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Organization of an Architectural Environment Based on Spatial and Constructive Modules in a Severely Continental Climate

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Abstract The development of modern cities is impossible without planning the architectural environment in the urban structure in the context of the climatic conditions of a region and the factors influencing this process. The greatest planning efficiency is achieved through the efficient use of capital investments in the urban structure and well-founded decisions on the formation of a comfortable architectural environment with due regard to the historical development of settlements, national traditions, local characteristics, and landscape. The main problem for architects designing objects located in a sharply continental climate is the search for architectural solutions and development models that would create a comfortable environment in conditions of a large amount of precipitation, aggressive sun, complex wind patterns, and a large temperature range (low in winter and high in summer). This study is aimed at understanding the relationship "man – space – habitat" and identifying more advanced directions and principles in the formation of the architectural environment. The principles of constructing a conceptual and theoretical framework allowed the authors to propose a model and optimize the decisions made in a specific urban planning situation. The spatial and constructive module proposed in the work demonstrates wide architectural possibilities in the formation of a comfortable socially-oriented architectural environment in a sharply continental climate. The introduction of the proposed modularity will ensure the transition to the sustainable development of society and improve the comfortable environment for finding and living people and the ecological situation in the study area.

Keywords Architectural Environment, Spatial Planning, Space Structures, Comfortable Conditions, Constructive Module, Conditions, Factors, Principles, Model

1. Introduction

A socially oriented urban environment (the territory of some cities that meets modern requirements for improving the comfort of an architectural environment) contributes to improving the quality of life [1] with due regard to natural, climatic, and regional conditions [2].

In the present stage of the development of architecture, it is necessary to predict how the socially oriented territory of a city should be formed to effectively use capital investments in the urban structure and justify decisions on the formation of a comfortable architectural environment with due regard to the historical development of

settlements, national traditions and local features, landscape, climate, and scientific and technological progress. On the one hand, despite the importance of integrated urban design and the relevance of this issue, the harmonization of the urban environment is occasionally violated in the design and implementation of architectural objects [3]. On the other hand, cities, houses, enterprises, and buildings should be built to provide a comfortable living for their inhabitants. Architecture creates psychological and physiological well-being [4]. Thus, the high rate of socio-economic and administrative changes had a significant impact on the comfort of living and migration of the population, as well as on the population's understanding of what urban space should be for comfortable living. We note that the issues of the development of socially active places in the urban structure in connection with urban socio-economic development are relevant.

The existing publications on the study of various aspects of the formation of an architectural environment can be divided into three main areas.

The first direction comprises works that reveal the historical development of spatial structures in world architecture in general and in the architecture of the Republic of Kazakhstan in particular: J.J. Cardet García [5], D.E. Arkina [6], T.L. Kilpe [7], E. Frolova [8], I.A. Bartenev, V.N. Batazhkova [9], E.A. Vorontsova [10], N.I. Brunov [11]. The analysis of these works helped to interpret archival and historical documents in the course of this study.

The second direction includes works on the application of spatial structures at the present stage. The use of spatial structures in an architectural environment is studied by A.Ya. Lakhov [12], M. Wimmer, I. Humann, A. Martovitskaya [13], A. Giyasov [14], A.V. Ikonnikov [15], Olga Semenyuk [3].

The third direction consists of works that reveal the regional features of Northern Kazakhstan. Regional aspects are the main factors influencing the organization of an architectural environment based on the use of spatial and structural modules are highlighted by A.S. Uteshev [16], K.A. Alisheva [17], A.N. Nusupbekov [18], K.D. Duisebaeva, A.S. Akasheva [19].

As the literature analysis shows, modern researchers should conduct comprehensive studies on the formation of a socially oriented architectural environment in the urban structure of a particular region and identify the main factors influencing their formation, as well as develop the principles of their organization.

The important factors determining the organization of the architectural environment occur by considering the natural, climatic, and regional conditions affecting the standard of living of the population. The main feature of the severely continental climate is the very large seasonal amplitudes of temperature fluctuations; the farther inland the continent is, the sharper these fluctuations are expressed [20]. Therefore, the architecture of cities located in a severely continental climate is characterized by the presence of covered spaces of various sizes. Covered spaces perform important functions, such as recreational, environmental, economic, social, aesthetic, recreational, and cultural [21]. Thus, despite a significant number of studies, the formation of an architectural environment in a severely continental climate was not given due attention in the listed sources.

