One implementation of an energy efficient buildings calculator

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Abstract—In this paper a novel - simplified method for calculating energy efficiency, and its implementation were presented. Technical details of the method were explained. It was shown how this software should be used, and how results should be interpreted. In this way, the use of software for energy efficiency calculations was simplified, and that was achieved with minimal loss of accuracy and precision. The results were compared with the results from a similar software tool – used in Serbia, using concrete data from location studies. Possibilities for further improvement were suggested.

Index Terms—energy efficiency; simplified calculation method; sustainable architecture; thermal gains; thermal losses.

I. Introduction

SUSTAINABLE architecture seeks to minimize the negative environmental impact of buildings. That is achieved by enhancing efficiency and moderation in the use of materials, energy and development space and the ecosystem at large. Sustainable architecture uses a conscious approach to energy and ecological conservation in the design of the built environment [1]. That way we do not just ensure that our actions today do not inhibit the opportunities of future generations [2], but also enable financial savings.

Energy efficiency over the entire life cycle of a building is the most important goal of sustainable architecture. There are many different passive and active techniques to reduce the energy needs of buildings and increase their ability to capture or generate their own energy [3]. The first step is to choose a good site and properly orient the building. Arrangement and sizing of rooms, windows sizing and orientation is also very important. Heating, cooling and ventilation systems should be precisely projected. On the other side, there are some simple renewable energy generators. Solar panels provide sustainable electricity for any use. They are usually installed on the roofs. Multiple factors such as orientation, latitude, number of sunny hours, etc. influent on efficiency, but as technology advances, efficiency is growing. Solar water heating generates hot water for a home. It is very efficient since there is no energy conversion, and there is no hi-tech involved. Heat pumps can be thought of as reversible air-conditioners. They can take

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heat from a relatively cool place and dump it into a relatively hot place. Wind turbines are also one of the solutions, but as their size is decreased, their cost-efficiency coefficient decreases.

In this paper we concentrate on the materials that make the thermal envelope. To be more specific – the roof, facade and windows, as they are the most common investments in the thermal characteristics of buildings. A simplified model for calculating energy efficiency was explained in the following chapter. According to this theory, an appropriate software tool was developed. Our main goal was to make it is easy to use, not only for professionals, but also for ordinary users. It helps the common user decide what the optimal investment is, in a short amount of time. Results and comparison with similar solutions and site study was provided in the fourth chapter.

II. Theoretical Background - Calculation Method

Theoretical background for calculating thermodynamic characteristics of buildings is obtained from [4]. In this regulations book, it was described how to calculate the water vapor diffusion, building's thermal stability in the summer, thermal transmittance of construction elements, coefficient of transmission losses, coefficient of ventilation losses, energy performance of the building, annual energy use for heating, the total annual energy use. In addition to the aforementioned methodology, in the regulations book were defined the limit values: maximum value of heat transfer coefficient of thermal elements of the building envelope, the maximum value of specific transmission heat losses, depending on the shape of the building (for non-residential buildings) and the permitted annual consumption of energy (for new and existing buildings). Methodologies described in the regulations are based on ISO standards [5 to 10].

A. Standard model

The first step in the calculation of heat loss is to obtain the heat transfer coefficient of the construction element – U [W/(m² K)]:

$$U = \frac{1}{R_{Si} + \sum \frac{d}{\lambda} + R_{Se}}, \tag{1}$$

where R_{Si} and R_{Se} are internal and external resistance to the passage of heat; d - the thickness of the layer; λ - thermal conductivity of the layer. This method applies to all non-transparent positions in the building that are between a heated area and the outside air or unheated space. In addition to the above listed elements of the thermal envelope, there are transparent elements, and there are positions on and in the ground. For positions on the ground methodology from

standard [11] is used ("Via Ground" method). This method takes into consideration: insulation characteristics of the ground, geometrical ratio between contact area and bond length, and impact of insulation properties of connected positions, which provides more precise results then method used for other positions. If the soil type is known, thermal characteristics are taken from [12], or in other case we use: $\lambda = 2.0\ \text{W/mK}$ and $\rho c = 2.10^6\ \text{J/}(\text{m}^3\text{K})$, where ρ - density of non-frozen soil, c - specific heat of non-frozen soil. The impact of groundwater can be ignored in most cases, and it was not discussed in this paper.

The first step of Via Ground method is to determine dimensional characteristics of the floor. This is achieved using relation:

$$B' = \frac{A}{0.5P}, \tag{2}$$

where B' - dimensional characteristic of the floor, A - floor area, P - perimeter of the floor which is in contact with outer space.

The next step is to calculate the equivalent thickness of the floor and the wall:

$$d_t = w + \lambda_S(R_{SI} + R_f + R_{SE}), \tag{3}$$

$$d_w = \lambda_S(R_{SI} + R_w + R_{SE}), \tag{4}$$

where w - overall thickness of the wall; λ_S - coefficient of thermal conductivity of the soil; R_f - thermal resistance of the floor construction; R_w - thermal resistance of the basement wall. Thin layers and high density layers could be neglected.

After this, ratio between equivalent floor thickness and dimensional floor characteristics should be calculated. In case that $d_t < B'$, the heat transfer coefficient becomes:

$$U = \left(\frac{2\lambda}{\pi B'} + d_t\right) \ln\left(\frac{\pi B'}{d_t} + 1\right), \tag{5}$$

or in the other case:

$$U = \frac{\lambda}{0.457} B' + d_t. \tag{6}$$

In the case of non-insulated or poorly insulated basements, the heat transfer coefficient is calculated the same way as in relations (5) and (6), and by replacement of d_t value with $d_t < B'$, where z is the height of the basement under the ground.

