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LIFE CYCLE COST OPTIMIZATION OF RESIDENTIAL BUILDINGS IN BULGARIA: A CASE STUDY OF THE BUILDING ENVELOPE

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Abstract

Around 60 % of residential buildings in Bulgaria are constructed before the Nineties of the last century, i.e. they have been in use for more than 30 years. Furthermore, the final energy consumption of Bulgarian residential buildings is the highest in Europe. This raises the question of the improvement of the energy performance of existing residential buildings. The current study is intended to assess the influence of the heat transmittance coefficient of the external building envelop elements on the annual energy consumption for heating and cooling and finding its optimal value. Life-cycle cost (LCC) as the optimization criterion is using. The optimization procedure is conducted for the climatic and economic conditions in Bulgaria and taking into account the existing legal framework. The minimum of the building life cycle costs is determined by using a genetic algorithm.

Keywords:

Building envelope;
Energy performance of a building;
Energy use;
Life cycle cost analysis;
Optimal thermal transmittance coefficient.

1 Introduction

According to the information in [1], there are five basic types of construction systems for residential buildings in Bulgaria: buildings made of prefabricated elements, reinforced concrete buildings, brick buildings with concrete slabs between the floors or with trimmer joists (without reinforced concrete), other building construction (buildings made of stone, clay, timber and etc.). The brick buildings with concrete slabs between the floors or with trimmer joists (without reinforced concrete) cover the largest percentage of the total useful area of the dwellings 37 % and 26 %, respectively. The second largest percentage is in the case of prefabricated buildings 22 %. The portion of reinforced concrete buildings, on the other hand, at a mere 9 %.

Analyses [1] demonstrate that around 60 % of the residential buildings in Bulgaria are constructed before the Nineties of the last century, i.e. they have been in use for more than 30 years. Moreover, the part of electricity in the final energy consumption of Bulgarian residential buildings is the highest in Europe — 39 % against an EU-27 average of 30 % [1]. The main reason for this situation is that the use of electricity for heating is high, while the use of natural gas for generating heat by combustion in local or district heat sources is very low.

Therefore, the task associated with the improvement of the energy performance of existing residential buildings plays a vital role in the sustainable energy development of the building sector in Bulgaria. A scientific way to solve the defined problem is the searching of optimal values for thermal transmittance coefficient of the building elements and prescribing of the energy and cost-optimal building envelop retrofit measures.

A considerable amount of literature has been published to asses optimal values of the thermal transmittance coefficient *U* or the thickness of the thermal insulation. These studies [2- 4], however, consider the optimization problem at significantly different climatic and economic conditions compared with those in Bulgaria. For example, a survey such as that conducted by Nasrollahi et al. [2] has shown the optimum *U*-value for an office building in the warm and dry climate of Iran. The optimization procedure is conducted with nine different building envelopes. Loukaidou et al. [3] have established the optimal thermal transmittance coefficient of the external envelope elements and the optimal window properties for a building located in Cyprus. In addition, the authors of [4] have calculated the minimum thickness of the thermal insulation layer taking into account the climate data for four different regions in Turkey.

The aim of the current study is to determine the optimum average thermal transmittance coefficient U_{avg} - value of the external envelope elements for a residential building in Bulgaria. This can be achieved by improving the mathematic model from a previous study made by authors [5], i.e. considering U-values of the external walls, roof, floor and windows as independent variables and adding the energy consumed during the cooling period as a function of the heat transfer coefficient of the external envelope elements.

In order to define the optimal thermal characteristics of the building elements, first, a modeling of the energy demand of the test-cell residential building is conducted. Then, the global cost of a measure or group of measures is calculated by applying Life Cycle Cost Method (*LCCM*) and took into account the effect of the inflation and interest rate. In this paper, the optimal values searching for the defined optimization problem is carried out using a Genetic Algorithm (*GA*). Finally, the correlation degree between the yearly energy demand for heating, cooling and the life cycle cost for each external envelope element is evaluated and compared to identify the most influential input variables of the mathematical model.

