II) in a cement specimen (Xu et al., 2021)

Table 2. Comparison of different triggering mechanisms in terms of triggering efficiency, repair targets, and limitations

Trigger Unit	Triggering Method	Triggering Rate	Performance Recovery			Applicable Environment	Reference
			Mechanical	Durability	Corrosion Resistance		
Gelatin Capsule	Crack-triggered	95 % success rate in capsule rupture	√	√	—	Lighting environment	(Lv et al., 2020)
Poly(methyl methacrylate) (PMMA) based macrocapsules		100 % rupture when a 0.3 mm thick wall intersects a crack with an average width > 69 μm	√	√	—	—	(Araújo et al., 2018)
Polyacrylamide (PAM) hydrogel capsules		Triggering rate up to 90 % in simulated pore solution	√	√	—	Humid environment (RH > 95 %)	(Gao et al., 2022)
Polyethylene glycol (PEG) based macrocapsules		—	√	√	—	Water environment	(Yuan et al., 2017)
Polyethylene (PE) based macrocapsules containing TiO <sub>2</sub>		100 % rupture when the crack width is > 20 mm	—	√	—	Lighting environment Water environment	(Wu et al., 2021b)
Ethylene-vinyl acetate (EVA) polymer		—	√	—	—	Water environment	(Xu et al., 2020)
Ethyl cellulose (EC) based microcapsules	pH-triggered	—	—	—	√	Water environment	(Thimmareddy and Theja, 2018)
Polyvinyl alcohol (PVA) based microcapsules		Over 80 % successful capsule release	—	—	√	Water environment	(Li et al., 2021)
Crosslinked poly(ionic liquid) based microcapsules	Ionic-triggered	—	—	—	√	Ocean environment	(Liang et al., 2018)
Nano Fe <sub>2</sub> O <sub>3</sub> and paraffin-based microcapsules	Electromagnetic-triggered	100 % release rate of microcapsules in an electromagnetic field environment with an output voltage of 600 V and a frequency of 124 kHz	—	√	√	Electricity environment	(Li et al., 2020)
Microcapsules composed of graphite, paraffin, and polyethylene wax (PEW)	Microwave-triggered	—	√	√	√	Electricity environment	(Vijay et al., 2017)

When triggering units are randomly and uniformly distributed in the specimen, the triggering mechanism under a pH trigger has a higher triggering efficiency compared to a single crack triggering mode. Ress et al. (2020) synthesized pH-triggered microcapsules using resin as the encapsulation material through the water-in-oil-in-water (W/O/W) double emulsion method, and fitted their release kinetics to a power-law model, with results showing a release efficiency

of over 80 %. Furthermore, for the self-healing mechanism triggered by cracks, improving the interface bonding strength between the capsule surface and the concrete matrix can also enhance the triggering efficiency of self-healing units. Lv et al. (2020) used an alkyl coupling agent [3-(2-aminoethylamino) propyltrimethoxysilane (KH792)] to increase the crack triggering rate of phenol-formaldehyde (PPF) microcapsules. SEM observation of the fractured surface of the test

block revealed a significantly higher triggering rate for the surface-modified microcapsules compared to the untreated control group, reaching up to 63 %, while the triggering rate of the unmodified microcapsules was only 22 %.

Some new triggering mechanisms have surpassed traditional mechanical triggers in triggering efficiency and overall performance recovery. Ultrasonic triggering is an efficient, controllable, and environmentally friendly self-healing triggering mechanism, and extensive research has confirmed its feasibility for application in microcapsule self-healing concrete. Xu et al. (2021) found that specimens triggered by ultrasonic waves achieved a strength recovery rate 2–4 times higher than mechanically triggered samples. Morphological observations further indicated that ultrasonic waves have a better triggering effect on microcapsules. Similarly, electromagnetic triggering also has high efficiency and precision, as Li et al. (2020) achieved a triggering efficiency of 100 % by placing microcapsules constructed with nano- $\text{Fe}_3\text{O}_4$  and paraffin in an environment with an output voltage of 600V and a field frequency of 124 kHz. It can be seen that the triggering efficiency, application scenarios, and material preparation costs of different triggering mechanisms vary, and therefore the appropriate triggering mechanism should be chosen based on specific requirements.

Due to the different service environments of concrete structures, the potential degradation issues and repair targets may vary. Therefore, it is crucial to understand the performance restoration of concrete after repair under different triggering mechanisms when designing and applying self-healing mechanisms for concrete. Crack-triggered self-healing concrete mainly addresses cracking and the durability of structures after cracking. Alghamri et al. (2016) immersed healing agents into lightweight aggregates (LWA) under negative pressure, and encapsulated them with polyvinyl alcohol (PVA) to obtain self-healing coarse aggregates. Cracked specimens containing self-healing coarse aggregates showed a maximum crack repair width of 0.135 mm after 28 days of water curing, and the average sorptivity index of the repaired specimen was very close to that of the uncracked specimen. Rais and Khan (2021) studied the use of recycled aggregates (RAC) as the carrier for self-healing bacteria, inducing  $\text{CaCO}_3$  precipitation as a strategy for crack self-repair. After 56 days of curing, the maximum crack repair width in the self-healing concrete with cracked bacterial colonies reached 0.63mm, and the change in the permeability coefficient (Rk) ranged from 143 % to 181 %.

pH-triggered and ion-triggered self-healing mechanisms mainly target concrete degradation caused by steel reinforcement corrosion. Liang et al.

