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SIMULATION MODELLING DEVELOPMENT IN DESIGN OF ENERGY EFFICIENCY IMPROVEMENT OF ARCHITECTURAL SOLUTIONS

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Abstract. The article deals with the methods of using and improving the work of the simulation modelling method in architectural design. As a result, the authors have tried to optimize their work with criteria such as energy demand, environmental impact, geometry, and materials. The rational use algorithm of these software products in the integrated design of energy efficiency improvement of buildings, complexes and urban structures have been proposed.

Key words: simulation modelling, energy efficiency improvement, architectural climatology, energy analysis, BIM design, environmental impact.

Problem statement

The modern information technologies development creates opportunities and prerequisites for the search for fundamentally new approaches to the architectural space organization, new means and techniques of artistic expression in architecture. The new time requirements reflect an attempt to transfer architecture from a designer's subjective ideas plan to the rational plan of objective solutions and tasks, in particular in the architectural solutions energy efficiency design. Due to the Ukrainian law harmonization program with the European Union standards and the adoption of energy development strategy (Nova enerhetychna stratehiya…, 2020), which includes issues ensuring country energy independence, the question of high-quality architectural and energy design arises. Buildings consume about 40 % of the total energy. The European countries reconstruction and new construction requirements are much stricter. For example, as of 2019, the energy consumption standard for new buildings in Germany is <15 kWh per m^2 of a building per year (German Federal Ministry of the Interior, Building and Community (BMI), 2018). The European Performance of Buildings Directive (EPBD) requires all new buildings in the European Union to be “nearly zero-energy” buildings by

2020 (Directive (EU, 2018). In Ukraine, according to current state standards, this indicator is almost 7 times higher – <100 kWh per m^2 per year.

The energy efficiency design software products evolution occurs simultaneously with the growing relevance of these issues and the technical and informational potential development. It is significant to apply them in the early stages of design, where the decisions with the most significant impact on the final energy consumption operational indicators and costs are made

Analysis of recent research and publications

The most widely used concept in architecture theory today – "digital modelling" – cuts across all domains literally: design, engineering, graphics, tectonics, and even the style directions creation, (Hygh, and others, 2012), (Nadyrshyn, 2013). It is not so much associated with the computer-based design tools but with the parametric modelling and new technologies, materials and approaches in construction. We can say that this is a transition to a new ideology, a new way of designing, a new way of thinking in architectural design. The advantages of the computer-based design are high speed, low cost, versatility and convertibility of results, as well as the ability to use network resources for collective design (Shubenkov, 2006). This progress was already anticipated in 1992 by G. A. van Nederveen and F. P. Tolman through introducing the term BIM (Building Information Modelling) (Van Nederveen, Tolman, 1992). The correspondence of individual industry and related systems require certain standardization and consistency both at the conceptual/methodological and hardware levels (Saprykina, 2017), (Khayman, 2008). Therefore, many critical questions are raised by the design practice immersed in interdisciplinary research, the materials behaviour testing and the design processes, which are directly related to the computerization of architectural creativity (Shuldan, 2002), (Shuldan, Brods′kyy, Hutnyk, 2011), (Shuldan, Al-Ahmmadi, Shtendera, 2018). In this article, we have continued to explore the relationship between spatial design and energy efficiency, as it involves computational methods, thermodynamic processes, and experiments with geometrically controlled performance logic. Today there is a significant amount of scientific research and materials that consider simulation models as a component of parametric design but they are not considered as a separate and significant tool for architectural design.

Objective of the article

The simulation models in the energy efficiency improvement design are the object of the article, in particular analytical models created with the help of special equipment and maquettes, and computer models based on digital models (calculated, graphical and multicomponent). The main task of the article is to define simulation models as one of the main tools of architecture research, which is done in several stages – the study of software, their application in educational and practical architectural objects, the study of energy efficiency for the given parameters of computer modelling, and theoretical scientific generalization.

Results and discussions

The last two decades have seen the expansion of modelling and simulation capabilities in architecture, engineering and construction (AEC), which has improved production efficiency, modelling capabilities, and data exchange as well as collaboration between processes. These advances provide the foundation for a variety of next-generation capabilities driven by the development of large-scale integrated digital and physical ("cyber-physical") systems that connect the embedded environment with real-time modelling and analytics via Cloud and IoT technologies. New research programs that combine information science, systems, and sounding using traditional embedded design and engineering systems to support the development of scalable intelligent cyber-physical systems will be one of the central operating means of the next generation construction industry.

The energy efficiency improvements design of architectural solutions, comparison and selection of optimal measures and their sets at any stage can be solved using simulation models. At the same time, the most important among them are the following:

1. External climatic factors simulation.

2. Microclimatic parameters simulation of the building.
3. Building or complex geometry options simulation and selection.
4. Structures selection and calculation.
5. Simulation of the effects of the surrounding development and complexes development prospects.