2 Optimization problem. Independent variables and objective function

In the present study, the optimization problem is formulated, as well in previous research of the authors [5]. Over again, the following combination of design variables was investigated: the thermal transmittance of building envelope and life cycle costs of the measures for increasing energy efficiency level in the building.

The new detail in the current investigation is that the average thermal transmittance of the building envelope, $U_{avg} = x$ [W/(m^{2}K)], is taken as a decision variable.

In the current paper, the average thermal transmittance is quantified through the time-averaged heat flow crossing the envelope for a 1 K temperature difference between internal and external air temperature. It is used the following equation [7]:

$$U_{avg} = \frac{H_{tr}}{\sum_k A_k} = \frac{H_D + H_g + H_U + H_A}{\sum_k A_k}. \tag{1}$$

The transmittance heat loss coefficients H_D, H_g, H_U and H_A are determined according to [15].

In case of opaque surfaces of the building envelope, in order to modify the thermal transmittance coefficients, and to search for optimal values of U_{avg}, it is acceptable to vary the thickness of the thermal insulation layer, y_i. Its value will change in a defined allowable space, Γ_x:

$$0 \le y_i[m] \le 0.2, i = 1,2,...,4, \text{ or } \quad y \in \Gamma_x. \tag{2a}$$

The allowable space for transparent building elements (windows and doors) is defined as follows:

$$1.2 \le x_5 \text{ [W/m}^2\text{K]} \le 2.7 \quad \text{ or } \quad x_5 \in \Gamma_x. \tag{2b}$$

In addition to the independent parameters, in the vector of input variables are also included:

• Vector of constructive parameters:

$$d = (A_k, A_f, V, A_{sol}) \in \Gamma_d, \tag{3}$$

where:
A_f -the total area of the heated/cooled spaces in the building, m^2;
A_k - the area of the k-th building element (walls, roof, floor, windows and etc.), m^2;
A_{sol} - the effective area of transparent and opaque enclosures, m^2.

• Vector of constant parameters:

$$x^c = (R_{t,w}, \Phi_r, F_{sh,ob}, \Phi_{int}) \in \Gamma_c \,, \tag{4}$$

where:
$R_{t,w}$ - the heat resistance of non-insulated opaque building elements, W/(m^{2}K);
Φ_r - the heat flux resulting from the emission from k-th element to the sky, W;
$F_{sh,ob}$ - the shading factor of the receiving solar energy surface;
Φ_{int} - internal heat gain of people, appliances and lighting, W.

In this article, the building is considered as a constructed object. Therefore, d is constant and refers to x^c ($\Gamma_d \subset \Gamma_c$).

The optimization problem is defined as in previous research [5]: looking for a minimum of the total monetary cost of the building and the building elements for a certain period of time, τ, $C_{g,\tau}$, expressed in the following objective function:

$$f\left(U_{avg}\right) = C_{g,\tau}\left(x\right), \tag{5}$$

in a space defined by $x \in \Gamma_x$.

3 Mathematical model

In the present investigation, the mathematical model consists of two parts. In the first one, the yearly energy needs of the building are modelled. The second part deals with the global cost over the calculation period, τ. It is important to note that the purchasing and mounting costs of the heating and cooling system of the building are considered as a dependent variable of the mathematical model.

The justification of the decision is presented in Fig. 1 and the paragraph below.

