BIM-technologies and digital modeling in educational architectural design

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Abstract. The article analyzes the results of the implementation of numerical methods of architectural form finding in educational design in the second year of study developed at the design department of KSUAE as part of the undergraduate course. The original method of form finding is a combination of tabular methods for setting the geometric parameters of architectural forms in Revit Architecture and visual programming tools such Grasshopper and Dynamo. This experiment in the field of "design of the architectural environment" (DAS) with extensive use of BIM-technologies and digital modeling in the educational process, has been conducted for more than 3 years and gives positive results, the main of which is the intensification of the educational process and the variability of complex geometric shapes based on the use of advanced numerical methods. According to this approach, the entire course consists of 4 stages, which students consistently perform during the second year of study, work on one architectural topic, which covers four coursework projects: "Composite design of an architectural form" (structural “skeleton”), “Design of an architectural facade” (“architectural skin”), “ Design of the internal space "(interior), "Design of the external space" (exterior). They represent four parts of one general topic, each of which should demonstrate the influence of different subsystems of the structure on the overall volumetric and planning solution. In the process of work at each stage (course project), there is a constant resolution of the contradictions that arise during the design process between the various subsystems by regenerating the general architectural model as part of the Revit Architecture parametric modeling program, which plays an important role in the formation of students' professional skills.

Keywords: BIM-technologies, educational architectural design, designer-architect, architectural environment design, compositional structuring, digital modeling.

1 Introduction

BIM technologies, parametric design, numerical and algorithmic methods of form finding are necessary elements of educational design in all advanced architectural schools. This trend is relevant both in theoretical and methodological terms for architectural and design practice. Analysis of publications in leading scientific journals shows that modern building information modeling (BIM-technologies) revolutionizes the traditional practice of the construction industry and enhances the impact of the design process on the overall life cycle of construction and operation of structures, including the topic of sustainable and green architecture [1], as well as the use of integrated approach in design [2]. The quality assessment of architectural design also takes place on the basis of BIM-technologies, which, of course, affects the decision-making process [3]. All this applies equally to educational design.

Parametric design is actively used to create, document and manufacture projects with a high level of detail and differentiation, often at the level of individual building components [4]. Therefore, parametrics plays an increasingly important role in educational design both for the intensification of the form finding process, and for the automated production of drawings. In addition, parametrics, as a design tool, affects the stylistic and artistic qualities of the educational project. In the parametricism
their own areas and varieties appear, for example, “meta-parametrics” [5], “parametricism 2.0” [6].

The ability to create highly artistic works within the framework of parametricism produces a creative and competitive environment in educational design, which undoubtedly increases students’ potential. Along with the constant evolution of sustainable design and architecture [7], as well as the strengthening of the ecological trend within this framework [8], today in educational design the question is more and more often raised about the formation of “parametric design thinking” among students, its theoretical foundations, cognitive roots and principles [9], which are formed at the intersection of various knowledge systems: cognitive models of typological and topological design in architecture; technological models of digital design; digital tectonics of the design and manufacture of materials [10]. All this determines the methodology of modern design as a whole in terms of ensuring the sustainable development of structures, the formation of the concepts of ‘sustainable processes’, ‘recyclable processes’ and ‘building seeds’ in parametric architecture [11].

Today, for the full-fledged training of a specialist in the field of architecture and design, intellectual and digital technologies must be implemented from the first stages of the educational process. Modern experiments in the field of architectural morphology [12], including digital architecture, may be incomprehensible to unprepared students without clearly built methodology and algorithms for design work. A review of sources shows that the most popular parametric design tool is the Autodesk Revit [13] with a wide range of basic tools and add-ons for implementing the generative method of three-dimensional modeling of the form [14], outputting the necessary design documentation and the subsequent presentation of their product [15]. That is why most of the leading architectural universities in the world use it as one of the main tools for educational design. Many researchers, for example, Tsai M., Chen K. note the success of combining the traditional and online forms of training for organizing the digital environment [16], Abbas A., Din ZU draw attention to certain barriers to BIM integration technologies, inertia of the education system [17], and LóPez-Zaldívar O., Verdú-Vázquez A. - show great interest in this design method, in the absence of well-established rules and standard protocols of action [18]. All this increases the importance of the formation of a set of educational tasks in parametric modeling [19], as well as BIM technologies in the curriculum of architectural universities [20], and also distance learning should be added to these tasks [21].

