Using of BIM, BEM and CFD technologies for design and construction of energy-efficient houses

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Abstract. The article presents the concept and the process of integrated design and construction of energy-efficient house during the life cycle based on the use of BIM (Building Information Model), BEM (Building Energy Modeling) and CFD (Computational Fluid Dynamics) technologies. The task of complex design is to create a house with harmonious architecture and minimal energy costs to maintain a comfortable microclimate, including using renewable energy sources. The article shows the effectiveness of the use of an integrated approach in the design of a house close to the Passive House standards.

1 Problem of construction of energy efficient house

The idea of building energy-efficient houses with the possible lowest energy consumption "hovered in the air" in the 80th years of the last century. First calculations of a house without heating were presented by Wolfgang Feist and Bo Adamson for climate conditions of Germany in 1988 [1–4], later this concept was become known as the concept of a passive house. In Russia, interest to this topic has been actively developing over the past decade, research and development of concepts of houses with zero energy consumption have been published [5–9].

The main criteria of a passive house are [1–3]: specific consumption of thermal energy for heating ≤ 15 kW·h/(m²·year); air exchange rate at a pressure difference of 50 PA of external and internal air $n_{50} \leq 0,6$ 1/hour; total primary energy consumption ≤ 120 kW·h/(m²·year); specific heating load not more than 10 W/m².

Climate in Russia is more severe than in Germany, so in our country there are no houses that would meet the standard of "passive" house. However, there are already "active" buildings that compensate higher energy consumption by the use of renewable energy sources (RES) [10]. According to tests [11], the thermal resistance of the walls of modern buildings (99% of panel and more than 90% of buildings with ventilated facades) does not meet the project and regulatory requirements. Most of these buildings have high heat losses through the enclosing shell.

In this regard, it is necessary to find reasonable solutions for the construction of energy-efficient buildings that would solve the tasks of comfortable living of citizens, efficient use of resources, the

introduction of advanced technologies using alternative energy sources.

The book [12] sets out the concept of the 3rd industrial revolution, which would be based on five pillars: "the transition to renewable energy sources; the transformation of all buildings into mini-power plants that produce electricity at the place of its consumption; the use of technology in each building for the accumulation of periodically generated energy; the use of Internet technology to transform the power system of each continent into an intelligent power grid; conversion of the car park to electric vehicles that can receive energy from the intelligent continental grid and give the excess to the network." This concept seems quite reasonable for the twenty-first century.

The aim of the work is to build an energy-efficient building with minimum energy consumption during the life cycle "from cradle to grave" for at least 100 years.

2 Basic design solutions for the application of BIM technology

The shape of the house is designed for external dimensions close to the cube, to reduce the heat losses of the building through the outer surface of the house: the length of the building – 12 m, width – 11 m, the height of the roof ridge above ground level 10 m.

The roof is gable, the roof area on the South side is 130 m² to accommodate solar collectors and solar panels. Veranda under the roof is on the South side and has a size of 12 m × 3 m = 36 m². In summer, a canopy over the veranda protects the building from solar overheating, and in winter, when the sun is low, the sun rays freely penetrate into the house through the window and glass door. The arrangement of the veranda with a canopy on the South side distinguishes this building from the traditional "passive" houses, which have most windows

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facing South to increase the heat flow through them in winter, but in the absence of solutions to protect the house from overheating, there are difficulties with cooling it in summer.

Insulation of the roof is made by wood fiber Steico Zell with thickness 30 cm, as well as non-combustible and environmentally friendly material URSA PureOne with thickness 15 cm (glass fiber with acrylic binder having a certificate for use in child care and medical institutions). The calculated coefficient of thermal resistance of the roof was $12 \text{ m}^2\cdot\text{K}/\text{W}$ [13].

Windows are the weakest element in the shell of building, so the choice of windows was made by analyzing the characteristics of the glass and profile of different manufactures. As a result, PVC windows of the company Deceuninck with insulated profile Eforte and double-glazing filled with argon were chosen. These windows have two sprays: energy-saving and multifunctional (to protect against overheating in summer and insulation in winter). The coefficient of thermal resistance of double-glazed windows was $1.67 \text{ m}^2\cdot\text{K}/\text{W}$, and the profile – $1.05 \text{ m}^2\cdot\text{K}/\text{W}$.

