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Formation of the principles of tectonics of modern architectural forms

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

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

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

INTRODUCTION

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

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

quality considers both technical and promising aspects of materiality in architecture.

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

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





environmental requirements, and cultural context on the development of architectural tectonics.

LITERATURE REVIEW

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

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

S. Buravchenko (2019) developed a theoretical understanding of the aesthetic and typological foundations of modern architecture. The paper offers a methodology for analysing tectonic solutions through the prism of the historical evolution of architectural forms, which allows predicting promising areas for the development of the architectural language. In the subsequent study, S. Buravchenko (2023) develops an understanding of the tectonic prerequisites for the development of various architectural

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

A. Copley & O.M. Weller (2024) offer a perspective on understanding construction tectonics on a landscape and urban scale by considering continental tectonics in a geological context. I. Bulakh *et al.* (2022) expand the understanding of tectonics to the scale of the urban environment through the study of the integrity of the artistic image of the city based on symbolisation. B. Yazdani *et al.* (2023) analyse the role of spatial tectonics in the development of cultural buildings. The study highlights the importance of the relationship between internal space and external form in the formation of the tectonic principle. M. Naghibi *et al.* (2023) expand the understanding of tectonics from a single building to a landscape scale through a tectonic approach in landscape architecture. Yu. Ivashko *et al.* (2020) analyse the impact of the natural environment on the transformation of architectural styles, identifying important aspects of the development of modern tectonic principles, considering environmental factors. C. McCoy (2021) examines building structures in the context of architectural theory, emphasising the importance of integrating technical aspects into the



theoretical understanding of tectonics. Y.B. Mahmood & H.A.S. Al-Alwan (2023) offers a new approach to integrating environmental principles into tectonic solutions by studying the relationship between tectonics and sustainable architecture. Y.I.P. Hematang & I. Ikaputra (2022) present a systematic approach to the analysis of tectonic principles in modern architecture by defining four aspects of structural tectonics. M.P. Louw (2021) reveals the importance of cultural context in shaping tectonic principles through the study of hybrid tectonics in modern African architecture.

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

MATERIALS AND METHODS

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

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

The theoretical analysis covered research on modern construction projects for the period from 2020 to 2024, based on the systematisation of scientific publications in leading architectural journals and professional databases. In particular, studies by A.F.H. Almaz & M.A.F. Farahat (2023) on stable tectonics, Y. Akgün *et al.* (2022) on kinetic architecture, and B. Yazdani *et al.* (2023) concerning the role of spatial tectonics in the formation of cultural buildings were used. The projects were analysed through the prism of three main aspects: technological innovations in architecture, reflected in the study by M.A. Kamal (2020), environmental solutions considered by Y.B. Mahmood &

H.A.S. Al-Alwan (2023), and the cultural context considered by M. García Vergara & A. Pizza (2021). This approach helped to comprehensively understand current trends in the development of tectonic principles and substantiate the theoretical model.

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

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

RESULTS AND DISCUSSION

Modern architecture is increasingly weaving dynamic tectonics into its designs, creating shapes that convey a sense of movement and liveliness through complex geometric structures. This trend reflects the transition from traditional static forms to more organic and plastic solutions. Based on parametric design and digital technologies, architects can implement complex curved shapes. Environmental considerations are becoming an important factor in modern architectural tectonics. Biomimetics inspires the creation of buildings that not only resemble natural forms, but also function like natural ecosystems, which contributes to increased energy efficiency and sustainability. The concept of smart tectonics is becoming increasingly





relevant as it integrates intelligent systems into architecture, allowing buildings to adapt to changing environmental conditions and the needs of residents. This can manifest itself in changing facades, adjusting lighting and ventilation, and transforming the interior space. Tectonics ceases to be static and reacts to external and internal variables. Modern architecture does not develop in a vacuum, it is closely linked to culture and social change. Architects strive to express collective values and identity through architectural forms, making structures expressive of social and cultural aspects. Globalisation and digital technologies have a significant impact on the development of modern tectonic approaches. This observation is consistent with research by L. Tiutina (2021), which analyses plastic language as a consequence of the evolution of tectonic principles in the architecture of the 20th and 21st centuries. The results of the conducted research on the impact of technological innovations on the development of tectonic principles correspond to the fundamental studies by L. Tiutina & A. Davydov (2021). In these studies, the researchers analysed in detail various factors that influence the development of the aesthetic language of modern architecture. The studies demonstrate how innovations in the technological sphere significantly affect tectonic solutions, which, in turn, leads to significant changes in architectural design methods and construction processes. The fusion of different architectural traditions with innovative technologies creates a new hybrid language of architectural expression that can adapt at different scales – from global to local.