Modern experiments in the field of architectural morphology, which are carried out in leading universities on the basis of avant-garde techniques in the framework of the educational process, are often inconsistent, and even moreover, not oriented towards the use or development of existing building technologies. In our opinion, this is the main contradiction between the existing practice of construction and new trends in architectural design. It is caused by the shifts in today’s theory of architecture and design, aimed at the use of numerical and algorithmic methods of finding a form. As part of the original methodology of educational architectural design1 experiments are carried out to introduce modern methods of defining a form, and design aimed at using building information technologies (BIM) and modern methods of digital modeling. First of all, this technique is based on the use of visual programming methods (Grasshopper and Dynamo) in combination with BIM technologies, within the framework of programs such as Revit Architecture, Digital Project, ArchiCAD and Tekla Structures. The combination of geometric modeling programs and building software systems like Revit makes it possible to embody architectural fantasies into the framework of existing technologies. The main difficulty of this transition to new technologies is the introduction of a new “parametric” paradigm in the traditional process of architectural design.

1 An original technique was developed at the Department of Design of Kazan State University of Architecture and Engineering (KSUAE).
Thus, the aim of the study was to develop a comprehensive methodology for the effective teaching of undergraduate students in the course “design of the architectural environment” using methods of algorithmic design of architectural structures based on modern approaches in parametric form finding.

The following main tasks were solved:
- development of a technique for setting the geometric parameters of structural elements in tabular form in Revit Architecture to build complex architectural forms of shells and envelopes; use of visual programming tools (Kangaroo) to determine the shape of soft membranes and canopies; application of algorithmic design methods (Grasshopper) for the construction of solid, lattice and bar structures.
- development of an interconnected step-by-step learning system, which consists of 4 stages, covering the entire course with four coursework projects: “Composite design of an architectural form” (structural “skeleton”), “Design of an architectural facade” (“architectural skin”), “Design of the internal space” (“interior”), ”Design of the external space” (“exterior”).
- the use of advanced methods for the presentation of student projects based on programs such as Lumion, 3D MAX and Photoshop.

The subject of research includes modern methods of digital modeling and algorithmic design of architectural structures and design objects.

To ensure that transition, a special logic of the educational process was adopted. Traditionally, in the second year in accordance with the proposed curriculum, bachelor students carry out 4 projects (two in the autumn and spring semesters, respectively). Within the process of delivering these four projects, students must master the basics of architectural design. After the second year, the task is set to carry out specialized projects that are dedicated to the actual design topics. In contrast to architectural students who, over the course of four years, have been moving from simple projects to complex ones, designers have to spend only a year on the formation of an integrated and interconnected view of the problems and design fundamentals. In addition, the traditional approach to teaching architects is based on the paradigm of functional and compositional design, which was formed at the beginning of the twentieth century. First of all, it implies the development of a functional solution of the building, spatial modeling and the plan of the structure. A constructive and structural system that usually does not go beyond the prevailing standard solutions, is “adjusted” to the previously obtained volume. Actually, the architect’s method itself, its content, is revealed throughout the entire period of training on a fairly large number of typological examples (educational architectural projects). Thus, design students are not able to sufficiently study the traditional design methodology in all typological diversity that architects have.

Due to these limitations, the traditional sequence in teaching from simple to complex objects was supplemented and complicated by a different concept. In accordance with the new concept, undergraduate students of the DAS (design of architectural environment school) work on one topic throughout the whole year, which is devoted to four course projects. Each project should demonstrate the effect of various subsystems of the structure on the composition of the volumetric and layout solution. Four coursework projects are four sections of one common theme: the “structural skeleton” (1), its “architectural skin” (2), the “internal space” or building interiors (3) and the “surrounding architectural environment” or exterior (4). Upon completion of the topic, students prepare the resulting exhibition and presentation, including animated video series and a slide show using relevant software such as Lumion and Cinema4D. Such a sequence is the basis for the formation of a holistic understanding of the fundamentals of architectural design within the framework of the bachelor's program at DAS and, as time has shown, gives stable good results. The level of elaboration of the design solution and detailed documentation is stipulated in the design assignment, which is prepared by the methodological commission of the department. As part of the design, a series of practical exercises are carried out aimed at mastering the modeling and visualization techniques within the framework of such programs as Revit Architecture, Lumion and 3D Max. For some exercises employ
the basics of Rhinoceros software. Traditional graphic tools are also used at the stage of development of the preliminary sketch of the project, including Abode Design Suite.