Mineral-cotton insulation with ventilated facade was chosen for the insulation of the external walls, which allows you evenly on all sides to remove moisture from the building through the air gap. As an external protection of the walls of the building were chosen fiber-cement panels KMEW with thickness of 16 and 18 mm, the service life of which is more than 50 years. For fixing panels the metal vertical T-shaped fastening system were applied.

Calculations have shown that the payback period of thermal insulation is about 9 years. According to [14] at a service life of 100 years the payback period of thermal insulation in 10–20 years is considered quite acceptable and favorable. So the design process for creating such buildings took into account the entire building life cycle.

3 Application of BIM technology

Complex building design includes all stages of creating a dimensional model of the building with optimal characteristics of the building shell and efficient energy consumption, as well as monitoring the results of maintenance after construction. So it covers all stages of the life cycle of the building. Exactly a combination of Building Information Model (BIM) and Building Energy Modeling (BEM) in the design allows you to see through all the processes inside the simulated space and implement them in practice. ArchiCAD software package allows us to structure all elements of the model in certain groups, analyze them separately and together, excluding collisions, while working through the spatial elements of all sections of the working documentation in one system.

The BIM model of the experimental energy-efficient house was created in the ArchiCAD software. At the first stage, planning and spatial solutions were developed taking into account the preliminary placement of equipment and furniture, while taking into account the needs for residential and technical spaces, the location of

zones was set relative to each other in order to minimize the time of transitions from one room to another, the entry groups was set relative to the area, to the paths of neighboring houses and to the main road, the location of the cardinal points were taken into account. When designing a harmonious and energy-efficient space, the requirements are multidirectional and sometimes conflicting [15, 16], so the task was to bring all the requirements into balance in one model through a dialogue of specialists of different fields, united in one team. Technical and economic indicators of the building are presented in Table 1.

Table 1. Technical and economic indicators of the building.

Num.	Indicator	Quantity
1	Building area/ from them the house area/ verandas	115 m ² /115 m ² / 56 m ²
2	Total building area	205 m ²
	aboveground part	165 m ²
	underground part	40 m ²
3	Number of residents	4-5
4	Building volume	962 m ³
	including overhead part	829 m ³
	underground part	133 m ³
5	The volume ratio	4,6 m

The concept of planning and spatial solutions became the basis for further development of working documentation and inner design project. The sequence and interrelation of design stages is reflected in Figure 1, where the problems of choosing the architecture and design of the building, its design and engineering system are solved and refined in the iterative process.

Fig. 1. BIM of energy-efficient house in Archicad-22.

On the basis of the architectural project structural and engineering sections of the house were designed according to the selected parameters of the thermal shell and engineering equipment. In the course of design works the most convenient locations of engineering equipment and heating, ventilation, water supply and drainage routes and domestic sewage were chosen. In the ArchiCAD software package, all elements are structured according to layers, detailing elements was used LOD 300. All constructive elements and finishing materials that were used in the BIM model are shown in Table 2.

Table 2. Construction and finishing materials of the house.

Type of material / structural	Material
Supporting structure of the building	Reinforced concrete foundation construction and zones
Fencing structure of the building	Aerated concrete block $300 \times 200 \times 600$ mm D500
First floor insulation	Expanded polystyrene as a Swedish plate 200 mm
Insulation of wall basement	Expanded polystyrene 200 mm
Windows	PVC profile double-glazed two-chamber: argon 90%; sputtering energy saving and multifunctional
Finishing and facing materials Facade fastening system	Ventilated hinged facade with fiber cement panels 16–18 mm Vertical T-shaped subsystem
Floor heating system	Heat pipes
Roofing materials	Soft roof tile
Partitions (enclosing structures)	Aerated concrete block D500 $200 \times 200 \times 600$ mm
Thermal insulation materials (enclosing walls)	Mineral wool 50 kg/m^3 200 mm and 80 kg/m^3 50 mm Fiberglass plugs 300 and 260 mm
Thermal insulation materials (roof)	Inflatable thermal insulation from wood fiber 150 mm

In the original model, the equipment was placed and the routing of engineering tracks was made in the optimal way (Figure 2).

Fig. 2. Engineering equipment with wiring routes.

