OPTIMIZACIJA MERA ENERGETSKE EFIKASNOSTI JEDNOPORODIČNE ZGRADE POMOĆU DETALJNIH SIMULACIJA¹

THE OPTIMIZATION OF ENERGY EFFICIENCY MEASURES FOR A SINGLE-FAMILY RESIDENTIAL BUILDING USING DETAILED SIMULATIONS

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One of the biggest problems in the modern world is the exhaustion of non-renewable energy resources, considering that the demand for energy is becoming bigger with time. Since public and residential buildings represent a big part of the global consumption of the final energy, among the primary goals in the process of the development of the energetic and socio-economic sustainability, the improvement of their energetic performance is emphasised. This paper analyzes the potential of improving the energy efficiency of an existing residential building through the process of optimization of the proposed energy retrofit measures of its thermal envelope. The optimization was carried out with the exhaustive search method, while modeling and detailed simulations were chosen for the assessment of the energy properties of the object. Required final energy for heating and cooling of the facility for each hour was obtained with the EnergyPlus simulation tool. Primary energy and global cost are calculated using the appropriate standards. The main goal of the optimization is to precisely allocate project solutions that simultaneously achieve positive effects both in terms of energy and finances. This paper presents the successful optimization of combinations of proposed measures whose implementation can improve the energy properties of the building, while achieving great savings in terms of total annual energy consumption for heating and cooling. Pareto optimal solutions show that the global cost might be reduced for 7 % simultaneously decreasing primary energy for 23 %. In addition, primary energy can be reduced for more than 55 %, but at the expense of the increased global cost.

1 Introduction

Building sector is a worldwide significant consumer of energy. Consequently, the energy efficiency of buildings is essential to consider both from the global aspect and from the individual, that is, from the aspect of the object's users.

On the side of the user of the object where the energy process brings energy in order to ensure the internal comfort, by implementing adequate measures of energy efficiency, except for the positive effects on the energy and ecological system, it would also achieve the reduction of the global costs necessary for the supply of energy by the facility. Energy efficiency of buildings is a concept that requires a wide range of analyzes in the fields of energy, ecology and economy. The goal of the work is to define Pareto optimal packages of energy retrofit measures for the envelope of a chosen object. The objective functions are the global cost and primary energy consumption related to building heating and cooling. Final energy for heating and cooling is calculated with the EnergyPlus simulation tool. Based on the results of simulations, the primary energy and global cost are calculated according to the standards.

2 Object description

The subject of the analysis is the existing free-standing single-family residential building with three floors located in the wider city area of Niš (Figure 1). The construction of this object was completed in 2007. The house is moderately sheltered, while the façades are exposed to the wind. The zones are organized with a garage, isolated boiler room and a studio, with a separate entrance from the yard, located on the ground floor, and with a housing unit on the next two floors, consisting of a living room, kitchen and bedrooms in the attic. There is also a lavatory on each floor.

The facility was built in solid masonry system with walls of brick block and the horizontal and vertical reinforcements. The external walls are insulated with 5 cm thick polystyrene layer and decorated with high quality façade paints. The building is covered with a pitched roof. It is made of tile with a wooden sub-construction and insulation layer of 5 cm thick stone wool that is protected by plasterboard panels from the inside. Floor joists are semi-detachable TM type, which means that their main structural materials are a hollow brickwork and cement screed. These constructions towards the unconditioned area, as well as the inner walls, also have a 3 cm thick thermal insulation layer. The fenestration has wooden frames and double transparent glass. The windows are both single and double, while on the south façade there are balcony glass doors for the exit to the terraces. Table 1 shows the thermal characteristics of the object's structural elements, depending on the position.

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Figure 1. 3D model of the analyzed object (SketchUp)

Table 1. Overview of the thermal characteristics of the object's structural elements [1]

Position	Exterior façade wall	Inner wall towards the unheated area	Floor joist towards the unheated area	Pitched roof	Fene-stration
Heat Transfer Coefficient U [W/m²K]	0.57	0.74	0.50	0.62	2.90
Maximum value of Heat Transfer Coefficient U _{max} [W/m²K]	0.40	0.55	0.40	0.20	1.50
Solar Heat Gain Coefficient - g	-	-	-	-	0.71

The building is heated with a hot water heating system whose operation is regulated manually by the user, whereby each room, as well as bathrooms, is provided with a radiator of the required size. The system uses firewood as a source of energy. The cooling of the object is carried out by the split system which uses the electricity for functioning. In addition, electricity is used in the object for everyday comfort and effective functioning of the household, the lighting, and home devices and appliances.