Simulation modelling, depending on the tasks set, allows you to:

A. Determine the level of aerodynamic form of the building, that is, explore existing buildings, design and adjust the form of the new building and its parts;

B. Determine the level of premises illumination, calculate the insolation, shading and passive solar energy receiving;

C. Solve buildings design issues on open areas and in an existing development, solve issues in terms of their form, planning and dimensions;

D. Associate the previous tasks with:

– adjusting the amount of filtration heat loss in a building or complex of buildings;
– the ability to create appropriate microclimatic conditions around buildings and on their territory;
– the possibility of providing conditions for a comfortable stay on the premises.

E. Recommend and design the use of energy-generating wind and solar elements in the architecture of a building or architectural environment, or, conversely, elements of wind and solar protection.

During the second half of the XX century, as well as the beginning of the XXI century, the leading role in performing simulations and calculations of the certain phenomena impact in architecture played special equipment that performed specific types of simulations. This equipment was usually located on the premises of special laboratories or research institutes. Simulation processes were studied on scale models performed for each type of simulation.

To calculate the illumination of buildings, a device called “Artificial Sky” was used, which was founded in Moscow as part of a complex called Helioclimatron (Гелиоклиматрон – Russian). The device is a dome with a diameter of 17 m and a complex lighting system, built in 1981 for the lighting complex of the Research Institute of Building Physics. In Helioclimatron, the lighting of buildings was modelled (Fig. 1). But at the end of the 60s of the last century, the similar equipment to “Artificial Sky” was installed in the laboratory of architectural physics of the Lviv Polytechnic National University (at that time – Lviv Polytechnic Institute) (Fig. 2). Its employees work on the problems of architectural climatology, as one of the main scientific directions of the Department of Architectural Structures, now the Department of Architectural Design and Engineering. The staff of the Department is still obliged to Bedyl O. T., Zapolskyi V. H., Stasevych I. V. for the establishment of the Architectural Physics Laboratory with its unique equipment and installations. Among the climate simulation installations created during this period, there were: “wind tunnel", “Artificial Sun” (Fig. 3) and stands for research of thermal properties of opaque materials and transmission of thermal radiation by various types of glass. Thanks to this, tests were carried out on the order of enterprises and for scientific experiments of employees of the Department: Shvets Ya. D., Kazakov H. V., Yatsiv M. B., Shuldan L. O.

This type of equipment is now used in the educational process for simulated processes visual demonstration. Working with them provides the necessary basic level of knowledge that allows you to master the corresponding software products. Measurements and simulations using mechanical methods of execution have a large statistical and informational error (due to the peculiarity of measurements – from the conditions of the laboratory itself; the “researcher's factor”, to possible errors in the execution of the maquettes or the use of materials with other characteristics). Software programs also allow you to get more accurate results and use a much wider range of tools (Fig. 4).

Available software products can perform almost all stages of design, construction simulation, impact analysis and operation of buildings or structures – from creating two-dimensional drawings of individual structural or decorative elements to creating objects of complex parametric architecture and objects complete construction process visualization at all stages based on BIM technologies. The European Union and our closest neighbours are rapidly implementing BIM technologies: 1 FIEC, Annual Report, 2017 and European

Commission (European construction industry federation, 2019.); 2 Accenture, Demystifying Digitization, 2017 (Móstoles, Castaño, Coppens, 2017); 3 McKinsey Global Institute, “Reinventing Construction: A Route to Higher Productivity”, February 2017 (McKinsey Global Institute, 2017); 4 BCG, “Digital in Engineering and Construction”, 2017 (Castagnino, and others, 2016); 5. Economist Intelligence Unit, “Rethinking productivity across the construction industry”, 2015 (Lara V., 2015).

Projects based on BIM technology have become the standard for building design in the UK since 2016 (Galiano Garrigós, Mahdjoubi, Brebbia, 2017), and in other countries of Europe and North America, they have officially become as much a part of the design process and documentation preparation as the usual drawings of various two-dimensional building planes. BIM is an abbreviation and stands for 'Building Information Modelling'. In general, Building Information Modelling is an approach to the construction, equipment, maintenance and repair of a building (to the management of the object's life cycle) (Fig. 5), which provides the collection and complex processing of all architectural, technological, economic and other information about the building with all its relationships and dependencies, where the building and everything related to it are considered as a single object.