2 Methods
To intensify the process of educational design, a numerical method was developed for constructing complex architectural forms using a tabular set of geometric parameters (element sizes) in Revit Architecture. This table prescribes the initial values of dimensions and the pattern of their change in space depending on the system-forming factor or parameter, for example, the serial number of a typical structural element in the system. This element can be a rib, a bar, or, in the general case, a pivot of simple outline and filling between adjacent elements. When it is loaded into a new family of components and propagated using the “array” tool, a gradual change in the entire geometry of the structure occurs by changing serial numbers. The sequence number of the structure is changed using a simple script created in Dynamo. Thus, a simple-in-form element obtains complex behavior in space, and the system of these components of the same type forms curvilinear smooth shells consisting of strips that can be turned into flat blanks. The curvilinearity and smoothness of changes in the geometry of the shells is achieved through the use of trigonometric functions. The parametric dependencies in the table allow students to change the shape of the structure in the process of modeling in real time by experimenting with various coefficients (mainly the frequency and amplitude of the generating function). This method has also been applied to spatial pivot constructions using the special “Generic Model Pattern Based” component, which is part of the standard set in Revit. To use this method in educational design, a special system of exercises was developed that encompassed a fairly wide range of structural elements. In addition, algorithmic design methods were used using visual programming tools based on the Grasshopper plugin. This method was used to determine the shape of soft shells based on the Kangaroo simulation tool, which is an important part of Grasshopper. It should be noted that the implementation of spatial models in educational design is possible only through a combination of various methods and tools.

3 Results
3.1 Compositional Structuring of Architectural Forms
The first project is devoted to the basics of compositional modeling based on the development of a structural system or a "skeleton" of a future structure. At this stage, the project is aimed at developing students' skills in artistic modeling using spatial bar structures based on BIM technologies. The unusual nature of this approach is that students, starting designing, from the very beginning (from the moment the assignment is issued) are not limited by the purpose of the future structure, moreover, they do not have the knowledge of the typology of existing architectural structures (in accordance with the curriculum, they begin to study this subject a little bit later). Of all the restrictions they follow are the overall dimensions: span (15-24 m), height and length of the structure. Basic elements, of which the structure should be “assembled”, are rods and plates. Thus, the designed load bearing skeleton refers to the rod structures, in the form of a system of joists and the connections between them. The main task at this stage is to develop an interesting volumetric composition of this type of structure. The functional tasks of organizing the architectural space are not solved at this stage. The design process itself is carried out within the framework of the Revit Architecture program, which allows not only to build geometrically correct structures, but also to attach real elements with specific dimensions to abstract geometry. Naturally, the design process itself is provided by methodological material: a manual, instructions, and most importantly - tutorials for performing practical exercises in the classroom. Depending on the resulting compositional design of the architectural form, the projected facility is given a certain functional purpose. If an elongated shape is obtained as a result of the experiment, then the final result can be interpreted at further stages, for example, as a pedestrian
bridge, if the width and length of the structure have the same dimension, then the truss structure of the hall space of a large span can be obtained, and at a considerable height - a tower structure may be designed. Upon completion of the first project, usually, students are already able to define the purpose of the structure. In addition, already at the stage of development of the skeleton of the building, a figurative idea of an architectural composition is formed, for example, branching tree-shaped supports can lead to the idea of an unusual covering of a greenhouse, etc. Thus, already at the very early stages of the student project, the task is set to stylistically comprehend the supporting structure and constructive form of the future building. Using building information modeling programs of the Revit type allows you to study architectural and technical graphics in an accelerated mode as part of a training project, in accordance with the requirements for the implementation of architectural drawings, since the program itself includes the ability to automatically produce drawings and specifications. Another important aspect is the use of parametric design methods for the implementation of architecturally complex architectural forms, the possibility of such an approach is included in the Revit program. For this, a special technique has been developed at the design department, which allows you to establish relationships between the geometric parameters of structural elements, which vary with each serial number of the element (in other words, the construction element number increment). Moreover, the elements themselves have a fairly simple form, but rather complex behavior in space. As a result of a change in the planar contour at each step of the roof or bridge structure, students obtain, through geometric transformations, a rather complex shape of the architectural object. This is achieved on the basis of a tabular specification of the dimensions of the structure in Revit (Family Types Dialog), and their changes depending on any main or control parameter, for example, the serial number of the structure element. This “numerical” approach to construction as part of educational architectural design is intended to complement the traditional methods of architectural form finding, significantly broadens the horizons of students, and the desire for complex and interesting forms leads them to the study of architectural geometry. Using this technique, students receive the basics of the design of rod systems taking into account the geometric immutability of the supporting structure, ensuring the longitudinal stability of the building, by establishing the necessary number of connections. In addition, in the framework of practical exercises, students get acquainted with the rules for designing swivel joints of rod systems using the tools of three-dimensional modeling in Revit Architecture.
Figure 1. The project №1 "design of architectural form", completed by a 2nd year student Sokolova M.