The scientific novelty and practical significance of the article are as follows:

- The principles of development of a comfortable architectural environment based on the use of a spatially constructive module in a severely continental climate in Northern Kazakhstan are determined;
- The main factors and conditions for the formation of a conceptual and theoretical model for organizing a comfortable architectural environment are identified;
- Predictive trends in the use of a conceptual and theoretical model of a comfortable architectural environment based on the use of a spatially constructive module in a severely continental climate are revealed.

The study aims at developing the theoretical foundations for the formation of a comfortable architectural environment of cities in a severely continental climate based on historical and modern experience in the design and the use of indoor spaces.

The article consists of "Introduction", "Materials and Methods", "Results and Discussion", and "Conclusions". In the "Materials and Methods" section, we described how the collected data was analyzed and generalized. This made it possible to develop a conceptual and theoretical model of the organization of the architectural environment and its components.

In the "Results and Discussion" section, we described the principles of constructing a conceptual and theoretical model that dictates (defines) the scope of the proposed module and optimizes the decisions apprehended in a specific urban planning situation. The space-constructive module proposed in the work demonstrates wide architectural possibilities in the formation of a comfortable socially oriented architectural environment in a sharply continental climate. The introduction of the proposed modularity will ensure the transition to green energy and improve climatic conditions and the environmental situation.

2. Materials and Methods

2.1. Research Structure

Based on the above-mentioned objective, we opted for a mixed research structure following a combination of requirements regarding the collection and analysis of data necessary to achieve the research goal.

In the course of the study, we used the following methods:

- The analysis of the material collected (historical and theoretical materials);
- The method of architectural modeling;
- The analysis of the psychological and social life of the population;
- The analysis of the sociological survey of the population;
- General scientific approach and research methods.

All the analytical conclusions are based on the materials collected in the process of conducting this research.

2.2. Research Tools and Procedures

2.2.1. The Analysis of the Collected Material

In this case, it is proposed to consider the organization of the architectural environment as socially oriented, including social design, with due regard to the results of sociological research, as well as the round-the-clock and year-round comfort in the architectural environment. In the synthesis of social, urban planning, and environmental factors, we obtain the best option for the formation of a socially oriented architectural environment.

2.2.2. The Method of Architectural Modeling

The method of architectural modeling was used in the process of comparing the proposed options for experimental models of indoor spaces and determining the optimal one for the construction of a real-life object.

2.2.3. Expert Survey

We developed a questionnaire consisting of 15 key questions for the survey of 20 experts to clarify social aspects in the formation of a comfortable architectural environment based on the use of spatial and constructive models in a severely continental climate.

2.2.4. General Scientific Approach and Research Methods

A general scientific method acts as a kind of intermediate methodology between philosophy and the fundamental theoretical and methodological provisions of special sciences.

These research methods allowed us to reasonably approach the formulation of a theoretical and practical model for the formation of a comfortable architectural environment based on the use of a spatial and constructive module in the severely continental climate of Northern Kazakhstan and thereby achieve the research goal.

3. Results and Discussion

3.1. Principles for the Formation of a Socially Oriented Architectural Environment

The analysis has demonstrated that large-span structures were not widely used until it became possible to apply this technology. Gradually, they became popular in public and civil buildings. However, the use of large-span structures has not received proper development in the formation of an architectural environment.

With the development of human capabilities, the size of large-span structures and materials for their construction also change. The introduction of pumice as the main component of concrete allowed reducing the weight of large-span structures, which increased the span. The invention of auxiliary wooden structures in the form of a formwork system expanded their application and use as large-span structures, as well as introduced new types of large-span structures. Metal structures also enriched the possibilities of using large-span structures in architecture and urban planning.

With the development of calculation and design technology, spatial structures enlarged which provides room for the further development of world architecture and urban planning.

In the field of designing spatial structures, there is a trend toward a modular structure [22] reflected in its size, floor area, and unification of large-span spatial structures. It is necessary to introduce spatial and constructive modules in optimizing the process of engineering and designing large-span structures.