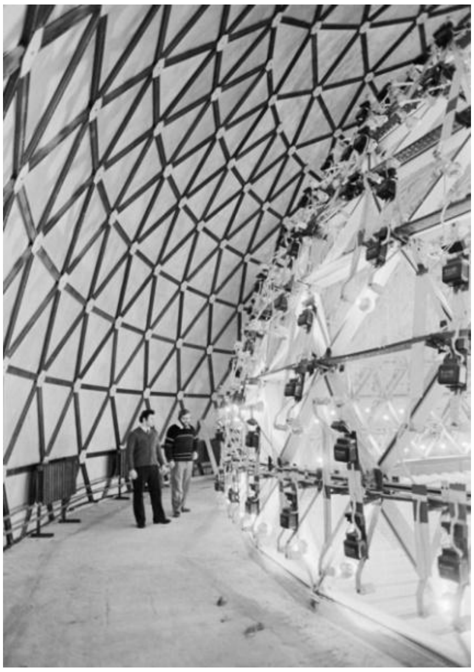


Fig. 1. The “Helioclimatron”
of the Research Institute of Building Physics,
1981 (Koshevoy, 1981)

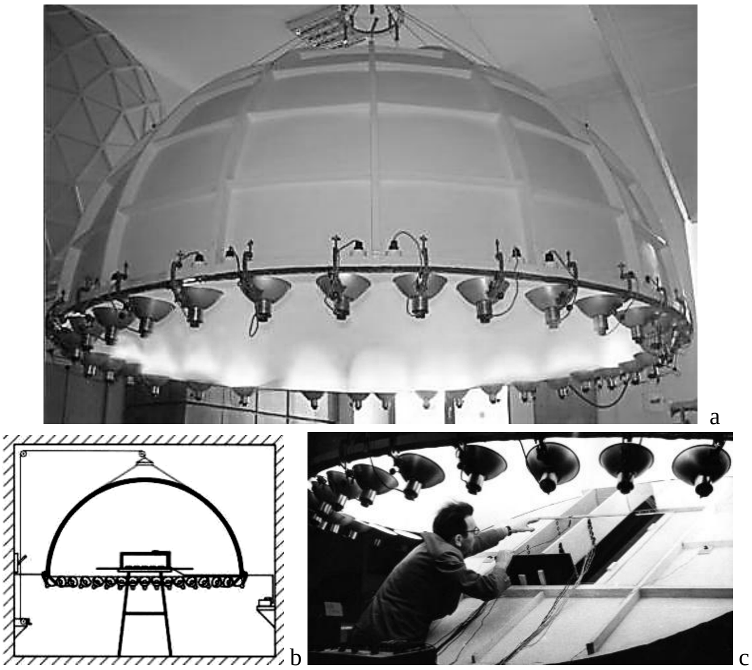


Fig. 2. The “Artificial Sun” installation
at Lviv Polytechnic National University, Lviv:
modern look (a); installation diagram (b);
during the experiment, 1971 (b)

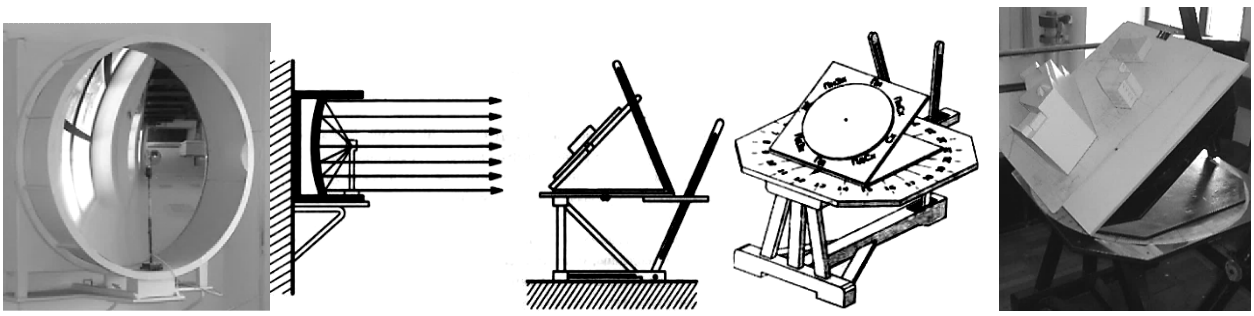


Fig. 3. The “Artificial Sun”, Department of Architectural Structures of the Institute
of Architecture of Lviv Polytechnic National University, built in the late 1960s