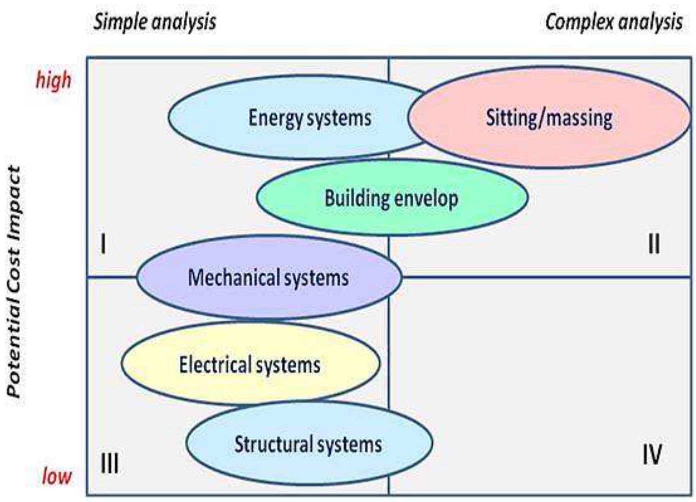

Fig. 1: LCCM decision matrix [6].

As can be seen from Fig. 1, the approach used to develop the mathematical model is in Quadrant I. Therefore, the current model of a residential building should be considered as a model with the highest priority because it characterized by high potential cost impact [6].

3.1 The energy demand of the building

Modeling of the energy demand of the considered residential building is conducted with the following information:

▪ The modeling procedure takes the climatic conditions into accounts, such as average monthly outdoor air temperature, average solar radiation, wind speed, wind direction, etc. They are defined according to the data in the Bulgarian Regulation №7 for energy efficiency in buildings for climatic zone №1 [7]. The used climatic data is summarized in the table below.

Table 1: Climatic data used in current investigation.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
The average monthly external air temperature												
θ_e, °C	1.9	2.7	5.1	10.2	15.6	20.2	23.7	22.3	19	13.8	9	4.3
Solar radiation, W/m^2												
East	40.4	59.2	68.4	85.5	108.3	122	126.4	126.2	104.5	68	45.8	36.6
West	40.4	59.2	68.4	85.5	108.3	122	126.4	126.2	104.5	68	45.8	36.6
South	72.7	95.9	87.5	83.7	90.5	97.4	104.9	126.5	133.7	104.3	80.6	67.8
North	22.9	34.8	47.7	63.6	77.7	84.3	83.7	75.9	60.7	40.9	26.1	20.2
Horizontal	50.1	81.2	109	149.7	194.1	218	226.5	219.7	166.5	97.2	58.3	43.9

- The building is located in a residential neighbourhood with a predominant building construction with low height (10 m mean height of the surroundings);
- Thermal resistance of the non-insulated external walls, the ground floor, floor over an unheated basement, the roof are considered as constant variables in the mathematical model of the reference building. Description of the construction layers of the reference building elements are listed in Table 2.

Table 2: Construction layers of building envelope elements.

Building elements	Construction layers
External walls	2 cm lime, sand plaster (outside), λ = 0.97 W/(mK); y_1 cm expanded polystyrene , λ = 0.034 W/(mK); 25 cm brick masonry, λ = 0.52 W/(mK); 2 cm lime, sand plaster (inside), λ = 0.7 W/(mK).
Roof	2.5 cm ceramic tiles, λ = 0.99 W/(mK); 0.4 cm bitumen, λ = 0.17 W/(mK); y_2 cm mineral wool with λ = 0.037 W/(mK) and ρ = 30 kg/m^3; 0.3 cm vapor barrier, λ = 0.17 W/(mK); 3 cm oriented strand board, λ = 0.13 W/(mK); 12 cm wooden ribs (beech), λ = 0.41 W/(mK).
Ground floor	14 cm gravel, λ = 3.5 W/(mK); 12 cm reinforced concrete, λ = 1.63 W/(mK); y_3 cm extruded polystyrene, λ = 0.033 W/(mK) and ρ = 32 kg/m^3; 2.0 cm cement screed, λ = 0.93 W/(mK); 0.7 cm tile, λ = 1 W/(mK).
Floor over an unheated basement	12 cm reinforced concrete, λ = 1.63 W/(mK); y_4 cm extruded polystyrene with λ = 0.033 W/(mK) and ρ = 32 kg/m^3; 2.0 cm cement screed, λ = 0.93 W/(mK); 0.7 cm tile, λ = 1 W/(mK).
Windows	Frame: PVC; Glass package: triple glazing 4/9/4/9/ 4mm and air filled; Low-emission coating.