When forming a socially oriented architectural environment in urban places, it is necessary to be guided by the following principles [21]:

- The principle of the synthesis of architecture and nature;
- The principle of reducing climatic discomfort;
- The principle of improving the environment;
- The social principle;
- The urban principle.

The revealed theoretical patterns of forming an architectural environment allow concluding that it is necessary to ensure the synthesis of architecture and nature. The analysis of natural and climatic factors showed that only 30% of the territory of Northern Kazakhstan has comfortable natural conditions. In this regard, the organization of an urban environment aims at reducing discomfort and improving the environmental situation by architectural means (the principle of reducing climatic discomfort [23] and improving the environmental situation [24]).

The social principle is needed to consider national, historical, and cultural requirements in the formation of a socially oriented architectural environment. The town-planning principle is to consider the existing situation and create a unified architectural environment (ensemble).

Socio-economic factors are an integral part of the conditions forming community centers and developing urban spaces. Socially significant areas of the urban environment will undergo major changes and will be

transformed into a comfortable architectural environment based on spatial and constructive modules.

In the course of the research, we have developed a spatial and constructive module to organize a comfortable architectural environment in urban spaces.

3.2. Conceptual and Theoretical Model of the Organization of the Architectural Environment

The conceptual and theoretical model of an architectural environment based on a spatial and constructive module is a set of requirements that considers all the factors, trends, principles, and methods of organizing socially significant urban areas.

We determined the stages of development for large-span structures based on reinforced concrete and metal structures as well as their temporal development and trend.

At present, spatial structures are developed alongside the geodesic dome technique [25]. This allows introducing a modular polyhedron-based system into the calculation of spatial structures.

Form-making based on spatial structures has practically no limits. The classification of spatial structures, their geometric and static nature, and the constituent elements of spatial structures allows for designing diverse structural elements of an architectural environment. A typical feature of spatial structures is that their form takes part in the static work of the entire structure. A better system of spatial structures is the folded structure.

Folded plates made of reinforced concrete are a system of thin-walled slabs, working like a beam, monolithically connected at the calculated angle. Folded shells began to be used back in the 1920s. This was facilitated by reinforced concrete structures which effectively work both in compression and tension [26].

As a rule, folded-plate roofs are from two to six meters wide, and long-span structures are from 1/20 to 1/30 high. Trapezoidal roofs are from two to three meters, with a span of up to 24 meters. Depending on the building plan, folded-plate structures are arranged in parallel and radial directions. This overlaps the spatial environment of a round and trapezoidal shape.

There are folded-plate structures wedged into each other. The production technology of folded-plate structures is simple, consisting of reinforcing bars and formwork. An example of a folded-plate construction is a specialized children and youth sports school on Vasilyevsky Island built in Leningrad in 1972 (Figure 1). Architects S.I. Evdokimov and T.F. Khrushcheva, designer G. Leibovich, and engineers A. Korsakov and L. Prostakov worked on the project. G. Leibovich suggested using a multi-wave reinforced concrete structure (folded-plate structures) from prefabricated components.

The waviness, dynamics, and rhythm of folded-plate structures allow creating a unique and memorable building architecture.

Figure 1. Specialized Children and Youth Sports School in Saint Petersburg (Source: https://prawdom.ru/foto/gr-143400.jpg)

K. V. Sakhnovsky classified reinforced concrete dome structures as follows: according to the shape of the surface (smooth or ribbed) and according to the shape of the plan (round or polygonal). H. Rühle provided another classification of dome structures depending on the surface of rotation and the shape of the building plan [27,28].

In practice, a smooth monolithic dome is the most rational form of reinforced concrete. Since spatial structures are small, it is possible to cover a large environment. An example of a unique structure where a dome is used in combination with other structural elements is the project of the Japanese architect K. Tange (Concert Hall in Matsuyama, Ehime Prefecture, Shikoku Island).

According to the author's idea, it was supposed to host not only sports events but also various concerts. In this regard, K. Tange departed from the usual concept of sports halls. In collaboration with other designers (T. Asada, Yu. Otani, engineer Y. Tsuboi), he proposed to use a concrete flat dome covering a vast interior.

