The System Principle of Compactness as a Defining One in the Formation of Functional and Planning Structure and in the Forming of Power-Saving, Power-Active, Environmentally-Friendly and Hi-Tech Buildings

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Abstract. The adaptation of methodological peculiarities of the functioning of general-system principles, acting in comprehensive architectural systems (demecosystems) to the projects, meeting the energy-saving criterion (power-saving, power-active, environmentally-friendly and hi-tech buildings), allows concretizing with regard to projects under study the system regularities, based on the principles of compactness (least action) and structure invariance. The power-saving and compactness of a space-planning solution are the cornerstone of forming the power-saving, power-active, environmentally-friendly and hi-tech buildings with any number of storeys. The article presents the calculations of the external envelope compactness for one-, two- and three-storeyed buildings of various plan forms, comparable in the floor surface area criterion. Apart from meeting the criterion of external envelope compactness, the architectural and space-planning solution of a building should meet the optimal functional, economical, compositional and ecological criteria. Among the methods of analyzing architectural solutions the special attention in the article is paid to the system method of transit area, noted for its considerable practical exactness and promptness, which allows performing the quality evaluation of designed projects of different levels of complexity. In the design process with the use of BEM-packages and on the basis of BIM-modeling of buildings, which should meet first of all the requirements of energy-efficiency, it is reasonable to substantiate the compactness of the outward shape of buildings by calculating the efficiency criterion of architectural and space-planning solutions of a building, reflecting its functional properties (consumer properties) and based on the system principle of compactness.

Introduction

At present, when developing a space-planning solution and functional-planning structure of a modern building, the task is to select its optimal shape and the optimal architectural and space-planning design. The architectural design in the modern building and construction is more and more involving efficient decisions with the use of renewable power generation and energy-saving technologies.

The problems of searching new efficient solutions in the modern and future power industry are dealt with in the works [1, 2, 3]. The theoretical issues of forming the energy-efficient residential
buildings, passive houses and their energy performance are considered in the works [4, 5]. The selection of optimal space-planning solution for multi-storey residential buildings is studied in the research [6–7]. The questions of space-planning methods of forming the power-efficient and power-active residential and public buildings and the analysis of the issues of using nonconventional power sources are touched upon in the works [8–11]; the application of energy modeling in designing buildings in [12–14]. The issues of energy-efficiency of high-rise buildings are dealt with in the publications [15, 16]. The organization of environmentally-friendly low-rise residential construction at the territory of Russia and its regional aspects is considered in [17–19]; the surface shape of relocatable buildings as the means to improve their efficiency is researched in [20]. The methods of analyzing architectural solutions are studied in a number of research works [21–23]. The methods of environmental impact assessment of buildings are given coverage in the works [24–26].

Topicality
At the stage of concept development and design one of the main energy-efficiency measures is the optimization of the space-planning solution of a building [6–8], which allows not only improving the application properties of the design solution, but also ensuring the sparing use of energy, financial, material and labor resources, as well as minimizing the overall quantity of work at the project construction.

The purpose of the research is determining and substantiating the importance of the system principle of compactness in the formation of functional-planning structure and in the forming of power-saving, power-active, environmentally-friendly and hi-tech buildings (through the example of residential and public buildings).

Research objectives:
- specifying the methodological peculiarities of using general-system principles of the functioning of comprehensive architectural and urban-development projects with regard to power-saving, power-active, environmentally-friendly and hi-tech buildings;
- developing the scientifically-based methodological recommendations concerning carrying-out system researches and designing the power-saving, power-active, environmentally-friendly and hi-tech buildings through the example of residential and public buildings.

The object of the research are the power-saving, power-active, environmentally-friendly and hi-tech buildings through the example of residential and public buildings as comprehensive architectural systems (subsystems) of various hierarchy levels and functional complexity.

The subject of the research is the system regularity, based on compactness principle, in the formation of functional-planning structure and in the forming of power-saving, power-active, environmentally-friendly and hi-tech buildings.

The methodology of the research is based on using functional models of architectural objects, based on methodological provisions of the general systems theory and on the comparative analysis of space-planning, architectural-compositional and functional-technical solutions of power-saving, power-active, environmentally-friendly and hi-tech residential and public buildings.