3 The considered energy efficiency measures

The process of selecting optimal energy retrofit measures is guided by the norms and acts related to this field. As already shown in Table 1, the overall heat transfer coefficient (U) of the elements of the constructive structure of the analyzed object deviates from the allowed values prescribed in [1], and indicates low resistance to heat transfer and poor thermal characteristics of the envelope. This state of the envelope means higher transmission and ventilation losses and gains, and the object higher need for final energy during the year [2]. Accordingly, the measures for improving the energy efficiency of the facility are directed towards the improvement of its thermal envelope. When selecting appropriate combinations of measures, it is important to achieve a compromise between energy efficiency and financial attractiveness. Table 2 presents the considered energy efficiency measures.

Table 2. Considered energy efficiency measures

NUMBER	POSITION	DESCRIPTION
1	EW	Adding a thermal insulation layer to the exterior façade walls
2	IW	Adding a thermal insulation layer to the inner walls towards unheated area
3	FJ	Adding a thermal insulation layer to the floor joist towards unheated area
4	PR	Adding a thermal insulation layer to the sloping roof from inside
5	W	Replacement of windows and balcony doors

The first 4 measures aim to increase the resistance to heat transfer or decrease the heat transfer coefficient of the structural elements due to the low thermal conductivity of the thermal insulation materials [3]. Based on the analysis of the characteristics and types of insulating materials available on the market, expanded polystyrene of various thermal conductivities and stone wool have been adopted for potential options, depending on the position of the structural element. Table 3 gives the values of the thermal conductivity coefficients for selected types of thermal insulation materials according to the structure of the element and its position.

Table 3. Overview of the selected thermal insulation materials depending on the position

Thermal insulation material	δ [m]				λ [W/mK]
	EW	IW	FJ	PR	
Expanded polystyrene (EPS AF)	0.01 – 0.15	0.01 – 0.07	0.01 – 0.07	-	0.040
Expanded polystyrene enhanced with graphite (EPS AF PLUS)	0.01 – 0.15; 0.20	-	-	-	0.032
Stone wool (NaturBoard FIT PLUS)	-	-	-	0.05 – 0.20	0.037

Figure 2. Influence of the thickness of the thermal insulation layer on the change in the heat transfer coefficient depending on the material

In addition, it is suggested that the different thickness of the insulation layer be incorporated, since the transmission losses are largely dependent on it. Figure 2 shows the results of the influence of different thicknesses of the insulating layer on the heat transfer coefficient of the exterior facade wall in relation to the chosen type of thermal insulation material.

The fifth considered measure implies replacing all existing windows and balcony glass doors with new elements with a lower value of heat transfer coefficient and solar heat gain coefficient. It is a joinery with frames made of a combination of aluminum-wood with different types of glasses and improved thermal breaks. Besides the combinations of measures that include the existing state of the joinery, 11 additional types of fenestration were analyzed. The investment costs include assembly and disassembly in addition to the elements costs.

4 Methodology

The primary goal of the work is to determine solutions with the lowest annual primary energy consumption, and the lowest global cost for the lifetime of the project (15 years). The optimization of measures was performed with the exhaustive search method [4]. This method evaluates all possible combinations of measures. There were 122880 combinations of considered measures that meet the specified regulatory constraints according to [1]. The optimization process includes the financial analysis of combinations of proposed measures, and in this regard, the global cost is defined as the primary indicator of financial performance [5], which also represents the primary objective function.

For the calculation of the energy properties of the object, detailed energy simulations of analyzed building were used, in accordance with the standard [6]. The required energy for heating and cooling the facility is calculated with the EnergyPlus simulation tool [7], based on the model of the object. The obtained hourly results are further summed up to the seasonal level, while the total annual required primary energy for heating and cooling is determined using the mathematical formulas and coefficients from [1].

