Parametric optimization of an architectural object’s form as a method to improve its energy efficiency

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Abstract. Parametric optimization of an architectural object’s form is one of the design tasks, which architects and project designers face at the stage of structural concept development and design. Improving the performance qualities of a design solution, while providing its energy efficiency, is the purpose of system research in the sphere of architecture and urban planning. The article gives the comparison of calculated compactness ratios of the external envelope for one-, two- and three-, four-, five-, six-, seven-storey 6-apartment compact-form residential houses, comparable in the floor surface area criterion. The application of BEM software packages on the basis of BIM-modeling of buildings is reasonable to substantiate with the optimal functional (consumer) properties of an architectural object. Systematic methodology allows considering the architectural and design problems in the interdisciplinary way. Computer modeling of architectural objects should solve the optimization tasks on the basis of version design and contain an optimization module, which would allow taking the optimal decision at the specified design constraints (conditions) and normative parameters. Computer modeling of architectural objects with the use of structural optimization methods for the version design is a promising area, which requires the formalization of project procedures and developing automated design system tools for designing buildings of various purposes.

Key words. Parametric optimization of an architectural object’s form, form making, energy efficiency, compactness principle, compactness criterion of a building form, modeling methods, computer modeling of architectural objects, optimization problem, optimization module, version design, transit area method.

1. Introduction
Optimization of space-planning solutions of a building is one of the main energy-saving measures at the stage of structural concept development and design. The theoretical insights in the form-making of energy-efficient residential buildings, passive houses and the possibilities of their implementation are considered in research works [1–8]. The questions of selecting an optimal space-planning solution for multi-storey residential buildings are dealt with in works [9, 10]. In modern science the research works, dealing with BIM-technologies are carried out in a number of areas [11–15]. The special attention is paid to using Building Energy Modeling (BEM) on the basis of Building Information Modeling (BIM) of buildings and constructions [16, 17]. The analysis of experience of designing energy-efficient buildings and applying the space-planning methods of their form-making with account of using non-conventional energy sources is considered in [18–20]. The formation of environmentally-
friendly and energy-saving low-rise housing development at the territory of Russia is considered in research works [21–24]. To systematic methods of architectural solutions’ quality assessment a number of works [25–27] are devoted. The theoretical questions of decision-making and optimization are considered in works [28–30]; the methodology of system synthesis of decision-making techniques is dealt with in [31].

2. Materials and Methods
The object of this research is the integral architectural objects as systems (subsystems) of various hierarchy levels and functional complexity through the example of multi-dwelling medium-rise residential buildings. The subject of research is the optimization procedures of space-planning solutions and the geometrical parameters of architectural objects' forms, aimed at improving their energy efficiency.

The methodology of research is based on methodological provisions of general systems theory in relation to architectural objects as the integral systems (subsystems) of a certain hierarchical level, as well as on the version design and the comparative analysis of space-planning solutions and engineering-and-technical solutions of buildings through the example of multi-dwelling medium-rise residential buildings.

The purpose of research is to determine and substantiate the essence of parametrical optimization of an architectural object’s form as a component of a system procedure of optimizing space-planning solutions of architectural objects, aimed at improving their energy efficiency (through the example of multi-dwelling medium-rise residential buildings).

3. The theoretical part
In this research work the energy efficiency of a building is understood as providing measures for saving energy for building’s climatisation. In 2011–2012, due to the demand for green construction and buildings and constructions certification in Russia, a number of standards, including the principal provisions of rating systems LEED, BREEAM, DGNB, HQE and normative requirements of the Russian GOSTs and SP [32–33], have been developed.

The selection of the shape of building, its number of storeys and configuration depend on a system of internal and external factors [34], which influence the form-making and functioning of architectural objects [25]:

– group of factors of the «Population» subsystem, which reflects demographical, social and economical aspects of environmental conditions;
– group of factors of the «Artificial environment» subsystem, which includes the scientific and technical aspects and production and consumption sphere;
– group of factors of the «Natural environment» subsystem, which reflects natural and climatic conditions, topographical and geological features of terrain, the state and potential of natural resources.

The development of computer engineering means has resulted in the increase of decision-making speed in most cases due to automation of algorithmic operations [31]. Determining an optimal design solution consists of the following basic procedures:

1) modeling (building a system's model);
2) determining the efficiency criteria of solutions;
3) optimization (comparing the efficiency of acceptable solutions);
4) selection of the optimal solution from comparable variants.

The modeling functions are [28–30]:
– descriptive function;
– forecasting function;
– normative function.