3.2 Architectural facade design
Another important aspect of this teaching methodology is feedback, or the need to adjust the source object in connection with new tasks and the interaction of architectural subsystems. So, the second project “design of an architectural facade”, carried out in the first semester, is devoted to the development of facade elements of the structure obtained as a result of the first project. At this stage of work, the skeleton of the building is dressed in an “architectural skin”. During this project the ratio of solid and glazed surfaces of enclosing structures is determined, and the task is to design stained-glass windows and supporting elements of glazing, such as a “spider” type fixings, as well as the entrance block with a canopy, the platform in front of the entrance, with elements of landscaping and evening lighting. An important part is in the system of exercises dedicated to the development of parametric ornaments and facade panels. As part of practical exercises, students learn the methodology of the parametric design of wall panels, with a variable geometry that depends on environmental parameters, for example, resizing the panel's light opening following the trajectory of the sun, which is important for creating uniform lighting without direct sunlight for long-span halls with art exhibition. Within the same project, issues of creating an accent at the entrance in the form of art objects, urban sculpture, graphic elements and shop windows are addressed. The solution of these issues naturally leads to the need to adjust the constructive solution implemented in the first draft. Since the project is carried out as part of the parametric modeling in the Revit program, the adjustment of the initial structure appears to be quite painless for students, due to the automatic regeneration of the entire project. At the same time, it is forbidden to completely redo the initial project (only in case of an unsatisfactory assessment, and by a special decision of the department). Thus, the relationship between the supporting system and the enclosing structures, between the volumetric-structural solution and the entrance to the building, etc., is clearly demonstrated. An important component in mastering the basics of architectural design is the development of evening illumination of the facade of the structure, revealing (or visually transforming) the general shape and plasticity of the building at the level of its perception in the dark during artificial lighting. Architectural visualization of the building with the illumination of its facades by various elements of outdoor lighting is an obligatory component of the project “Design of the architectural facade”, the second project stage of the overall work. By this time, in order to visualize the main projections, students, in addition to Revit and Showcase, begin to master more complex programs such as 3ds Max with Vray, and to further adjust the received images using Adobe Photoshop.
3.3 Interior design