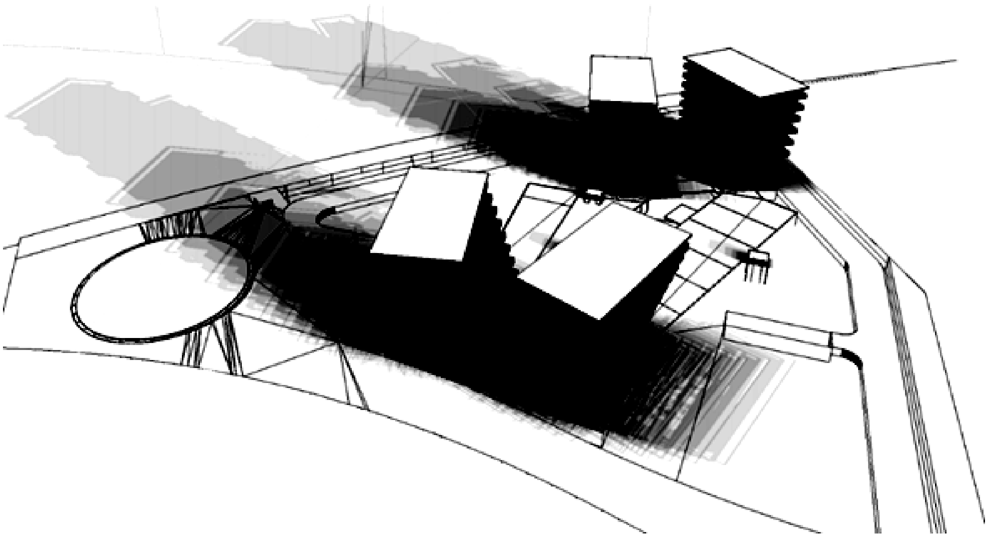


Fig. 4. Facade planes shading and lighting visualization during the year in the Autodesk Ecotect software

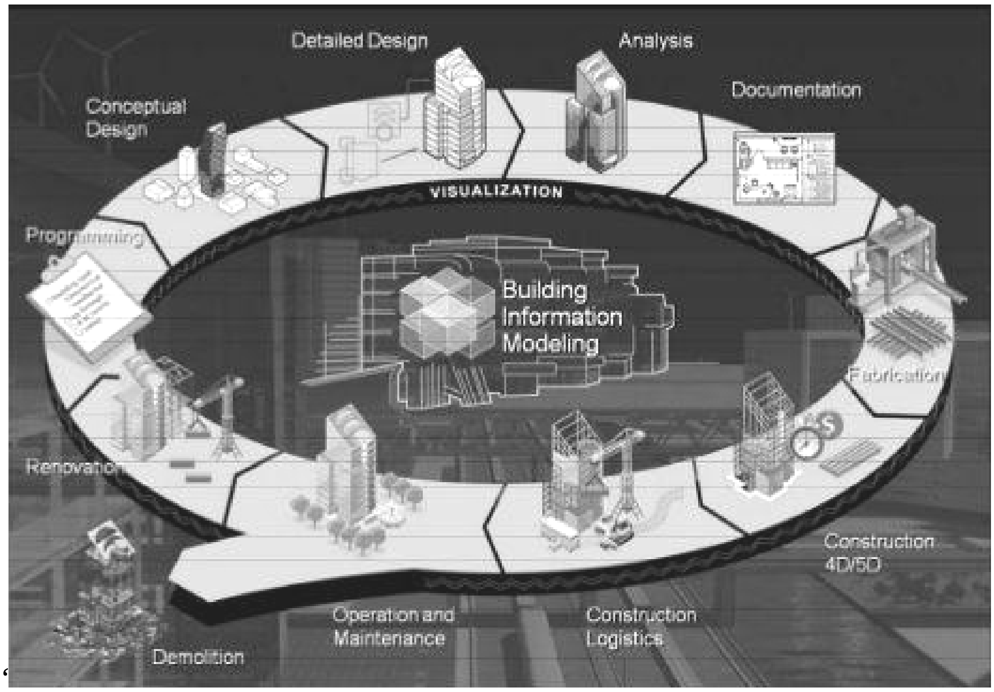


Fig. 5. Object's lifecycle illustration in BIM design (BIM Technology Logo. 2019)

Building models made under BIM standards using data parameters in design software (e.g. ArchiCAD, Revit, MicroStation), or based on export data to other software products (e.g. Autodesk CFD, Autodesk Flow Design, Autodesk Ecotect, EcoDesigner, Velux Daylight, Velux Energy and Indoor Climate Visualizer), can study building lifecycle parameters at all its stages from the first stage of the design process, which in return allows improving the methodology and results of the architectural process, and as a result, the qualitative indicators of building parameters. Design software products are more suitable for creating operating documentation than for a search cycle. Therefore, simulations of processes and preliminary analysis at the stage of creating a conceptual design are usually carried out in a combination with software programs [e.g. ArchiCAD + Autodesk CFD (aeration and aerodynamics), Autodesk Ecotect Analysis + VELUX Daylight (insolation and shading), or RHINO + Grasshopper and software applications (form search, aeration, aerodynamics, insolation and shading)]. Also, at the stage of conceptual design, the architectural model is imported into design and engineering software products, where it is worked out in analytical and calculation models.

To implement such or similar tools in domestic design, it is necessary:

– to create a legal base for working with 3D models;

– to change and update the particular paragraphs of the DSTU on the design documentation;

– to compose libraries of building materials, elements and structures;

– to certify software products;

– to introduce systematic training for students of architectural specialities.

One of the most important parameters in the design, especially in conditions of challenging terrain, restrained urban conditions or high-rise construction is the assessment of the construction impact on aeration, ventilation and wind direction or strength changes, both in the urban context and in the context of a single local building or some of its elements. Architects who design high-rise buildings, to ensure maximum resistance to wind load, resort to a set of measures to improve the streamlining of the building external envelope, such as rounding the edges, or the entire building in the direction of the prevailing winds, creating holes or cellular constructions of facade systems. Another possible technique is to create broken or cut forms to preserve or improve the aeration of neighbouring buildings, or to avoid swirls that create significant difficulties during operation of buildings and open spaces.