The production of paraboloid shells with a span from 18 to 102 meters began in the middle of the 20th century. The effective use of such shells is exemplified by the Finland Station in Saint Petersburg built in 1960 (Figure 2). The project was created by a team of architects P.A. Ashastin, N.V. Baranov, and Ya.N. Lukin and engineer I.A. Rybin. It shows many possibilities for spatial structures.

Figure 2. Finland Station in Saint Petersburg (Source: https://upload.wikimedia.org/wikipedia/commons/7/75/Финляндский_вокзал_2017.jpg)

Compressing stress is mostly formed in prefabricated shell structures made of reinforced concrete. Tensile strength is absorbed in supporting nodes by pre-stressed cable-stayed structures. Wide possibilities of prefabricated reinforced concrete shell structures are reflected by the bus fleet in Saint Petersburg, designed by architects E.M. Khevelev and O.B. Golynkin and engineers V.A. Ekman and M.I. Bregovsky [29]. Spatial structures cover a span of 96 meters without internal load-bearing columns and supports and can accommodate 500 buses. Its architectural image appears to be wavy, which gives the building an expressive exterior and interior. The building turned out to look unique and modern [30]. In addition, such structures were widely used to create covered markets in the territory of the USSR.

A significant architectural structure with the use of shallow shells is the international airport in the city of Boryspil, Ukraine (Figure 3). The airport was designed by such architects as A.V. Dobrovolsky, A.I. Malinovsky, and D.P. Popenko, and was built in 1965. The spatial structure covers the central room that has a rectangular layout with dimensions from 47 to 57 meters. It was erected from 126 prefabricated components made of reinforced concrete. A powerful aesthetic impression and a complete architectural image are achieved due to inclined reinforced concrete pillars and ample interior.

Figure 3. Boryspil International Airport (Source: https://kbp.aero/wp-content/uploads/2017/08/t1.jpg)

The above-mentioned spatial structures were made of reinforced concrete. Back in 1896, the Russian engineer V.G. Shukhov introduced the concept of a hyperbolic paraboloid built exclusively from metal structures.

A hyperbolic paraboloid is formed by the guideline of encircling the surface of double curvature. This allows drawing two intersecting lines through any point on the object's surface. Then a lattice frame is formed and a rigid form is obtained, which can withstand heavy loads.

The world's first building based on this technology was shown at the All-Russian Exhibition in the city of Nizhny Novgorod by the engineer V.G. Shukhov [31]. For example, Lenpromstroyproekt developed a spatial structure of prefabricated components from three to nine meters, which, when assembled, forms a roof from six to 18 meters. Using a hyperbolic paraboloid, it is possible to create a spatial environment with dimensions of 60-120 meters with a modular grid step of 30 meters. With the help of this design, beams were erected for various buildings and structures, garages, exhibition pavilions, shopping markets, and swimming pools.

Due to the ease of reinforcement, hyperbolic paraboloids and hyperboloids are widely used in pre-cast reinforced concrete pavements. The architect and engineer F. Candela believed that a hyperbolic paraboloid was *"the only surface of a double curvature that can be calculated using simple static calculation methods"* [32, p. 2].

A hyperbolic paraboloid creates an expressive architectural image and a contrasting spatial form. With the help of construction data, it is possible to create an architectural accent for public buildings in an urban environment.

The wide possibilities of a hyperbolic paraboloid are explained by its various installation options on bearing pads. Thus, a hyperbolic paraboloid has four types of bearings: the first type is installation on one bearing pad, i.e., mushroom- or cup-shaped buildings; the second type is installation on two bearing pads. This is how a spatial structure is formed in the form of a console; the third type is installation on three bearing pads. The objects being erected look like a cantilever; the fourth type is installation on four bearing pads with raised or lowered arches.

At the end of the 19th century, the Russian engineer V.G. Shukhov was the first to propose the concept of spatial structures of suspension. The global development of suspended structures began in the early 20th century, and it was widely used in the middle of the 20th century. Suspended structures are building structures that perceive tensile strength.