The third project, “interior design of a public building”, plays a key role in the entire chain of ongoing projects. As part of this project, students turn to the traditional methodology of architectural design, get acquainted with the basics of architectural typology. Along with functional planning, compositional and figurative-semantic tasks, students in this course project consider the design of horizontal and vertical communications in a building or structure. Particular attention is paid to the subject content of the interior space of the designed object, including the selection of furniture and equipment, which ultimately form a library of three-dimensional interior components used in the project in the Revit Architecture format. The plan of the premises with the arrangement of equipment is an obligatory component of the project. The general functional zoning and configuration of the planning structure are based on the “tree of shortest trajectories of movement” between the main functional zones of the structure. At this stage, the load-bearing structure and enclosing envelope are also adjusted taking into account the dimensions of furniture and equipment, as well as the artistic and compositional concept of organizing the internal space of the designed building. In our opinion, resolving the contradictions that arise during the design process between the various subsystems, by regenerating the architectural model within the framework of Revit Architecture, plays an important role in the formation of professional skills among students. Thus, based on the functional zoning scheme, which is built using the tools embedded in Revit, and the motion paths, the spatial structure of the structure and the composition of the interior space are determined. On the basis of the obtained schemes, and in accordance with the aesthetic idea and the concept of plasticity of the interior, students select all surfaces’ materials, which results in the corresponding plans and scans. An important role is played by floor surfacing, especially for such structures as greenhouses or specific exhibition halls, where the artificial relief can become the main element that forms the internal space. In addition, the project addresses issues of general interior lighting and highlighting of exhibits and art objects. Based on the selected lighting fixtures, for example, within the framework of Revit, a scheme of their placement is carried out and the structural elements of the suspension devices are shown. The

Figure 2. The project №2 “facade design”, completed by a 2nd year student A. Burova.
main element of this project - a perspective view of the interior - is performed by visualizing the architectural model in Showcase or 3ds Max with a combination of natural and artificial lighting.

![Figure 3](image)

**Figure 3.** The project № 3 "interior design", completed by a 2nd year student Salyakhutdinova A.

### 3.4 Exterior design

The final project "design of the architectural environment" covers the development of the built environment surroundings of the structure obtained at the previous stages of design. As part of this project, students study urban planning aspects of the design of the architectural environment. The knowledge and skills gained as a result of this project become the basis for specialization in the development of urban design elements during the following courses of later years of education. In the framework of this project, they should study basics of organizing transport services for urban areas, including parking design, route tracing and the location of public transport stops, the basics of planning structure design taking into account various types of urban development, the existing terrain, green spaces and other natural environmental features. In addition, the task is to design urban furniture, canopies, pavilions, and other elements of outdoor equipment, landscaping, elements that form the so-called city ground or parterre. To tie the designed building to the construction site, students create a simplified situational model within the framework of the project. To form an integrated approach and to solve this problem, students themselves are invited to model the initial situation with further linking their structure, which, naturally, distinguishes this approach from the actual design sequence, but is methodologically effective enough for a phased study of issues related to the formation of urban situation. In the process of implementing the course project for each of its sections (topics), students are provided with a small overview of examples, and after that each part of theoretical material is followed by an exercise performed in during practical lesson/workshop to test the understanding of theory part. In the process of developing the planning structure at a fairly generalized level, students have to consider the issues of transport services, the hierarchy of highways and roads, options for junctions and intersections, as well as their configuration and layout. An important place in the project is the development of the structure of pedestrian connections. Since it is believed that the projected building is part of the city center, it should be connected to the main centers of gravity (central alleys, embankments, squares, public transport stops, etc.). As a result, the built-up hierarchy of gravitational points within the projected territory is united by a tree of shortest paths,
which is implemented in the project as a system of pedestrian spaces. The most detailed in the project is the improvement of the alley connecting the nearest public transport stop with the main entrance of the projected building. Students select the appropriate types of green spaces and lawns in order to highlight the spatial and planning structure inherent in the project. For presentation and graphic design of the project students are taught to use software of the Lumion type.

Figure 4. The project № 4 "exterior design (design of the architectural environment)", completed by student 2nd year K. Eremeeva.

4 Discussions

4.1 Testing the methodology at the university

The developed methodology for the numerical form finding for teaching architectural design has been successfully tested for 3 years at the Design Department of Kazan State University of Architecture and Civil Engineering. The stability of the experimental results was ensured by the setting of tasks and the system of exercises. The feature of the developed methodology consists, firstly, in the universality of the created parametric model, and secondly, in a gradual increase in the number of tasks and their sequential complication in the learning process, thirdly, in the step-by-step modification of the parametric model created by the student, in its sequential change to the relevant project requests from the previous stage to the next one.