(2018) studied the anti-corrosion effect of chloride ion-triggered self-healing microcapsules on steel reinforcement in concrete in a marine environment. It was found that the addition of microcapsules effectively slowed down the rate of steel reinforcement corrosion after measuring the mass loss rate of different groups of steel reinforcement. Ress et al. (2020), in order to verify the protective effect of pH-triggered resin microcapsules against steel reinforcement corrosion, set up a three-electrode system to test the changes in the corrosion potential and corrosion current of different groups using a potentiostat. The results showed that in the experimental group containing microcapsules, the degree of steel reinforcement corrosion was much lower than in the control group.

The restoration of mechanical strength is also one of the main parameters to consider when selecting a concrete self-repair mechanism. Wan et al. (2021) compared the strength recovery rates of specimens containing microwave-triggered microcapsules and blank control specimens. Due to the combined effect of the repairing agent released by the microcapsules and the heat generated by microwave activation, the strength recovery rate of the specimens containing microcapsules was significantly higher than that of the control specimens after the same microwave time. Li et al. (2020) designed electromagnetic-triggered self-healing microcapsules incorporated into mortar, effectively improving the compressive strength recovery rate of pre-damaged specimens.

For encapsulated self-healing concrete, the triggering method and the type of healing agent jointly determine its applicable range. Bédard and Liang (Bédard et al., 2010, Liang et al., 2018) developed a chlorine ion-triggered self-healing microcapsule, which is only suitable for concrete structures in coastal or marine environments due to the need for chlorine ions to trigger the process, and may not function in environments without chlorine ions. Wu et al. (2021b) developed a  $\text{CaO-NaAlO}_2$  healing agent that requires an environment rich in chloride ions and sulfate ions to effectively carry out the repair work. Zhou et al. (2022) designed a photocatalytic self-healing material by adding photocatalyst  $\text{TiO}_2$  to the capsule shell. However, its application environment not only requires sufficient light but also ample water as a medium for the internal healing agent to react.

Water-oxygen-triggered self-healing concrete is usually only applicable in areas with abundant rainfall or in structures such as dams and underground water pipelines. Roig-Flores et al. (2015) studied the self-healing of concrete with crystalline admixtures in different environments and found that cracks can only be repaired when they are in direct contact with water, with a repair rate of 0 % in laboratory conditions or under humidity. Chandra Sekhara

(Thimmareddy and Theja, 2018) found that the higher the water content in the environment, the better the mechanical performance recovery of concrete containing crystalline admixtures (CA). When submerged in water, the strength recovery of CA concrete reached a maximum value of 95 %.

In order to meet the metabolic needs of bacteria, the healing process of bacteria-based self-healing concrete must involve water and air. Zhang et al. (2021) found that to harness the repairing ability of bacteria-based self-healing concrete, cracked samples need to be cured in water for 28 days. Other scientists (Rais and Khan, 2021; Xu et al., 2021) developed a microbiological self-healing mechanism based on artificial aggregates and ceramic particles, which also requires water curing to achieve crack repair. Feng et al. (2020) kept cracked samples in a standard curing room and continuously sprayed calcium lactate-containing tap water onto the cracked area during the curing stage to provide an appropriate ionic environment for crack repair. Compared to passive triggering methods, active triggering mechanisms are less restricted by the environment, but they present issues such as complex operation, expensive equipment, and higher preparation costs during application. Furthermore, some active triggering methods may have adverse effects on concrete structures. Xu et al. (2021) found that prolonged use of ultrasonic waves or high-frequency ultrasonic waves may increase the porosity of concrete structures, thereby reducing their durability and service life (Table 2).

### **Conclusion**

In the past twenty years, the concrete self-healing technology has seen rapid development,

as well as the design and development of self-healing mechanisms. In order to further promote the research and development of self-healing technology and its widespread application in civil engineering, this article provides a detailed summary of the relevant triggering mechanisms for concrete self-healing and systematically reviews existing methods for evaluating self-healing triggering efficiency. Subsequently, based on triggering rate, repair targets, and limiting conditions, the article summarizes the important factors that influence the selection of self-healing mechanisms in order to provide a more rational basis for researchers in related fields to design and practice self-healing concrete.