A.M. Anishchenko addressed the topic of suspended roofs in her book "The Architecture of Buildings with Suspended Roofs". Furthermore, the author classified such structures. Suspended roofs (one-layer) have a single and double curvature where structural ropes are attached either parallel or radial (for example, swimming pools in Wuppertal, Basel, and Vilnius), depending on a particular design solution.

The radial arrangement of suspended structures (cables) is typical of round-shaped buildings. The supporting structures in such buildings are external space rings made of reinforced concrete. If necessary, engineers install an additional framework in the central part of the building.

An 'architectural doughnut' with suspended roofs is the Cherkasy Central Market built under A.M. Anishchenko's project in 1971 (Figure 4). The building was the first round-shaped structure in the territory of the USSR.

Figure 4. Cherkasy Central Market (Source: https://procherk.info/images/news/022020/9cb418d8147a2373ce75ab71c8fe4da2.jpg)

At the present stage, the US architect R. B. Fuller made a major contribution to the development of spatial structures. In addition, A.G. Trushcheva described numerous experiments in the field of using structural elements of domed structures. The author provided examples of using spatial structures in architecture. The famous Soviet engineer M.E. Lipnitsky dwelled on the use of spatial structures in "Domes" [33].

Today the main task of architecture and urban planning is to balance an urban environment and the surrounding nature. The current position of the Republic of Kazakhstan on the world stage requires the intensive development of socially significant areas in cities and the development of a comfortable architectural environment.

1. The theoretical analysis of the historical development of spatial structures allows concluding that there are clear inventive breakthroughs. Each breakthrough has become a fundamental factor in the transformation of large-span spatial structures. The first breakthrough is weight reduction, the second breakthrough is construction, the third breakthrough is steel, the fourth breakthrough is lighting, the fifth breakthrough is fire safety, and the sixth breakthrough is a sliding spatial structure.

These inventions have become a decisive factor in the development of spatial structures.

2 In the course of the research, we have revealed that the architectural and planning structure of socially significant areas in the urban environment can be effectively developed through an integrated approach. Despite their small size, socially significant areas of each city are a complex and centric structure of the urban environment that forms the emotional and psychological mood of the population. The interaction and interdependence of nature, people and the urban environment form the emotional image of settlements.

3 Based on the analysis of the historical development of spatial structures, the proposed conceptual and theoretical model for transforming the architectural and planning structure of socially significant areas of an urban environment provides a modern idea of a socially oriented architectural environment integrated into urban structures and determines the main trends and principles for the formation of a comfortable urban environment.

4 According to the study conducted, the main trends include the use of the latest technology and the dominance of environmental priorities. The main principles of the proposed conceptual model of an architectural environment based on a spatial and constructive module are as follows: the principles of economic feasibility, emotional and physiological comfort with due regard to a particular natural and climatic situation in the region, and the possibility of further long-term development and transformation of urban areas.

4. Conclusions

A conceptual and theoretical model for the transformation of urban space and a spatially constructive module for organizing a socially oriented architectural environment are developed. The implementation of the developed concepts is facilitated by the proposed principles, which determine the sequence of the scientific work.

Further study in this direction will allow focusing on the relationship "person – space – habitat" and determine more advanced directions in the formation of an architectural environment, as well as the ways and main vectors for the formation of comfortable urban space.

Prospects for the development of scientific and practical research on a spatial and constructive module, as well as the developed principles for the formation of a socially oriented urban environment, are aimed at testing and introduced into production during the construction, reconstruction, and renovation of settlements.

The proposed methods can be used in design and construction to organize a socially oriented architectural environment. They are also applicable to educational institutions training specialists in the field of architecture, urban planning, and design, as well as administrative, public, and private structures responsible for urban development and improvement.

Building a socially oriented architectural environment in the future will be determined by a set of measures aimed at introducing high-quality conceptual projects for the use of modular structures proposed in this study.

The transformation and development of urban, public, recreational, and socially significant areas are among the most important tasks of architecture and urban planning at the present stage. The main condition for improving and developing a socially significant urban environment is to build a unified modular system and a fundamentally new planning scheme for socially oriented territories.

The theoretical and practical results achieved in the course of the research allow solving natural, climatic, and environmental issues of urban areas at the current stage.

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