- It is assumed that the transmission heat loss coefficient from heated space *i* to the exterior *e* through the unheated space, H_U, and the transmission heat loss coefficient from heated space *i* to a neighbouring heated space *j* heated at a significantly different temperature, i.e. an adjacent heated space within the building entity or a heated space of an adjacent building entity are equal to zero;
- The modeling of the energy demand of the considered building is conducted assuming that ventilation systems are absent, i.e. the building is naturally ventilated. It is assumed that the supplied air due to infiltration has the thermal characteristics of external air. The average hourly air exchange rate is set as 0.5 h^{-1};
- The total number of occupants of the building is 8 people;
- The internal heat gains from people, appliances, and lighting were defined to be Φ_{int} = 0.349 kW;
- Internal design temperature is set as θ_{int} = 22 °C in winter and θ_{int} = 27 °C in summer, respectively. Building spaces such as bathrooms are considered as uncooled space.

The yearly energy needs of the building, *Q*, are assessed according to [8]. The basis of this method is the following equation of the yearly energy needs of the building:

$$Q = Q_H + Q_W + Q_V + Q_C - Q_r \text{ kWh/year,} \tag{6}$$

where:
Q_W - the yearly energy needs for domestic hot water;
Q_V - the yearly energy needs for ventilation;
Q_r – the regenerated energy in the building.

In equation (6), the heating gains $Q_{H,gn}$ in the winter season and heat loss $Q_{C,ht}$ in the summer season, respectively, are taken into account through dimensionless factor for the utilization of the monthly heat losses and the monthly heat gains, respectively, $\eta_{H,gn}$ and $\eta_{C,gn}$. Then, the required energy for heating for each month of the heating period:

$$Q_H = Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}, \tag{7}$$

and the required energy for cooling for each month of the cooling period:

$$Q_C = Q_{C,gn} - \eta_{C,gn} \cdot Q_{C,ht}, \tag{8}$$

where:
$Q_{H,ht}$ - the total heat losses of the zone for the respective month,
$Q_{C,gn}$ - heat gains in the area for the respective month.

3.2 The global costs over a calculation period

The cost-optimal energy efficiency levels of the residential building are evaluated using the methodological framework of the European Directive 244/2012/EU [9]. The global costs of a measure or group of measures for improving the energy performance of the building envelop from a financial point of view are calculated according to equation [9]:

$$C_{g,\tau} = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \cdot R_d(i) \right) - V_{f,\tau}(j) \right]. \tag{9}$$

The output data for conducting the LCCA are presented in Table 3.

Table 3: The output economic data used in the conducted LCCA.

Economic life of the building elements	τ = 30 years
Real discount rate	r = 6 % [a)]
Energy price escalation	2 %
Electricity (purchase)	c_{el} = 0.11984 EUR/kWh [b)]

[a)]Based on the the guidance of the European Regulation 244/2012/EU [9]; [b)]According the actual price list

In this paper, initial investment costs, C_I, are considered as a sum of the cost of materials, labor, equipment, and design fees incurred for thermal insulation layer of the building's external walls. In addition, the initial investment costs of heating and cooling system for the building, $C_{I,HEAT}$., are considered as dependent variable. Therefore, initial investment costs are:

$$C_I = C_{I,ins} + C_{I,HEAT} + C_{I,P} \text{ , [€].} \tag{10}$$

The initial investment costs for the thermal insulation layer, $C_{I,ins}$, [€], is defined as follows:

$$C_{I,ins} = \sum_{n=1}^{i} C_{ins} \cdot y_i \cdot A_i + C_{mount} \cdot \sum_{n=1}^{i} A_i + a_1 \text{ , [€].} \tag{11}$$

The purchasing and mounting costs of the heating and cooling system of the building, C_{1HEAT}, [€], is taken as a sum of the mounting costs of the heat source (air to water heat pump), C_{1HP}, of the fan coils, C_{1C}, of the pipe network, C_{1nine}, and of the additional and auxiliary equipment, C_{1nx}. In the mathematical model of the reference building, the costs of purchasing and installing the heat source, C_{1HP}, and fan coils, C_{1C}, are also considered as dependent variables. They are defined as a function of the design heating and the cooling load of the building.