The theoretical part
In this research a power-saving building is a building, designed with account of saving the energy for its climatisation. A power-active building is a building, which is constructionally combined with the units for renewable power utilization. An environmentally-friendly building is a building, which is biologically adapted for preserving the living conditions for various species of plants and animals by using environmental materials and the energy usage reduction [11]. A hi-tech building (a high-technology building) is a smart building, the architectural, structural and engineering solutions of which allow improving the indoor climate of the building and its environmental safety with the simultaneous energy usage reduction by means of using the ambient energy in the best possible way [10].
At the design stage of power-efficient projects the up-to-date technologies of building model development find their application; they contain the data about its power consumption and the ways to minimize it by means of Building Energy Modeling (BEM) packages and on the basis of Building Information Modeling (BIM) technologies [27]. In the design process the BEM-software allows comparing and substantiating the architectural solutions in the first place. Among the calculation data, obtained with the help of energy modeling software suites, there is determining the building’s compactness, the total area of exterior wall envelope, the area of heat losses and heat gains during the period under consideration, the automated calculation of the best orientation of a building, calculation of artificial and natural illumination etc., depending on the used information models of buildings.

The functional-planning structure of a building, corresponding to the most compact solution, should meet all the necessary requirements to the quality of the designed architectural space (consumer, economical, architectural, compositional and environmental criteria). In the context of objective assessment of consumer and economical properties of design solutions the methods with the sufficient practical exactness and operational efficiency are needed, both in the preliminary calculations and at using the software products. In a number of works [6, 7, 28] as a criterion of building’s shape energy efficiency the calculated compactness ratio was chosen, expressed by the ratio of the building envelope’s area to its volume:

$$k_v^{det} = \frac{A_v^{sum}}{V_v}$$  \hspace{1cm} (1)

$A_v^{sum}$ – the total area of internal surfaces of the exterior wall envelope, including the ceiling of the upper storey and flooring of the lower heated space, m²;

$V_v$ – the heated volume of the building, confined with the internal surface of the building envelope, m³.

The process of architectural modeling can be traced through the example of volumes, made of simple (square, rectangle, circle, triangle, trapezoid, rhomb, segment) or compound (made of the simple ones) geometrical shapes, brought to comparability upon the area criterion. In Table 1 the examples of space-planning solutions of buildings of various shapes are presented. For the comparability of variants a square shape 12.0x12.0 m with a total area 144.00 m² is assumed as a basis. On the basis of this area, several plan forms of buildings and the consequent space-planning solutions 1-3 storeys high were ranked according to the criterion of energy-efficiency of their shape (the calculated compactness ratio $k_v^{det}$).

In the work [17], through the example of residential buildings, the dependence of ecological performance of the designed indoor environment on the floor-to-ceiling height is shown, according to which the recommended height of the living space with account of the area of indoor residual aerial contaminations, in its upper part amounts to 3.0 m from floor to ceiling. According to this criterion the floor-to-ceiling height of the living premises in our research is taken equal to 3.0 m, the thickness of the flooring 0.3 m.

According to the calculations the most power-efficient are the rounded shapes of buildings, polygonal, streamlined and close to square. According to the research [6, 29] at increasing the compactness ratio of the shape by 0.01 the energy consumption increases by 2.6 %. So, in comparison with the square shape the energy consumption for a one-storeyed rounded-shaped building is reduced by 9.88 %; for a building with the aspect ratio 1:4 in the plan form it is increased by 21.58 %.