To create the most effective building in terms of interaction with the wind, a thorough study of its structure, a shift of influence in the existing environment, and other things are needed. Aerodynamic processes simulations are designed to solve this particular task. One of the best software products for performing this kind of computer simulation of real-world conditions is the Autodesk Flow Design software. Unlike others, in particular online counterparts (e.g. SimScale, AirShaper), it has the widest range of formats for data import, and, as a result, provides the most extensive information about the architectural object of research. It is also possible to perform simulation processes in a general-purpose Comsol.

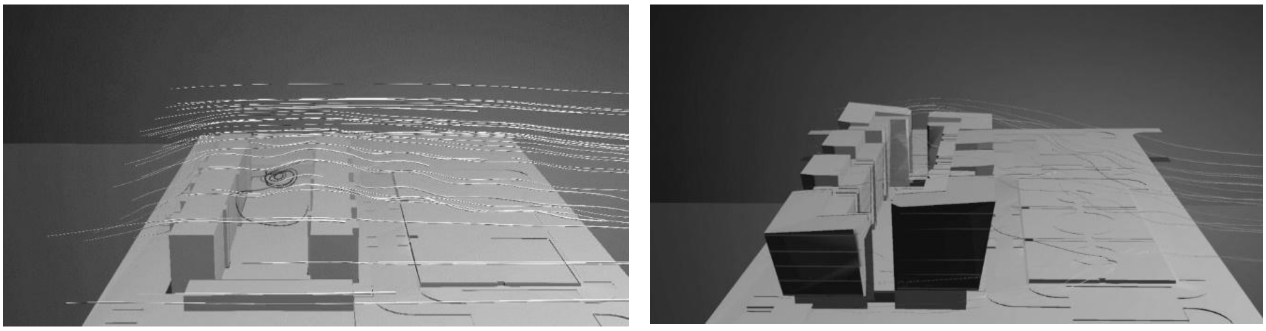
Multiphysics software for the study of physical and chemical processes, but due to the extremely wide range of possible research areas it is necessary to operate with a significant number of optional parameters of the environment and the nature of impacts, so the use of Comsol Multiphysics is one of the most accurate but a quite labour-intensive tool for calculating and visualizing aerodynamic processes in architecture.

Autodesk Flow Design allows performing detailed monitoring of the projected building impact on existing air flows, changes in their direction and speed, to determine the dynamics of these changes both in the general view and on a certain image plane, which can be important for determining flows, for example, at a pedestrian level. Also, the software allows determining the wind load areas in all their possible spectrum (Fig. 6). A significant component of Autodesk Flow Design is a possibility to get a picture of the conventional boundaries of influence on changes in the aerodynamic situation, which is one of the constitutive parameters at determining the location of a building in the urban structure of a district, street or block. The resistance force of a form plays a key role in calculating the aerodynamic properties of a building or structure and depends directly on the geometric characteristics of the object (Fig. 7). It determines the degree of influence of existing and projected air flows on the building or structure itself, as well as on the surrounding development.

It is most efficient to use the appropriate analysis at the stages of pre-design analysis, concept creation and conceptual design since the results of simulations significantly affect the forming and solving of the exterior content.

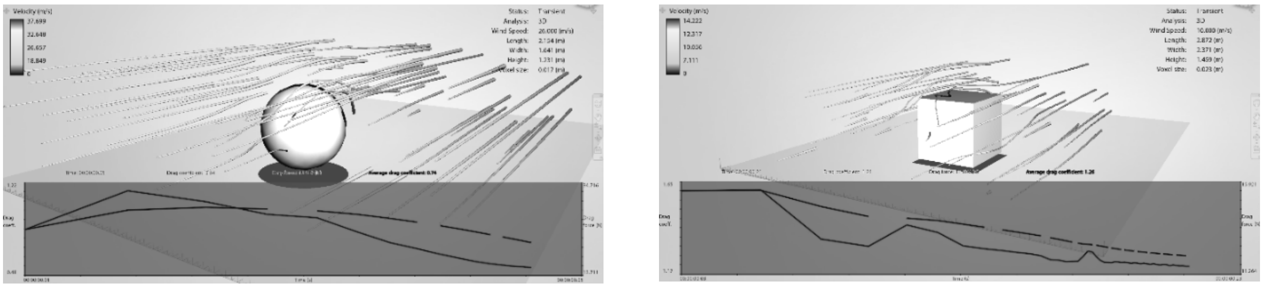
Another Autodesk product works on a similar principle – CFD, which, however, uses a much wider set of source data, but also produces more accurate calculations. It opens up the potential for using it in the study of not only aerodynamic processes but also the movement of heat in constructions, rooms or buildings, with data that allows further accurate calculations.