The initial investment costs for the heating and cooling system, $C_{I,HEAT}$, are determined after analyzing the purchase costs of the air-to-water heat pump and fan coils provided by different manufacturers, the following equations are derived:

$$C_{I,HP} = 0.171 \cdot \Phi_{t,HL}^2 + 0.021 \cdot \Phi_{t,CL}^2 + 75.16 \cdot \Phi_{t,HL} + 19.755 \cdot \Phi_{t,CL} + 1072.729 \text{ ,} \tag{12}$$

$$C_{I,C} = 1.02 \cdot 10^{-4} \cdot \Phi_{t,HL,i}^2 + 0.51 \cdot 10^{-4} \cdot \Phi_{t,CL,i}^2 - 0.00686 \cdot \Phi_{t,HL,i} - 0.0074 \cdot \Phi_{t,CL} + 332.1 . \tag{13}$$

The determination of the design cooling, $\Phi_{t,CL}$, and heating loads, $\Phi_{t,HL}$, was conducted using the methodological framework presented in [15].

In the mathematical model of the reference building, maintenance costs during the *i*-th year are considered as the sum of the repair, recommissioning, replacement, $C_{I,P}$, and asset preservation costs of the heating and cooling system and the heat insulation layer of the external walls. Under current market prices, these costs can be defined as:

$$C_{I,P} = 1\% \cdot C_I \text{, [€] .} \tag{14}$$

The operating costs of heating and cooling system, $C_{H/C}$, include with the fuel costs incurred during the *i*-th year of the building's economic life. They are defined as a product of the annual energy demand of the building, and the electricity price as of 01.07.2019.

4 The optimization algorithm

The numerical solution of the optimization problem is performed by applying the Genetic Algorithm (GA). The set values of the turning parameters in the algorithm and the schematic diagram of the used GA are presented in the previous publication of the authors [5].

5 Sensitivity analysis

In order to determine the most important input parameters for building energy performance, the sensitivity analysis is conducted. In this regard, the sensitivity coefficient is used. It is defined as following [10, 11]:

$$S_i = \frac{\left(\Delta L_i / L_n\right)}{\left(\Delta P_i / P_{i,n}\right)}, \tag{15}$$

where: ΔL_i and ΔP_i are the value of an output parameter and an input parameter variation, respectively.

In the current paper, the output values, L_i, are the yearly energy demand for heating or cooling and the life cycle cost of the object. It is assumed that the input parameters, P_i, are the thermal transmittance coefficients of the external building envelop elements, i.e. the independent variables of the mathematical model.

As can be seen from Eq. (8), the sensitivity coefficient is calculated concerning the base case model values - L_n and $P_{i,n}$. In this paper, as the base case model is selected two-family residential building located in Varna, Bulgaria. Geometric specification of the test building is summarized in Table 4.

Table 4: Geometric specification of the base case residential building.

The total area of the heated and/or cooled spaces	179.2 m^2
The volume of the heated and/or cooled spaces	510 m^3
Area of opaque building elements (walls)	206.16 m^2
Area of transparent building elements	36.15 m^2
Windows/walls ratio **South** **North** **East** **West**	17.54 % 57.94 % 68.24 % 0 % 0 %
Area of the ground floor **Area of the floor under the unheated basement**	72.35 m^2 17.65 m^2
Area of the roof	90 m^2

As input parameters of the base case model, $P_{i,n}$, are accepted the heat transmittance coefficient of the building envelop elements. It is assumed that the walls, roof, and floors are insulated and triple glazing for the windows is used. Thus, the elements of the building envelope meet the requirements of the Bulgarian Energy Efficiency Standard [7]. Yu *et al.* [10] have used a similar approach.