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

Drastic changes in approaches to tectonics occurred in the 19th century with the spread of the latest building materials. The introduction of metal and reinforced concrete structures has radically transformed the methods of creating architectural forms. Of particular importance was the transition from traditional load-bearing walls to innovative frame systems, which opened up new horizons for creative facade solutions and allowed architects to use

space much more boldly (Kamal, 2020; Tiutina, 2021). Over the course of the evolution of architectural styles, there was a clear transformation from classical canons to modern experimental forms. Each epoch brought its own unique understanding of tectonics, which was reflected in the characteristic features of the erected structures. From the strictness of the classical order to the smooth forms of modernity, from the functionalism of modernism to the complex configurations of deconstructivism – each style developed its own tectonic language, interacting with the technical capabilities and aesthetic requirements of a particular time (Tiutina, 2021; Remizova, 2023).

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

Kinetic architecture opens a new chapter in the development of tectonic principles. Mobile building components, adaptive facades, and transformable spaces form dynamic tectonics that respond to changes in the environment and user needs (Akgiin *et al.*, 2022). This radically



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

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

With the development of virtual and augmented reality technologies, a new level of virtual tectonics is emerging, where the physical structure is enriched with digital elements, opening up new opportunities for creative solutions and rethinking the relationship between form and function. Modern approaches in the field of tectonics serve as an important tool in creating a more sustainable and environmentally responsible environment. This is confirmed by numerous studies that analyse the practical application of the basic principles of sustainable tectonics in the development of building structures that can withstand the test of time (Mahmood & Al-Alwan, 2023). In modern conditions,

architects are increasingly considering building structures not only as separate objects, but as an integral part of a larger ecosystem, focusing on their organic integration with the surrounding landscape and natural processes. This approach contributes to the development of environmentally responsible strategies in the field of architecture, where tectonic solutions are harmoniously combined with advanced environmental design strategies, ensuring a balance between innovation and maintaining natural balance (Almaz & Farahat, 2023).

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

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

Table 1. Principles of tectonics of modern architectural forms

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





Table 1. Continued

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

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

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

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

Modern architecture not only embodies the logic of structures, but also reflects cultural and social features, becoming a means of expressing collective identity and values. The impact of globalisation and digital technologies has led to the emergence of hybrid architectural forms and changes in traditional construction practices (Dmytrenko *et al.*, 2024). This encourages the development of a unique tectonic language that meets global trends and at the same time adapts to local conditions, considering local features and historical heritage. New advances in design and construction have significantly expanded the traditional understanding of the relationship between the

shape and structure of a building (Zhangabay *et al.*, 2023). Sustainability is becoming a priority in modern tectonics due to the introduction of environmental solutions in construction. Architects are increasingly considering buildings as part of an integral ecosystem that interacts with natural processes, which, in turn, affects the transformation of architectural styles under the influence of the environment. The integration of natural elements such as vertical gardens and roof landscaping is becoming an important component of the new architectural language, shaping the tectonic approach in landscape architecture (Ivashko *et al.*, 2020; Almaz & Farahat, 2023).