On average, a person spends more than 90 % of their time in-buildings every day (U.S. Environmental Protection Agency, 1989). Therefore, under conditions of designing the microclimate of premises, it is significant to obtain information based on simulations not only of processes that occur outside, but also those that the building user faces directly. There are a large number of software tools that allow performing not only calculations according to the specified formulas, but also to conduct a detailed analysis of graphical processes of air movement, insolation, lighting, energy loss, etc.



a b

Fig. 6. Wind flow simulation in Autodesk Flow Design software
current situation (a); after reconstruction (b)



a b

Fig. 7. Analysis of simple forms in the Autodesk Flow Design software with the determination of the form-resistance coefficient

Among these software tools, it is worth mentioning EcoDesigner software based on the BIM model created in ArchiCAD software, turning it into a BEM (Building Energy Model) based on which process modelling is created. The Energy Analysis component from Autodesk Revit software works similarly: it can be used to analyse the amount of energy supplied and consumed by all rooms and volumes of the building model, both individually and in general. This information helps architects make more informed and cost-effective decisions to increase efficiency, create a better microclimate and reduce the negative impact of the building on the environment. These software tools turn architectural and structural elements of the model into energy models with their energy intensity indicators and thermal conductivity for each of the types of structures.

The following key input parameters are used in this calculation and simulation of processes:

– Geometric characteristics of the research object (form, area, size of translucent structures, etc.);

– The type of building or room contains information about standard specifications depending on the terms of use. For example, usually, during a year a coffee shop works much longer than an office building, which leads to higher energy consumption. The temperature and humidity regime of the bathroom differs from the one in the living room, which also affects the energy calculation model;

– When selecting a location, the appropriate tools specify information about climate data (temperature conditions, orientation relative to the cardinal directions of rooms and surfaces, prevailing wind directions, amount of solar radiation, depth of soil freezing, etc);

– Properties of construction and structural elements: materials and structures of fences, their finishing; the presence of thermal bypass and so on;

– Characteristics of building engineering components (heating and cooling systems, ventilation, hot and cold-water supply, renewable energy sources).

Unlike any of the other software programs for calculating energy consumption and loss, such as PHPP (Passive House Planning Package) and DOE-2, the EcoDesigner ArchiCAD and Revit Energy Analysis software components allow not only getting quantitative data of the corresponding characteristics but also to illustrate the relevant processes within the created models, their progress, possible improvements, and so on. For example, these software components can display isotherms inside of structures and rooms (Fig. 8), which allows identifying possible problem areas of the future building at the design stage, and, as a result, make changes to the design to avoid them – at the volumetric planning and structural levels.

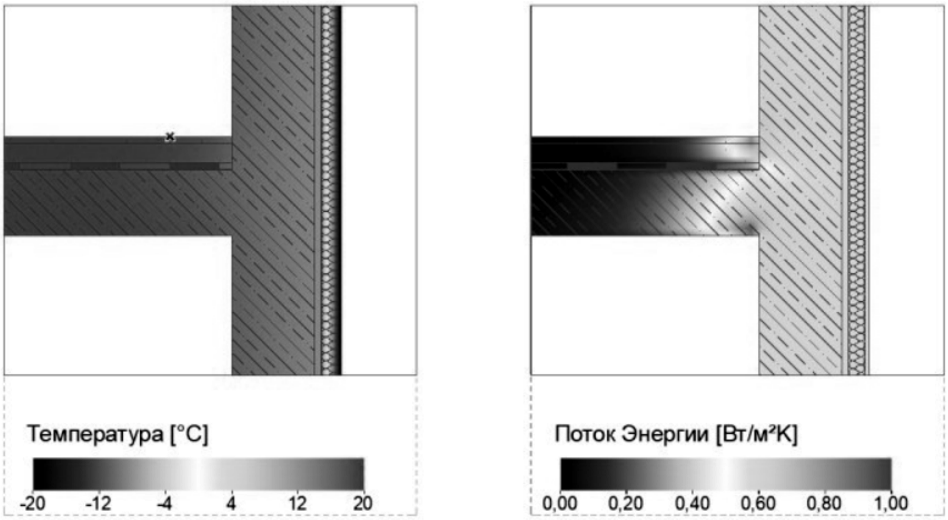


Fig. 8. Visualization of temperature and energy flow inside the structure in the Ecodesigner add-on for ArchiCAD

While tools such as PHPP or DOE-2 are most typically used in the P and RP stages, the advanced functionality of the Ecodesigner and Revit Energy Analysis software allows making preliminary calculations already at the stage of conceptual design.

Within certain zones, VELUX's software products – Daylight, Energy and Indoor Climate Visualizer are effective tools for calculating and visualizing processes, the first of which allows determining the illumination of rooms, dark and light zones and allows solving problems of insolation during analysis, and the second one allows analysing the thermal comfort of buildings at the design stage.

VELUX Energy and Indoor Climate Visualizer software focus on windows and shading from the sun and their influence on the formation of indoor climate, as well as on energy consumption for heating, ventilation, cooling and electric lighting. The software works with a specific orientation and location of the building, taking into account the specificity of particular data. Thus, the software can track the difference between the results of various geometric solutions of the building, the parameter variability of the windows, panels and shading from the sun.