The used values of input parameters of the base case model, $P_{i,n,}$ are as follows:

- Walls: $U_1 = P_{1,n}$=0.2746 W/(m^{2}K);
- Roof: $U_2 = P_{2,n}$ = 0.2405 W/(m^{2}K);
- Ground floor: $U_3 = P_{3,n}$ = 0.3562 W/(m^{2}K);
- Floor over unheated basement: $U_4 = P_{4,n}$ = 0.4539 W/(m^{2}K);
- Windows: $U5 = P_{5,n}$ = 1.4 W/(m^{2}K).

6 Results and discussion

In the current investigation, the developed energy model of the base case residential building was simulated and the results are shown in Fig. 2. The results are presented through the average heat transmittance coefficient, U_{avg}.

From the data in Fig. 2, it is apparent that there is significantly declining in the heating energy needs of the building as a result of the better thermal characteristics of the external building envelope elements.

On the other hand, Fig. 2 reveals that there has been a slight rise in the yearly energy need for cooling as a result of better thermal insulation of the building. What can be seen from this figure is that the line slope of the cooling energy needs is smaller than the trend line of the heating energy needs.

It is important to note that these results are valid in case of a residential building with small windows to walls ratio (*WWR*). In the current paper, the *WWR* is approximate 18 %, Table 4.

Fig. 2 also shows that the cooling energy required for the building is about 25 times less than for heating energy required. Therefore, the tendency to increase the yearly energy needs for cooling by decreasing the average heat transmittance coefficient does not significantly affect to the total yearly energy needs of the building. Because of this, the function describing the reducing of the total yearly energy needs of the building is the same type as in the case of the yearly energy needs for heating.

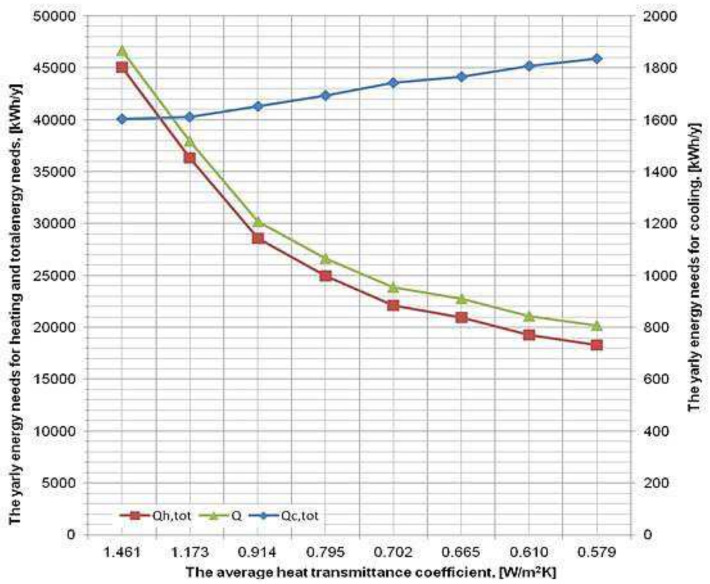

Fig. 2: Effect of thermal insulation of the yearly energy needs for heating, $Q_{H,tot}$, cooling, $Q_{C,tot}$, yearly total energy needs, Q.

In conclusion, the total energy needs for heating and cooling required for the building on an annual basis decreases with a decline in the average heat transmittance coefficient of the building envelope elements.

In the case of the considered test residential building and the construction layers of the building elements described in Table 2, the determined techno-economical optimal value of the average heat transmittance coefficient is $U_{avg,opt}$ = 0.576 W/(m2K). This result can be achieved by the values of the optimal heat transmittance coefficient of the building elements and using Eq. (1). Therefore, the presented data in Table 5 is the techno-economical optimal thermal transmittance coefficients of the building envelop elements.