In the present-day computational design of buildings and city-planning objects we can single out two basic tendencies: parametric (generative) and kinetic (robotic). Figure 1 presents a scheme, which shows the main approaches in modern computational design of buildings and urban-planning objects.
Figure 1. The main approaches in present-day computational design of buildings and city-planning objects.

Parametric optimization of a building’s form is a multicriteria problem, which should meet, first of all, functional requirements. Applying the general compactness (energy minimization) principle to architectural objects of any hierarchy level reflects the striving to minimize various system communication (linking) values. Achieving the compactness of the design solution in each specific case is possible only at achieving the conditions [25]:

\[ P_i \rightarrow Pn_i; \quad Pn_i \rightarrow \text{const}; \quad C_j \rightarrow \min \]  

(1)

where \( P_i \) – actual (design target) values of the \( i \)-th type of works of the first group (normalizable processes);  
\( Pn_i \) – normative parameters of the \( i \)-th type of works of the first group (normalizable processes);  
\( C_j \) – parameters of the \( j \)-th type of works of the second (communicational) group.

So, the closer are the target values of the processes \( P_i \) to the norm and the lower are expenditures for communications, the more compact is the solution, i.e., the more economically efficient are the costs for power supply. In figure 2, 3 the diagrams of normalizable processes (\( P \)) and communicational processes (\( C \)) alteration in architectural systems are presented [35]. Optimization of functional and planning solutions through the example of residential housing architecture is reflected in transit area method, described in works [26].

Among the space-planning solutions, which influence the energy efficiency of buildings, we can single out the following:

- locating on the lot (with account of the land topography and nearby buildings);
- building orientation with respect to the cardinal directions;
- number of storeys;
- form;
- floor plans configuration;
- storey height, determined with sanitary-hygienic and functional requirements;
- the presence of through openings between different parts of buildings;
- unevenness of the building’s facades with bay-windows, balconies, protruding or sinking articulations (the number of exterior angles, which reduce the heat-saving properties of the outer envelope structures);
- the area of glassed façade surfaces with account of illumination norms;
- correlation of depth and width of rooms.

The thermal efficiency of buildings is considerably influenced by their facades’ roughness. Depending on the degree of the façade’s unevenness with bay-windows, balconies, protruding of sinking
partitions, the number of exterior angles, which reduce the heat-saving properties of the outer envelope structures, the thermal efficiency of a building can be reduced by 12–15% [1].

The calculated building compactness ratio is the energy-efficiency criterion of the building’s form [1, 9]:

\[
k_{c}^{des} = \frac{A_{v}^{sum}}{V_{a}}
\]

\(A_{v}^{sum}\) – the total area of all the internal surfaces of exterior walls and attic floorings, including the ceiling of the upper storey and flooring of the lower heated space, m\(^2\);

\(V_{a}\) – the heated volume of the building, confined with the internal surface of the building envelope, m\(^3\).

For low-rise buildings the ratio of enclosing structures area to the volume increases in comparison with multistorey buildings, so, the compactness ratio increases with the decrease of the number of storeys. The building of the most compact shape has the highest thermal-efficiency (energy-efficiency) properties.

According to the research [26] the most compact solution for one-room apartments at the centrical grouping is a 6-apartment section. Through the example of planning solutions of a 6-apartment medium-rise residential building (up to 7 storeys) of various plan form let us determine a calculated compactness ratio for several variants. In figure 4 a planning solution for a residential section of a 6-apartment medium-rise meridional-oriented residential building (variant № 1) is presented. Such
scheme of planning solution assumes the blocking of residential sections in the narrow sides. The floor area by the inner surface of the building’s outer walls is 285.33 m².

To increase the compactness of form of planning solutions and their better comparability let us reduce the unevenness of facades and the number of exterior angles. Let us reduce the compared planning solutions to comparability upon the criterion of area, limited by the inner surface of outer enclosing structures of the building. In figures 5–8 there are schemes of planning solutions for a residential section of a 6-apartment medium-rise tower residential house (variants № 2–5). The compared planning solutions have a corridor system of blocking one-room apartments. For comparison in planning solutions schemes let us take the general dimensions by the internal perimeter of outer walls. The presented variants № 2–5 of the planning solutions suppose the arrangement of sections as stand-alone, without blocking.

The recommended room height with account of the residual air pollution zone in its upper part according to the research \[21\] makes up over 3.0 m from floor to ceiling. In accordance with this criterion, in our calculations we take the indoor height from floor to ceiling 3.0 m, floor thickness 0.3 m. Let us determine for each of the five variants the calculated compactness ratios $k_{c,\text{ru}}$ for one-, two- three-, four-, five-, six-, seven-storey residential buildings (table 1).
Figure 7. Scheme of the planning solution for a 6-apartment medium-rise tower residential house (variant № 4).