Another VELUX software – Daylight Visualizer is a lighting modelling tool for analysing daylight in buildings (Fig. 9). It works by predicting and documenting the levels of sunlight, illumination, brightness, and visualising the room before the construction of the building. The software does not calculate the premises insolation, which is standardised by the State Building Code but more importantly uses the daylight factor to determine the real state of lighting. DF (daylight factor) provides a qualitative rather than quantitative assessment of natural lighting in premises.

DF is the ratio of room light to outside light during an overcast sky. When the daylight factor is equal 2 %, the room lighting is considered sufficient, although it may require artificial light to perform some works. There is no need for artificial light when the daylight factor is more than 5 %, (Daylight, Energy and Indoor Climate Basic Book, 2014).

Rhinoceros 3D was created as a plug-in for Autodesk AutoCAD, but it gained popularity quickly and, as a result, autonomy (Payne, Issa, 2016). Starting with version 4 of the product, which was released in 2007, there is an available Grasshopper add-on, which is essentially a visual programming editor. Grasshopper allows you to perform almost any actions on a given or exported to Rhinoceros geometry, providing it with certain physical properties using open-type software algorithms. The Dynamo add-on for Autodesk Revit works on similar principles. The main goals are to increase the accuracy of construction and calculations, as well as parameterisation of modelling processes, development of specifications, pre-production of building or structure elements, and the construction process itself.

The software's wide range of tools provides almost limitless possibilities for design and analysis: form optimization, planning structures, volumes, orientation, and height, taking into account the most important set of properties and parameters of external and internal environments for each object.

As for the creation of simulation models and analysis of external climatic factors, the most common tools in this category are Ladybug, Sunflower, Archidynamics Plugin and Trnlizard for Rhinoceros. These tools allow you to perform calculations and visualizations necessary for a comprehensive analysis of a building in a climate and energy environment (Fig. 10). Using Rhinoceros tools at this stage allows you to perform all the listed calculations and visualisations, but the existing library of BIM objects does not allow you to work fully in the software at all stages of designing, which makes the software and applications effective at the stages of concept and sketch designing.