Table 5: The optimal thermal transmittance coefficients and corresponding insulation thickness.

Climatic zone	$U_{opit,i}$, [W/m²K]				
	Walls	Roof	Ground floor	The floor under the unheaed basement	Windows
	0.24	0.24	0.23	0.28	1.41
№1 Varna	**Insulation thickness, y_i,** [m]				
	0.117	0.119	0.087	0.056	-

Using the results presented in Table 5 to determine the yearly energy needs of the building, Q, leads to obtaining information about the optimal value of this parameter. For example, the value of the yearly total energy needs of the building corresponding to the minimum life cycle costs is 169.11 kWh/(m^2·year). This result decrease as much as 24 % compared to the case of building envelope without thermal insulation.

As Fig. 3 shows, there is a significant drop as much as 16 % in life cycle cost (LCC) between the building without thermal insulation and the building envelope elements with the optimal average heat transmittance coefficient.

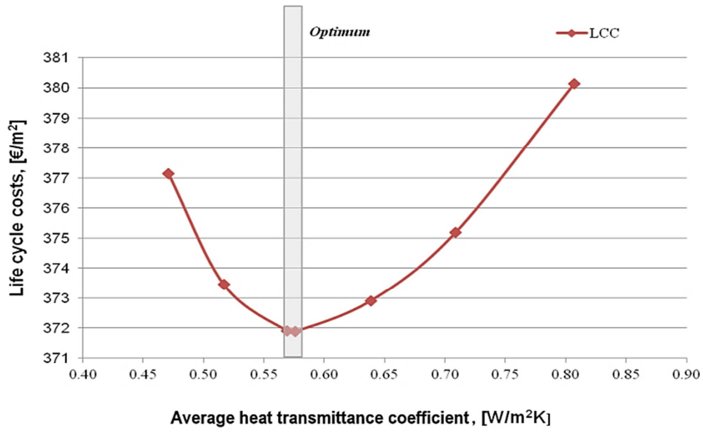

Fig. 3: Effect of thermal insulation of life cycle costs.

As a result of lower average heat transmittance coefficient compared to the optimal value ($U_{avg,opt}$ = 0.576 W/m^{2}K), the LCC slightly increase. The reason is the higher required capital investments for thermal insulation and the higher cooling energy needs.

In the left side of the Fig. 4 is showed the mean sensitivity coefficient of the independent variables on the heating energy needs of the considered base case residential building. As can be seen, the S_i of the heat transmittance coefficients of the external building envelope elements is positive. The sensitivity analysis also demonstrates that the heat transmittance coefficient of the walls is the most important parameter for reducing the heating energy use in the base case residential building S_w = 9.96 %, whereas the least significant is the U-value of the floor under unheated basement S_{FUUB} = 0.8 %.

Moreover, considering the better thermal insulation of the wall as an independent measure for improving the energy performance of the building envelope, from the data in Fig. 4, it is apparent that the heating energy needs of the building can be decreased by around 10 % for every increase of 50 % in the thickness of the wall thermal insulation.

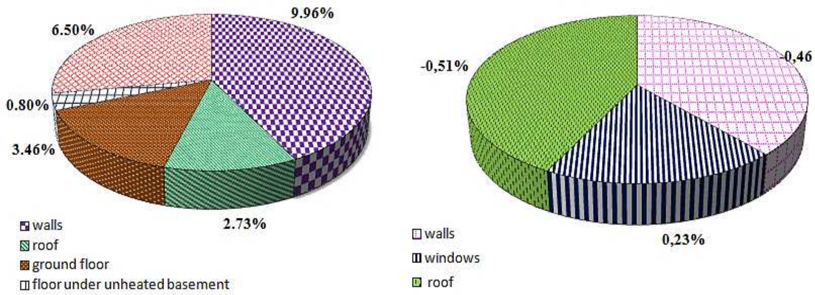

Fig. 4: Sensitivity coefficient of the independent variables on the heating energy needs (left) and on the cooling energy needs (right).