The heat source for heating and water heating - geothermal heat pump and solar collectors. The heating System is radiators in the basement, floor heating on the first floor and surface ceiling heating on the second floor used in winter for heating and in summer for cooling. The composition of the engineering equipment in the BIM model is:

1. Heat pump BUDERUS model Logatherm WPS 11;
2. Solar collectors model Solar (four pieces);
3. The storage tank JASPI GTV TEKNIK RD;
4. Heat storage fireplace Tulikivi KTU 1010/92 with an efficiency of 91%. Fireplace thermal performance testing showed that to achieve a given efficiency is required to lay down not two portions for 4 kg of wood (in this case, the temperature of exhaust gases rises to the level of more than 200°C and efficiency is reduced to 70%), and four portions of wood briquettes 2 kg, the temperature of the flue gas remains at 100°C , then efficiency is 90% or more. In addition, an environmental effect is achieved – the formation of NO_x and CO_2 is reduced, and the burning of wood briquettes allows to

have a practically zero balance of greenhouse gas emissions;

5. Air handling unit (AHUs) with heat recovery Turkov Zenit HECO 550 with an efficiency of 79%;

6. Low-temperature heating system of the first floor, Underfloor heating with improved characteristics. The operation range of the heat carrier is 22 to 30 degrees;

7. Ceiling heating and cooling system of the second floor;

8. The heated air downstream of the heat exchanger of the ventilation system;

9. All systems are combined into a hybrid system and work to obtain the maximum effect on energy efficiency.

4 Application of BEM technology

In the BEM model, the characteristics of the building envelope, the parameters of indoor and outdoor air, the work schedules of people, and the work schedules of fuel-generating devices are set. As a result of the calculation, building heat losses, heat gains are estimated, the work of heat pumps and solar collectors is analyzed.

In article [17] it was noted that BEM does not derive benefits from the continuous flow of information from the field of digital modeling. In particular, information relating to BEM needs to be manually entered into BEM tools, which is considered a time-consuming, expensive and time-consuming process, although this information is already available in the digital building model (BIM model), so a new approach for integrated building design has emerged, called "building Information modelling based on energy building modelling" (i.e. BIM based on BEM). BIM based on BEM involves the use of a pre-developed BIM model (including information about the architecture, mechanics and properties of building materials, heating, ventilation and air conditioning systems) to set the initial data in BEM packages.

Designers can use BIM approach on the basis of the BEM for the evaluation of design decisions and take the most effective of them in the course of designing buildings, and the energy efficiency of buildings is more easily attainable.

Using of BIM-technology was based on calculations of energy consumption of the building with the help of PHPP (Passive House Planning Package) and DesignPH (Design Passive House) programs, which allow you to model all components of the power supply system. With this design tool, you can set the parameters of the equipment, as well as climatic conditions, modes of operation of the building, shell parameters and other parameters, and calculate both the energy consumption of the equipment and its production.

The choice of additional thermal insulation thickness under the ventilated facade was determined on the basis of PHPP calculations. Calculations have shown that in order for the thermal resistance of the walls to become equal to 10 m²·K/W (which is typical for a "passive house"), it is necessary to have a thickness of thermal insulation of basalt fiber 25 cm, which was used for this house.

Five variants of the equipment composition were compared: ground heat, air heat pump and gas boiler. The ground heat pump was considered at 6 and at 36 solar panels. The most efficient system is one with ground heat pump and 36 solar panels [18,19]. Vertical probes are used with the heat pump. Here we have zero energy consumption of the system as a whole.

The calculation of the energy balance of the house was made for the resulting space in the PHPP software package. Heat losses (through the enclosing structures – windows, walls, floor, roof) and heat gains (from solar radiation, people, lighting and equipment) are calculated. According to the calculated load on the heating there were selected engineering equipment for several variants of the shell of the house. After several iterations of shell variants and engineering equipment, the heating load was reduced from 42 to 37 kWh/(m²·year).

For accumulation of the electric power generated by solar batteries, accumulator batteries will be used. For accumulation of thermal energy, the tank accumulator of hot water is used. During the warm period, the heat pump will not work, ground probes will be used to cover the load of the air conditioning system.

To achieve zero energy consumption of the house

there are required 36 solar panels with a nominal capacity of 320 W and four solar collectors of 2 square meters with appropriate thermal insulation characteristics [19].