At developing a building model by means of BEM-modeling packages on the basis of BIM as the main criterion of energy-efficiency the calculated compactness ratio of the outward shape of a building is usually taken, which doesn’t take into account the quality of functional-planning structure. In the most compact volume the optimal architectural and space-planning solution can be determined by transit area method, based on the system principles of compactness and least action.
(energy saving). According to a number of studies [22–23] an object of architectural science is not a technical system, determined by technical and economic criteria, but an ecological system – demoecosystem (from the Greek: demos – folk, population; oikos – home, house, native land), aimed at providing the living activity conditions for the population and satisfying their social and biological needs. The functional-spatial structure of an architectural project of any level of complexity is formed with account of organizing the processes of four types of population’s living activities: industrial (\( P_1 \)), household (\( P_2 \)), recreational (\( R \)) and communicational (\( C \)). The industrial, household and recreational activities are normalizable, i.e. for buildings and premises with the specified household, industrial or recreational function the required areas can be determined (normalized) in advance according to the capacity of the building. For the communication spaces (hatches, aisles, corridors, staircase and elevator sections etc.) the minimum width is set, but their total area can’t be normalized in advance at the project development stage. According to the transit area method, successfully tested on domestic architecture, the best functional (consumer), aesthetical and economical properties are possessed by the buildings with the minimum transit area. As follows from the compactness principle, in a designed architectural project the performance of the set functional processes should be accompanied with the lowest possible expenses. The target function (efficiency criterion) as a result of calculations by transit area method is a quantitative index of the system’s efficiency – the planning index \( K \), determined for the comparable design solutions. The transit area method demonstrates the opportunities of the system approach at the variant designing of residential and public buildings and allows determining among the variants of the designed architectural space the most cost-efficient ones and having the highest functional and compositional characteristics.

The practical relevance
This work is aimed at adapting the systematic method for the projects, meeting the requirements of power-efficiency, power-activity, environmental friendliness and high technology. Besides one-, two- and three-storeyed residential buildings the variants of space-planning solutions, presented in this article, can also be used for low-capacity public buildings. The concretization of the system principle of structure invariance (the inalterability of relations between the types of activity of architectural objects with various complexity degrees) allows applying the transit area method to the projects of various functional complexity and hierarchy level. The testing of transit area method on domestic architecture can be the basis for its successful application in modeling residential and public buildings’ projects by means of BEM-packages on the basis of BIM-technologies.

Conclusions
One of the essential characteristics of saving energy, saving-active, environmentally-friendly and hi-tech buildings is saving energy for their climatisation. Compactness of a building’s volume is a key criterion of minimizing expenses for heating in the cold period of the year and for cooling in the summer season. The optimal building compactness ratio is demonstrated by the buildings of rounded, polygonal and streamlined shape and the shape close to square. The confirmation of building shapes designs, meeting the requirements of power-efficiency, power-activity, environmental friendliness and high technology, is not possible without specifying the functional properties (consumer properties) of the planning solutions. The development of a software product on the basis of BIM-modeling, concretizing the system regularity of the spatial form of a building, which would meet the requirements of power-efficiency, and the ways of minimizing power consumption by using BEM-packages, should include the evaluation of the key component – the consumer properties of architectural and space-planning design solution on the basis of transit area method. The systematic replacement of energy-inefficient space-planning solutions of modern buildings with energy-saving ones and the simultaneous development of guidelines and standards for design solutions, as well as the mass construction of power-saving, power-active, environmentally-friendly and hi-tech buildings in the Russian Federation is a matter of national importance.
Table 1(a). Comparative analysis of calculated compactness ratios $k_{e}^{des}$ for one-, two- and three-storeyed buildings of various plan forms.

| Plan form (m) | The image of one-storeyed, two-storeyed and three-storeyed volume | $A_{w}^{sum}$ for one storey (m$^2$) | The calculated compactness ratio $k_{e}^{des}$ (m$^{-1}$) for a building with 1 story 2 storeys 3 storeys |
|--------------|-------------------------------------------------|---------------------------------|--------------------------------------------------|
|              | 144.00                                          | 415.61                          | 0.962                                            | 0.613 | 0.504 |
|              | 144.00$^{a}$                                    | 415.98                          | 0.963                                            | 0.614 | 0.505 |
|              | 144.00$^{b}$                                    | 416.45                          | 0.964                                            | 0.615 | 0.506 |
|              | 144.00                                          | 418.80                          | 0.970                                            | 0.620 | 0.511 |
|              | 144.00                                          | 419.07                          | 0.970                                            | 0.621 | 0.512 |
|              | 144.00                                          | 422.01                          | 0.977                                            | 0.628 | 0.519 |
|              | 144.00                                          | 425.23                          | 0.984                                            | 0.635 | 0.526 |
|              | 144.00                                          | 425.91                          | 0.986                                            | 0.637 | 0.528 |
|              | 144.00                                          | 427.96                          | 0.991                                            | 0.641 | 0.532 |
|              | 144.00                                          | 428.42                          | 0.992                                            | 0.643 | 0.533 |
|              | 144.00                                          | 428.95                          | 0.993                                            | 0.644 | 0.535 |
|              | 144.00                                          | 429.60                          | 0.994                                            | 0.645 | 0.536 |
|              | 144.00                                          | 431.21                          | 0.998                                            | 0.649 | 0.540 |
**Table 1(b).**