Similar training courses in architectural design appear today in other universities, having their own characteristics, for example, Vatin, N. I., & Usanova, K. Y. offer design with a consistent complication of the typology of the object from "residential to public" [19].

4.2 Problems of adaptation in the educational process

Judging by the reports of foreign colleagues, it is far from always possible to coordinate advanced avant-garde design methods with the educational process, moreover, they are often oriented towards the future and are ahead of the development of existing building technologies. Nevertheless, world experience in the field of architecture and design theory and practice shows us examples of successful solutions to these issues. The authors report on current trends in the development of the BIM
curriculum (for example, methods, timelines and contexts), as well as a synthesis of implemented pedagogical strategies with a detailed discussion of their consequences and effectiveness in various studies and contexts. These strategies are aimed at solving a number of important pedagogical issues, such as student enrollment, optional or compulsory use of BIM, important competencies and skills, training methods, participation in the industry, task development, as well as assessment methods and criteria. This synthesis shows that the development of pedagogical strategies for the formation of BIM is a difficult task, and it is necessary to find a compromise between the advantages and disadvantages associated with these strategies [20].

4.3 Use of distance learning
The modern educational process is increasingly focused on digital technology using distance learning. This trend is reflected in the teaching of design disciplines. For example, a distance learning course on the building information model was created at the St. Petersburg Polytechnic University, which is part of pre-university education and a tool of University Internet marketing [21] - an urgent and necessary idea for the development of design practice. The developed methodology for teaching architectural design is also fully digitalized and can be adapted and transferred to distance forms of the educational process.

5 Conclusions
As a result of the experiment on the implementation of numerical design methods and BIM technologies, we can conclude that the problems that arise in educational design have both similar and distinct features with real design in large offices, since their goals and objectives are quite different. So, the most crucial moment of the introduction of such methods is associated with the initial time-consuming stage of training students (or employees, if it comes to the office). This stage is aimed at performing specially designed exercises that step by step demonstrate the use of numerical methods in modeling spatial structures (solid, lattice and pivot curvilinear shells of various kinds of envelopes of complex geometry). The implementation of these exercises ensures the successful completion of the project to obtain an appropriate positive assessment. However, if specialized knowledge is needed for practice, educational design is aimed at providing students with parametric methods that allow them to realize their "architectural fantasies" in real structures.

The experiment clearly demonstrated the effectiveness of the developed methodology, which is based on the use of visual programming tools (Grasshopper and Dynamo) in combination with BIM technologies, within the framework of such programs as Revit Architecture, Digital Project, ArchiCAD and Tekla. It is a combination of geometric modeling programs and building software systems of the Revit type that makes it possible to realize the architectural concept within the framework of existing technologies.

The experiment showed that the use of numerical methods, within the framework of the developed methodology, solves the problem of variability and making changes at various stages of design. So, by simply sorting the values of the input parameters of geometric dependencies presented in tabular form in Revit, you can change the geometry of complex structural forms, which allows students to find the most effective and aesthetically pleasing design solution. The developed technique for the numerical finding of architectural forms is based on the “from simple to complex” sequence, that is, a simple element in its geometry receives a complex “behavior” in space when creating an array of these components, through the use of various kinds of dependencies and gradient changes in the geometric parameters of the original element. This technique does not require any prior knowledge and is easily absorbed by students. This approach fits well with the traditional design methodology and is applied in the range from compositional design to the organization of the internal and external space of the structure.
In conclusion, it should be noted that this experiment has been conducted for more than three years and demonstrated fairly good results. In addition, the flexibility of the principles laid down in this technique implies its further development. On the one hand, it is planned to further introduce parametric and algorithmic methods into architectural form finding, and on the other hand, it is necessary to implement the use of information modeling methods (BIM) and new construction technologies in conjunction with GIS based programs, such as InfraWorks as part of educational design. This methodology is consistent with the existing curriculum and can become the basis for the creation of a unified structure of methodological complexes, with the inclusion of subsequent architectural design projects and auxiliary subjects in a single training system for design students.

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