The selection of self-healing mechanisms should take into account the service life, scope of application, repair targets, preparation costs, and the impact on the concrete's inherent properties. Ideally, the chosen self-healing mechanism should ensure that it has no significant impact on the working and mechanical performance of concrete, which is a necessary condition for the engineering application of self-healing technology. Furthermore, the durability and resistance of the self-healing mechanism within the concrete are also important factors in determining the potential practical application of this technology in engineering, as the self-healing units will be sealed within the concrete for an extended period. Lastly, the simplification of the preparation process and control of preparation costs are also important directions for future research of this technology, while ensuring the triggering efficiency and repair effectiveness of the self-healing mechanism.

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## ИССЛЕДОВАНИЕ МЕХАНИЗМА ЗАПУСКА САМОВОССТАНОВЛЕНИЯ БЕТОНА МИКРОГРАНУЛАМИ

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### Аннотация

**Введение.** Бетон как традиционный строительный материал был впервые разработан британским инженером-строителем Джоном Смитом в XVIII веке. В 1894 году француз Жозеф Монье впервые ввел бетон в формы со стальными стержнями, положив начало железобетонным конструкциям. С тех пор бетон используется для защиты стальных стержней и повышения несущей способности и безопасности конструкций. Однако бетон имеет фатальный недостаток в своей устойчивости к растяжению, поэтому ремонт бетона как отрасль бетонных материалов в последнее десятилетие получил широкое внимание как со стороны академического, так и инженерного сообщества. **Методы.** Добавление инкапсулированных миллиметровых частиц на этапе перемешивания бетонной смеси доказало свою эффективность в реализации автономного восстановления бетона. При разработке самовосстанавливающегося бетона конструкция инкапсулированных частиц и механизма запуска является важным фактором, определяющим работоспособность самовосстанавливающихся элементов и общую эффективность восстановления бетона. **Результаты.** В данной статье описываются пассивные и активные механизмы запуска в двух направлениях, подробно объясняется основной механизм запуска самовосстановления бетона и соответствующий механизм восстановления, а также проводится сравнение и анализ технических характеристик и области применения различных механизмов запуска самовосстановления, что служит ориентиром для будущей разработки продукции.

**Ключевые слова:** микрогранулы; механизм самовосстановления; механизм запуска.

# **Guide for Authors**

## **for submitting a manuscript for publication**

### **in the «Architecture and Engineering»**

The journal is an electronic media and accepts the manuscripts via the online submission. Please register on the website of the journal <http://aej.spbgasu.ru/>, log in and press "Submit article" button or send it via email [aejeditorialoffice@gmail.com](mailto:aejeditorialoffice@gmail.com).

Please ensure that the submitted work has neither been previously published nor has been currently submitted for publication in another journal.

#### **Main topics of the journal:**

1. Architecture
2. Civil Engineering
3. Geotechnical Engineering and Engineering Geology
4. Urban Planning
5. Technique and Technology of Land Transport in Construction

#### **Title page**

The title page should include:

The title of the article in bold (max. 90 characters with spaces, only conventional abbreviations should be used); The name(s) of the author(s); Author's(s') affiliation(s); The name of the corresponding author.

#### **Abstract and keywords**

Please provide an abstract of 100 to 250 words. The abstract should not contain any undefined abbreviations or unspecified references. Use the IMRAD structure in the abstract (introduction, methods, results, discussion).

Please provide 4 to 6 keywords which can be used for indexing purposes. The keywords should be mentioned in order of relevance.

#### **Main text**

It should have the following structure:

- 1) Introduction,
- 2) Scope, Objectives and Methodology (with subparagraphs),
- 3) Results and Discussion (may also include subparagraphs, but should not repeat the previous section or numerical data already presented),
- 4) Conclusions,
- 5) Acknowledgements (the section is not obligatory, but should be included in case of participation of people, grants, funds, etc. in preparation of the article. The names of funding organizations should be written in full).

#### **General comments on formatting:**

- Subtitles should be printed in Bold,
- Use MathType for equations,
- Tables should be inserted in separate paragraphs. The consecutive number and title of the table should be placed before it in separate paragraphs. The references to the tables should be placed in parentheses (Table 1),
- Use "Top and Bottom" wrapping for figures. Figure captions should be placed in the main text after the image. Figures should be referred to as (Fig. 1) in the text.

#### **References**

The journal uses Harvard (author, date) style for references:

- The recent research (Kent and Park, 1990)...
- V. Zhukov (1999) stated that...

## **Reference list**

The list of references should only include works that are cited in the text and that have been published or accepted for publication. Personal communications and unpublished works should only be mentioned in the text. Do not use footnotes or endnotes as a substitute for a proper reference list. All references must be listed in full at the end of the paper in alphabetical order, irrespective of where they are cited in the text. Reference made to sources published in languages other than English or Russian should contain English translation of the original title together with a note of the used language.

## **Peer Review Process**

Articles submitted to the journal undergo a double blind peer-review procedure, which means that the reviewer is not informed about the identity of the author of the article, and the author is not given information about the reviewer.

On average, the review process takes from one to five months.