Figure 8. Scheme of the planning solution for a 6-apartment medium-rise tower residential house (variant № 5).

Table 1. Comparison of the calculated compactness ratios $k_{\text{calc}}$ for one-, two-, three-, four-, five-, six-, seven-storey residential buildings of various plan form.

| Plan form (m) | The area of one storey (m$^2$) | $A_{\text{sum}}$ for one storey (m$^2$) | The calculated compactness ratio $k_{\text{calc}}$ (m$^{-1}$) for a building with 1 storey | 2 storeys | 3 storeys | 4 storeys | 5 storeys | 6 storeys | 7 storeys |
|--------------|--------------------------------|---------------------------------------|---------------------------------------------|----------|----------|----------|----------|----------|----------|
|              |                                |                                       |                                             |          |          |          |          |          |          |
|              | 285.33                         | 785.03                               | 0.917                                       | 0.568    | 0.459    | 0.405    | 0.374    | 0.353    | 0.338    |
|              | 285.33                         | 772.63                               | 0.903                                       | 0.553    | 0.444    | 0.391    | 0.359    | 0.339    | 0.324    |
|              | 285.33                         | 763.51                               | 0.892                                       | 0.543    | 0.434    | 0.380    | 0.349    | 0.328    | 0.313    |
|              | 285.33                         | 762.48                               | 0.891                                       | 0.542    | 0.432    | 0.379    | 0.348    | 0.327    | 0.312    |
|              | 285.33                         | 754.76                               | 0.882                                       | 0.533    | 0.423    | 0.370    | 0.339    | 0.318    | 0.303    |

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4. Results
The comparative analysis of the calculated compactness ratios \( k_{deg} \) for one-, two-, three-, four-, five-, six-, seven-storey multi-dwelling residential buildings of the centrical grouping and various plan forms allows us making the following conclusions. According to the calculation, the most energy-efficient is the streamlined plan form (variant № 5), presented in figure 8. At the increase of the plan form compactness, the «opening» of the apartments to the heated external perimeter of walls increases as well, the rooms become longer and less deep.

In the research work [9] it is described that at the increase of compactness ratio of the form by 0.01 energy consumption increases by 2.6%. Compactness ratio of the form \( k_{deg} \) for one-storey building from variant №5 as compared to variant №2 decreases by 0.01 m\(^{-1}\), which corresponds to the decrease of expenditures for heating by 2.6%; for two-, three-, four-, five- and six- and seven-storey buildings of the comparable variants (variant № 5 and № 2) \( k_{deg} \) decreases by 0.02 m\(^{-1}\), which corresponds to the decrease of expenditures for heating by 5.2 %. The calculated compactness ratios of the form \( k_{deg} \) for one-, two-, three-, four-, five-, six- and seven-storey buildings from variant № 5 as compared to variant № 1 decrease in each case by 0.035 m\(^{-1}\), which corresponds to the decrease of expenditures for heating by 9.1%.

Parametric optimization of an architectural object’s form is determined not only by achieving the most compact shape of object, floor plans, minimization of facades unevenness etc. This procedure is complex, multilayered and requires taking into account the functional (consumer) properties of the accepted design-planning solutions. For example, at achieving the most compact round or spherical plan form, one could miss the other important functional-planning requirements in the designed object.

The up-to-date methods of computer modeling allow, on the basis of optimization task setting, developing an optimization module, based on the system principle of compactness (minimization of energy), which would at the same time take into account the functional and planning aspects of the designed object.

5. Discussion
Parametric optimization of buildings of any functional purposes as means of improving their energy efficiency requires system approach with the use of computer modeling methods. The object of optimization is searching the optimal space-planning and functional solution of an architectural structure. To find the optimal solution it is necessary to determine the efficiency criterion of architectural objects as integral systems (subsystems) of a certain hierarchical level.

6. Conclusion
Parametric optimization of buildings of various functional purposes with the subsequent development of norms and standards for making design solutions and their large-scale implementation in housing construction is a priority interdisciplinary task. Through the example of one-, two- and three-, four-, five-, six-, seven-storey 6-apartment residential buildings of the compact plan form, comparable in the floor area criterion, the comparison of calculated compactness ratios of their external envelopes has been performed. The further research in optimization of buildings' form is reasonable to carry out with account of the object's functional properties optimization and the economic feasibility of architectural and structural solutions. So, the parametric optimization of a building's form is a task of optimizing the quantitative and qualitative characteristics of an architectural solution at the stage of structural concept development and design. Development of algorithms in computer modeling is possible at setting an optimization task and determining an efficiency criterion of solutions. Optimization becomes possible at the comparison (commensuration) of the efficiency of acceptable solutions.
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