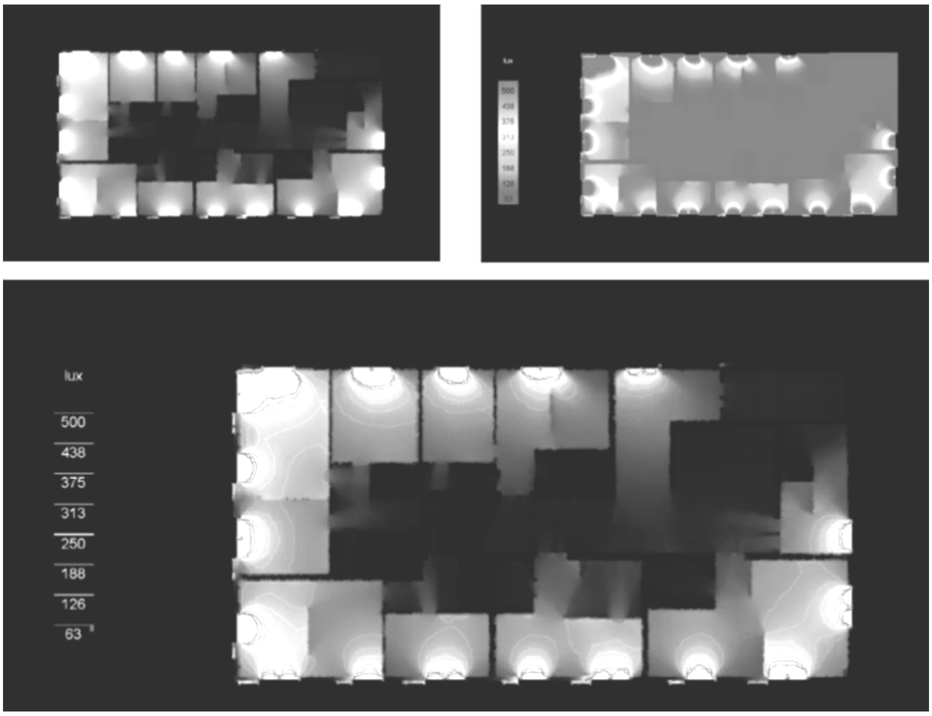


Fig. 9. A calculation example of indoor lighting in Velux Daylight Visualizer

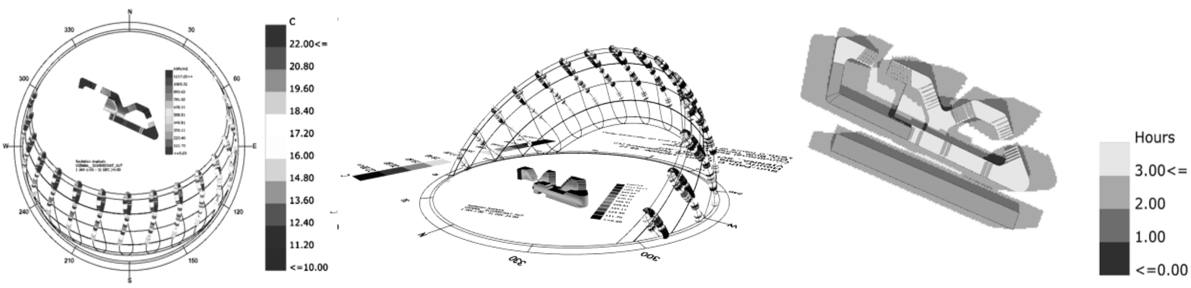


Fig. 10. Analysis of shading and solar radiation input in the Ladybug application

Conclusions

The simulation modelling method in architectural design has gone from devices and equipment of the 60s of the last century, through the first attempts of computer analysis of climate data Termo-Danfoss and the use of models on the ADA Soft platform (MDA) in the late 2000s to modern computational applications of available volume modelling software programs: ArchiCAD, Autocad, Revit. Energy efficiency improvement of architectural solutions, comparison and selection of optimal measures and techniques at any stage of design is solved by 1 – climatic factors simulation; 2 – microclimatic parameters simulation of the building; 3 – checking the building or complex geometry options; 4 – structures selection and calculation; 5 –simulation of the effects of the surrounding development and complexes development prospects. However, at this point, a single software product cannot perform all the necessary processes.

That is why only the combination of software allows you to pass all the stages of pre-project analysis, design and construction to solve the problems of increasing energy efficiency. For example, ArchiCAD (or similar) + RHINO + Grasshopper (form search), Autodesk Flow Design, CFD (aeration and aerodynamics), Autodesk Ecotect Analysis + IESVE, HIAT-2, HIAT-3, VELUX Daylight Vizualizer (insolation and shading); software bundles Flow Design – RHINO – Grasshopper, Archicad – SketchUp – PHPP (at the stages of EP, P, RP).

Accurate calculations, visualizations and taking into account more data are one of the main ways not only to improve the energy efficiency of buildings but also to increase the overall level of design solutions in architecture. However, computer modelling is just a tool and not a universal remedy that can replace knowledge and direction.

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РОЗВИТОК СИМУЛЯЦІЙНОГО МОДЕЛЮВАННЯ У ПРОЕКТУВАННІ ПОКРАЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ АРХІТЕКТУРНИХ РІШЕНЬ

Анотація. *Вимоги нового часу переводять архітектуру з площини суб'єктивних уявлень проектувальника в раціональну площину об'єктивних рішень. Розвиток сучасних інформаційних технологій створює передумови і можливості пошуку принципово нових підходів до організації архітектурного простору, нових засобів і прийомів художньої виразності в архітектурі. У своїй статті ми продовжили досліджувати взаємозв'язок між архітектурним проектуванням та енергоефективністю, а основне її завдання визначили як розвиток методу симуляційного моделювання з метою покращення енергоефективності архітектурних рішень. Проведення дослідження відбувалося у кілька етапів: визначення переліку основних впливів, аналіз існування програмних продуктів, їх практичне застосування у навчальному, реальному та пошуковому проектуванні, обчислення енерговитрат за змінними параметрами, теоретичне наукове узагальнення результатів та формування рекомендацій.*

Покращення енергоефективності архітектурних рішень на будь якій стадії проектування досягалося завдяки створенню симуляцій впливів, адже саме вони обумовлюють термодинамічні процеси і дозволяють досліджувати геометричнокеровану логіку продуктивності. Найважливішими серед них є: симуляція зовнішньокліматичних чинників; симуляція мікрокліматичних параметрів будівлі; симуляція і вибір варіантів геометрії будівлі чи комплексу; добір і розрахунок конструкцій; симуляція впливів навколишньої забудови та перспективної розбудови комплексів. Також окреслено перелік найважливіших архітектурних задач, що вирішуються завдяки застосуванню методу симуляційного моделювання.

Привернення уваги до деяких аспектів історії розвитку симуляційного моделювання, зокрема, в лабораторії інституту архітектури Національного університету "Львівська політехніка", дозволяє осмислити суть і форму його застосування сьогодні, а також відслідкувати еволюцію програм покращення енергоефективності та інструментів архітектурного проектування. Автори оптимізували роботу з критеріями, зокрема такими як потреба в енергії, вплив на навколишнє середовище, геометрію і матеріали. Значить аналіз та апробація найбільш поширених програмних продуктів з погляду застосування у цій галузі, як результат, дозволили запропонувати комбінації та способи їх використання для архітекторів.

Ключові слова: *симуляційне моделювання, покращення енергоефективності, архітектурна кліматологія, енергетичний аналіз, BIM-проектування.*