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

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



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

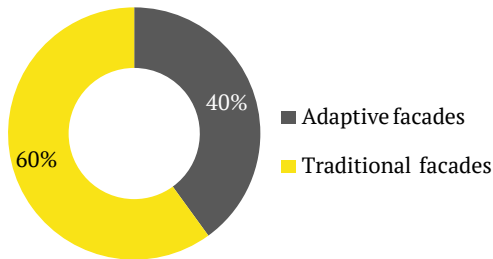


Figure 1. Use of adaptive facade systems in contemporary architecture

Source: created by the authors based on M.A. Kamal (2020), A.L. Samalavičius (2021), Y. Hurol (2022)

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

The development of modern architecture demonstrates the growing importance of environmental impact, embodied in the use of energy-efficient technologies and adaptive facade systems. The integration of these technological innovations with the principles of sustainable

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

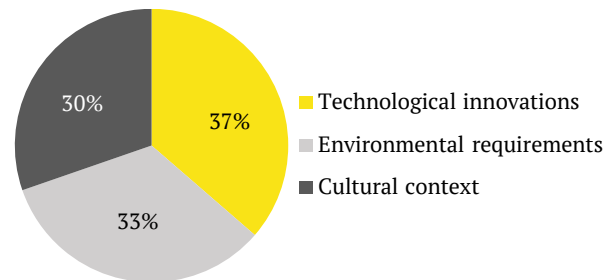


Figure 2. Interrelation of factors in the formation of tectonic principles

Notes: percentages indicate the degree of influence of each factor on the formation of tectonic principles

Source: created by the authors based on M.P. Louw (2021), Y.I.P. Hematang & I. Ikaputra (2022), Y.B. Mahmood & H.A.S. Al-Alwan (2023)

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

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





(Elsheshtawy, 2020). Table 2 shows that the concept of tectonics in the architectural field has undergone significant transformations over the course of historical development, reflecting technological innovations and the evolution of social demands. This periodisation coincides with the

study by O. Remizova (2023), which explores compositional languages and architectural logic in a historical context, which can provide a basis for understanding the evolution of tectonic principles. The study focuses on modernity and its specific challenges.

Table 2. Evolution of the concept of tectonics in architecture

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

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

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

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

In facade systems, the study of tectonic transformation marks a significant departure from traditional approaches. While the study by M. Lakkala & J. Pihlajaniemi (2021) focus on the classical principles of tectonics in static construction, the present study points to an important paradigm shift. Analysis of modern construction projects shows that 40% of structures use adaptive facade systems, which indicates the emergence of a new view on tectonic principles. Environmental factors are becoming increasingly important in architectural tectonics. Digitalisation significantly affects

the principles of tectonics, more deeply than it is presented in the study by C. McCoy (2021). Parametric design and the introduction of additive technologies radically change not only modelling methods, but also expand the boundaries of architectural expressiveness, opening up new prospects for experiments with form and space. The link between global technical capabilities and the local cultural context plays an important role. B. Yazdani *et al.* (2023) emphasise the importance of cultural identity in architecture. The study examines a more complex process, not only the preservation of cultural features, but also their creative transformation using modern technologies to create unique hybrid architectural forms. This multi-faceted study highlights the complex dynamics of tectonic changes in modern architecture and points to new areas for further research, in particular, in the field of integration of virtual technologies and the development of adaptive building systems.

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

The study focuses on a cultural context that plays a crucial role in shaping the principles of tectonics. This is consistent with the findings of I. Bulakh *et al.* (2022), which analyse the integrity of the artistic image of the city through the prism of symbolisation. The identified trend towards hybrid tectonics, which combines elements of local traditions with global technologies, is a reflection of the complexity of cultural identity in today's globalised world. Integrating technological innovations, environmental



requirements, and cultural context, the theoretical model depicts the multidimensional nature of modern approaches to architectural morphogenesis. The model was developed from the ideas about tectonic influences in modern architecture proposed by Y. Huroi (2022), and also serves as a basis for creating practical tools to implement these concepts in more specific applications. The main focus is not only on technical aspects, but also on the complex perception and use of architectural forms in various socio-cultural and natural environments. The described possibility of smart tectonics develops ideas of Y. Akgün *et al.* (2022) on the tectonics of kinetic architecture and the possibility of creating buildings that actively interact with their users and the urban environment.

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

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

CONCLUSIONS

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

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

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CONFLICT OF INTEREST

None.





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Формування принципів тектоніки сучасних архітектурних форм

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

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