Closer inspection of the right side of the Fig. 4 shows that the mean sensitivity coefficient of the heat transmittance coefficients on the cooling energy needs of the widows is positive, whereas the S_i of the heat transmittance coefficients of the walls and roof are negative. These results indicate that cooling energy use decrease with the decline in the heat transmittance coefficient of the windows. On the other hand, the negative values of the S_w and S_r are indicative of the fact, that when the *U*-values of the walls and roof decrease, increase the cooling energy demands of the building. The most important parameter for reducing the cooling energy use is the heat transmittance coefficient of the walls ($|S_w| = 0.51\% > |S_{win}| = 0.23\%$). A possible explanation for this result may be the small WWR.

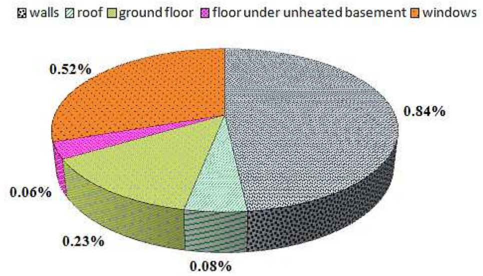

Fig. 5: Sensitivity coefficient of the independent variables on the life cycle cost.

Fig. 5 presents the mean sensitivity coefficient of the independent variables on the life cycle cost. This finding was expected and suggests that the life cycle cost decrease with the fall in each parameter value. The wall heat transmittance coefficient is the most apparent impact on the life cycle cost of the building. The results demonstrate that LCC can be decreased by around 0.8 % when increasing the thermal insulation of the wall with 50 %. Considering lower U-value of the windows as a measure for improving the energy performance of the building envelope, the results from sensitivity analysis demonstrate that LCC can be fall by approximately 0.5 % for every decrease of 11 % in the *U*-value of the windows.

It seems possible the low sensitivity coefficients of the independent variables on the life cycle cost are because that the economic parameters of the model (inflation rate, real discount rate, electricity price, *etc.*) are the most sensitive parameters on LCC.

The reported results of the conducted sensitivity analysis are similar to the data reported by Yu et al. [10] and Zhang et al*.* [14].

7 Conclusion

The current investigation was intended to assess the optimal heat transmittance coefficient of the external building envelop elements. The second purpose of the paper was to determine the most important design energy parameters of a residential building located in Bulgaria.

The results demonstrate that a residential building with thermal insulated envelop elements have lower energy needs and costs for heating, but higher energy needs and electricity costs for cooling. However, the rate of decrease of the heating energy demand is much higher than the rate of increase of cooling energy needs. Therefore, in the case of Bulgarian climate conditions and residential building with small *WWR*, the thermal insulation is an appropriate measure for a better building energy performance and economy in the heating period. In the cooling season, however, the better energy performance of the building envelope can be achieved by applying the low emissivity coatings of the transparent building elements and by using effective exterior shading.

By developing the mathematical model from our earlier investigation [5] and including the thermal transmittance coefficients of the roof, floor and windows as independent variables, it was reached around 5 % increase of the external wall optimal *U*-value.

The analysis of the results presented in this paper leads to the conclusion that concerning floor thermal insulation, further regulatory restrictions could be introduced. Thus, it can be also achieved better acoustical properties and suitable thermal storage capacity of the floor slab. However, the conducted sensitivity analysis shows that the heat transmittance coefficient of the wall and windows of the building with a small ratio of the windows to walls area is the most sensitive design energy parameter.

The methodology from the current investigation can be useful in the process of the investment design and in particular, in the process of developing the part "Energy efficiency of building" of the investment project.

Further work needs to be done to establish the optimal thermal properties of the transparent building elements and the influence of the windows cardinal direction and *WWR* of the building's yearly energy demands in more detail. The influence of the shape and shading coefficient of the building must be assessed.

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