| Plan form (m) | The image of one-storeyed, two-storeyed and three-storeyed volume | The area of one storey (m²) | $A_{e\text{sum}}$ for one storey (m²) | The calculated compactness ratio $k_{des}$ (m⁻¹) for a building with 1 storey | 2 storeys | 3 storeys |
|---------------|---------------------------------------------------------------|----------------------------|--------------------------------------|---------------------------------------------------------------|-----------|-----------|
|               | ![Plan form image](image1)                                    | 144.00                     | 431.59                               | 0.999                                                          | 0.650     | 0.541     |
|               | ![Plan form image](image2)                                    | 144.00                     | 432.00                               | 1.000                                                          | 0.651     | 0.542     |
|               | ![Plan form image](image3)                                    | 144.00                     | 433.55                               | 1.004                                                          | 0.654     | 0.545     |
|               | ![Plan form image](image4)                                    | 144.00                     | 433.93                               | 1.004                                                          | 0.655     | 0.546     |
|               | ![Plan form image](image5)                                    | 144.00                     | 434.40                               | 1.006                                                          | 0.656     | 0.547     |
|               | ![Plan form image](image6)                                    | 144.00                     | 436.25                               | 1.001                                                          | 0.661     | 0.552     |
|               | ![Plan form image](image7)                                    | 144.00                     | 438.00                               | 1.014                                                          | 0.665     | 0.556     |
|               | ![Plan form image](image8)                                    | 144.00                     | 438.55                               | 1.015                                                          | 0.666     | 0.557     |
|               | ![Plan form image](image9)                                    | 144.00                     | 440.71                               | 1.020                                                          | 0.671     | 0.562     |
|               | ![Plan form image](image10)                                   | 144.00                     | 442.74                               | 1.025                                                          | 0.676     | 0.567     |
|               | ![Plan form image](image11)                                   | 144.00                     | 444.34                               | 1.029                                                          | 0.679     | 0.570     |
|               | ![Plan form image](image12)                                   | 144.00                     | 445.20                               | 1.031                                                          | 0.681     | 0.572     |
|               | ![Plan form image](image13)                                   | 144.00                     | 446.36                               | 1.033                                                          | 0.684     | 0.575     |
|               | ![Plan form image](image14)                                   | 144.00                     | 448.20                               | 1.038                                                          | 0.688     | 0.579     |
Table 1(c).

| Plan form (m) | The image of one-storeyed, two-storeyed and three-storeyed volume | The area of one storey (m²) | $A_{esum}$ for one storey (m²) | The calculated compactness ratio $k_{ext}$ (m⁻¹) for a building with 1 storey | 2 storeys | 3 storeys |
|---------------|---------------------------------------------------------------|-----------------------------|--------------------------------|-------------------------------------------------------------|----------|---------|
|               | ![Plan form](image1.png)                                      | 144.00                      | 452.12                         | 1.047                                                       | 0.697    | 0.588   |
|               | ![Plan form](image2.png)                                      | 144.00                      | 458.19                         | 1.061                                                       | 0.711    | 0.602   |
|               | ![Plan form](image3.png)                                      | 144.00                      | 466.32                         | 1.079                                                       | 0.730    | 0.621   |
|               | ![Plan form](image4.png)                                      | 144.00                      | 468.00                         | 1.083                                                       | 0.734    | 0.625   |
|               | ![Plan form](image5.png)                                      | 144.00                      | 476.50                         | 1.103                                                       | 0.754    | 0.645   |

*Plan form has 24 faces

*Plan form has 16 faces

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