5 Application of CFD technology for modeling of ventilation system

Due to the fact that in an energy-efficient house, air infiltration through windows and exterior walls is minimized, the issue of ventilation of the house is acute. Heat losses for ventilation in "passive" houses are the largest items of heat losses [20], so for ventilation of the house was selected supply and exhaust system with heat and moisture recovery Turkov Zenit HECO 550. For air preheating after the recuperator (in the cold period) and for its cooling (in the summer period), a channel water heat exchanger Zilon ZWS-W 400x200/3 is installed in the supply air duct.

Heating is carried out with hot water from the heat accumulator, and cooling – with cold water, which will be cooled through the geothermal circuit of the heat pump.

The supply of fresh air to living rooms of the 1st floor is carried out through the ceiling anemostats, and to living rooms of the 2nd floor – through floor grilles located along the outer walls of the house, under the Windows. Extraction of the 1st and 2nd floor is organized through bathrooms and exhaust grates at the staircase hall.

The main lines of the ventilation network in the BIM-model of an energy-efficient house are made of galvanized steel air ducts, branches from the main air duct – flexible noise-damping air ducts. The use of flexible noise-attenuating air ducts together with silencers on the supply to the house and on the emission of air into the street has reduced the noise in the ventilation network.

To analyze the temperature and velocity fields across the home premises, the BIM model was exported to the Computational Fluid Dynamics (CFD) package of ANSYS Fluent. Numerical simulation in CFD solves differential equations of aerodynamics and thermophysics in partial derivatives by the finite element method [21, 22]. The essence of the finite element method is to divide the computational model into

Table 3. The estimated costs of the supply air in the rooms of the house.

Room	Room volume, m ³	Supply air consumption, m ³ /h	Ventilation rate, h-1
Basement technical room	52	25	0.48
Basement storage room	32	25	0.78
Technical room-first floor wardrobe	23	50	2.17
Kitchen-living	120	100	0.83
Room 1	36	60	1.66
Room 2	35	60	1.71
Room 3	35	60	1.71
Room 4	37	60	1.62
Lounge	87	110	1.26
Total consumption, m ³ /h		550	

discrete cells in which the calculations are made.

The following differential equations of hydrodynamics and heat transfer were used in the created mathematical model to describe the physical processes (the output of turbulent air flow from the air distributors, the interaction of the supply air flow with the air of the working zone) and the elementary methods of heat transfer:

- equations of motion or non-isothermal flow of viscous gas in Cartesian coordinates (k- ϵ turbulence model);
- continuity equation (conservation of mass);
- equation of energy (heat transfer) in rectangular Cartesian coordinates.

The grid of final elements is compacted in the places of air outlet from the air distributors, in the places of air removal through the exhaust holes, at the radiators in the basement.

In article modeling of ventilation of a cellar is carried out. The following boundary conditions were set – the air velocity at the outlet of the supply air ducts, the temperature of the supply air, the temperature of the heated surfaces (radiators, boiler equipment), the temperature of the window opening. The boundary condition on the hood – set through the pressure. For Figure 3 shows the image of the current lines in the basement. For Figure 4 shows the image of temperature flows in the volume of the basement.

Fig. 3. Indoor current lines modeled in Ansys Fluent software package.

Fig. 4. Simulation of temperature fields of space in the program complex Ansys Fluent.

Analysis of the calculation results allows to evaluate the efficiency of ventilation, choose the most optimal point of distribution and removal of air. According to the results of CFD-modeling of ventilation of the basement, it was decided to transfer the point of inflow in the pantry to the edge of the room.

During the operation of the house, the actual parameters are measured for comparison with the calculated data and microclimate control. Measured parameters: the temperature of the internal air at different heights in different rooms, the cost of the coolant in the circuits of the heating equipment, the temperature of surfaces, the cost and temperature of fluids at inlet and outlet of the engineering equipment, the air flow in the ventilation system, the air temperature at the inlet and the outlet of the heat exchanger.

6 Conclusion

In the design, construction and operation of energy-efficient buildings, it is recommended to apply modern methods of BIM-, BEM- and CFD-modeling in the complex.

The sequence and interrelation of design stages in BIM-modeling includes the tasks of choosing architectural and design solutions, building design and its engineering systems, taking into account many factors.

BEM-modeling based on the use of the programs Design PH and PHPP allows you to select the equipment of engineering systems based on the calculated heat load.

The use of computational fluid dynamics (CFD) technologies for modeling the ventilation system made it possible to calculate the air flow trajectory and temperature distribution in order to maintain a comfortable environment in the room.

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