5 Analysis of the results

As already mentioned, 122880 potential solutions were examined. The results of the calculation in terms of reducing the total annual consumption of primary energy related to heating and cooling, primarily indicate that most of the solutions obtained meet the requirements from [1] and that with their implementation it is possible to achieve a large percentage of savings. The project solutions that were analyzed first are those that involve the implementation of

individual proposed measures with the best considered values in terms of improving the heat transfer coefficient of structural elements of the object. By implementing these individual measures, project solutions are obtained which implies lower total annual primary energy consumption for heating and cooling than the current state, while the global cost is different in case of their application.

Taking into account the scope of the solutions obtained, then the energy and financial aspects from which they were considered, after isolating the combinations of measures that meet the energy efficiency standards of buildings, a multi-criteria analysis was carried out. According to the defined criteria, the annual consumption of primary energy and global cost, from the range of acceptable solutions, 58 Pareto optimal solutions were identified, as shown in Figure 3. For optimal solutions that have the lowest global cost, it is characteristic to maintain the current state of the transparent elements (region 1). After introducing the proposed transparent elements, with better specifications than existing ones, there is a noticeable increase in global costs, but of course, higher savings in annual energy consumption are achieved (regions 2 and 3).

The solutions in the region 1 are cost-optimal or nearly cost-optimal. They reduce the global cost for 5 – 7 %, and primary energy consumption for 23 – 25 %. The region 2 has the solutions that yield larger primary energy savings (33 – 38 %), but are not financially attractive because they increase the global cost for 16 – 20 %. Finally the solutions of region 3 show the total potential for primary energy consumption reduction of the considered measures, which is over 55 %.

Figure 3. All and Pareto optimal solutions

From the set of Pareto optimal solutions, two items with exceptional differences have been identified. The first solution has minimal global cost and second the lowest annual primary energy consumption. The energy properties of these combinations of measures (solutions 1 and 58) in relation to the characteristics of the current state of the object are summarized in Table 5. Observed from the energy aspect, the results of the simulations of the selected optimal solutions show an exceptional reduction in the total annual need for final heating energy in relation to the existing state of the building, while the high degree of reduction of the total annual need for final cooling energy is observed only in the second mentioned optimal solution. A big difference was observed between the total annual consumption of primary energy for heating and cooling between selected optimal measures, which is, in fact, proportionate to the difference at a global cost. The replacement of windows and balcony doors have a large effect on the calculation related to both criteria, and notably influences the choice of the optimal solution.

Table 5. The characteristics of analyzed measure combinations

Solution	Number of measure					$Q_{f,h,nd}$ [kWh/m ²]	$Q_{f,c,nd}$ [kWh/m ²]	E_{prim} [kWh/m ²]	GC [EUR/m ²]
	1 δ [m]	2 δ [m]	3 δ [m]	4 δ [m]	5 index				
Existing	0.05	0.03	0.03	0.05	W4g	145.59	29.09	54.13	119.64
1. opt	0.18	0.03	0.03	0.25	W4g	99.01	24.69	41.71	111.39
58. opt	0.25	0.10	0.10	0.25	W11g*	95.64	7.85	24.29	148.71

* W11g - a double reflection glass filled with argon ($U = 1,3 \text{ W/m}^2\text{K}$; $g = 0,37$)

The discount rate is one of the most influential, and at the same time, the most uncertain input parameters used for calculating the global cost. As the change in the discount rate directly influences the change in the global costs of potential

project solutions, this parameter determines the cost-optimal solution as well. The initial value of the reference discount rate is 3% and with its reduction there is an increase in global costs. Contrary, when the discount rate increases, the lower value of global costs would mean retaining the current state of first the constructive assembly of external façade walls, and after of the other elements, too. The increase of the discount rate favors the solutions with worse energy properties and thus increases the total annual consumption of primary energy for heating and cooling. With the discount rate of 9 % or more, it is financially optimal not to implement any measures. This is the result of adjusting the optimal measures with a change in the rate. Figure 4 shows the sensitivity of the optimization results to the change in the discount rate.

Figure 4. The sensitivity of the optimization results to the change in the discount rate

6 Conclusion

The analysis carried out in this paper shows that, according to the energy and financial bases, optimal project solutions can be identified, which, with relatively low financial investments necessary for the energy retrofit of the thermal envelope, can achieve energy performance with values that are far better than the minimum requirements prescribed by the legal regulations from the field of energy efficiency. In addition to this analysis, for the evaluation and optimization of project solutions to be fully valid, other engineering calculations which are not covered by the subject of this paper, such as water vapor diffusion and similar, should be done.