Calculation of the thermal transmittance coefficient of the basement wall is done according the formula:

$$U_{BW} = \frac{2\lambda}{\pi z}\left(1 + \frac{0.5 d_t}{d_t + z}\right) + \ln\left(\frac{z}{d_w} + 1\right). \tag{7}$$

In case that equivalent wall thickness is smaller than equivalent floor thickness, U_{BW} becomes:

$$U_{BW} = \frac{2\lambda}{\pi z}\left(1 + \frac{0.5 d_w}{d_w + z}\right) + \ln\left(\frac{z}{d_w} + 1\right). \tag{8}$$

In transparent positions, standards [13 and 14] are in use for windows, balcony doors and shutters, and [15] for wall curtains.

For external joinery, thermal transmittance coefficient of the windows is:

$$U_W = \frac{(A_G U_G + A_F U_F + l_G \Psi_G)}{(A_G + A_F)}, \tag{9}$$

where A_G - glass area, U_G - coefficients of thermal conductivity of glass; A_F - framework length; U_F - framework's heat transfer coefficient; l_G - length of the glass and the frame contact; Ψ_G - factor of temperature correction - on contact of the frame and the glass. The coefficients of the glass and the frame, as well as factor of temperature correction can be obtained in 3 ways: the investigation in accordance with the standard, calculation in accordance with the standard and by taking table values.

The second step of heat loss calculation is calculating the coefficient of transmission heat loss:

$$H_T = \sum (F_X U A) + H_{TB}, \tag{10}$$

where F_X is temperature correction factor; A - area of the position; U - coefficient of position's heat transfer; H_{TB} − coefficient of linear heat losses (thermal bridges). Temperature correction factor is used to minimize the coefficient of transmission heat loss for the positions that are not in contact with outside air, but with unheated rooms, the ground, or heated rooms with different temperatures. The impact of thermal bridges is calculated using the formula:

$$H_{TB} = \Delta U_{TB} A, \tag{11}$$

where A is the area of the thermal building envelope, and ΔU_{TB} is considered as a constant with a value of 0.1 W/(m^2K). If the influence of the thermal bridge of an element is precisely calculated, the surface of the element is subtracted from the surface of the thermal envelope during analysis of H_{TB}.

When H_T is calculated, we can obtain H_T' - specific building's transmission loss. It depends on the ratio of the building's volume and the area of the thermal envelope, and the percentage of transparent surfaces.

After calculating the transmission heat loss of the building, we can switch to the calculation of the ventilation heat loss of the building. This calculation is performed according to the formula:

$$H_V = \rho c_P V n, \tag{12}$$

where ρc_P is considered as a constant: 0.33 [Wh/m^3K] or 1200 [J/m^3K]; V - volume of heated space; n - number of air changes per hour. Number of air changes depends on the exposure to the wind, tightness and position of the building.

After calculating the coefficient of transmission and ventilation heat loss of the building we have all the information necessary to obtain:

- Total volume heat loss within the thermal envelope:

$$q_V = \frac{H_T + H_V}{V_E}, \tag{13}$$

- The annual energy requirement for heat loss recovery:

$$Q_{\text{H,ht}} = (H_\text{T} + H_\text{V})\,24\,H_{\text{DD}}\,10^{-3}, \qquad (14)$$

where H_{DD} is the number of heating degree days.

It is now possible to calculate the annual energy requirement for heating, according to the formula:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn}(Q_{\text{Int}} + Q_{\text{Sol}}), \qquad (15)$$

where $\eta_{H,gn}$ is the utilization factor of heat gains for the heating period; Q_{Int} - internal heat gain; Q_{Sol} - gain due to solar radiation. Utilization factor of heat gains for the heating period can be selected based on the type of construction or can be accurately calculated. If the construction type is heavy then $\eta_{H,gn} = 1$, if the construction type is medium heavy then $\eta_{H,gn} = 0.98$, and if it is light then $\eta_{H,gn} = 0.9$. The calculation method is complex, and since it is not present in the software implementation, it will not be provided here. It is available in [4].

The annual amount of energy gains originating from internal heat comes from two sources: heat from the people and the heat of the electric devices. It is calculated using the formula:

$$Q_{\text{Int}} = A_\text{F}\,(q_\text{P} + q_\text{E}), \qquad (16)$$

where A_F is the usable area of the building; q_P - heat component that originates from people; q_P - heat component that originates from electric devices.

Solar gains are calculated for the positions of windows, balcony doors, walls and roofs. Most of these gains come from the transparent positions:

$$Q_{\text{Sol}} = F_{sh}A_{\text{Sol}}I_{\text{Sol}}\tau_{\text{Sol}}. \qquad (17)$$

F_{sh} - shade factor; A_{Sol} - ratio of the surface and the other characteristic properties of the element; $I_{\text{Sol}}\tau_{\text{Sol}}$ - medium sums of solar radiation. The shade factor depends on F_{hor} - shading factor due to surrounding buildings; F_{ov} - shading factor due to horizontal facade elements; F_{fin} - shading factor of vertical facade elements:

$$F_{sh} = F_{hor}F_{ov}F_{fin}. \qquad (18)$$

Also, we have:

$$A_{\text{Sol}} = A_{\text{Sol,gl}} + A_{\text{Sol,C}}, \qquad (19)$$

where $A_{\text{Sol,gl}}$ is the ratio of the surface and the other characteristic properties of the element – transparent surfaces ; $A_{\text{Sol,C}}$ - the ratio of the surface and of the other characteristic properties of the element - outer walls. Those two values are obtained using relations:

$$A_{\text{Sol,gl}} = g_{\text{gl}}(1 - F_\text{F})A_\text{W}, \qquad (20)$$

$$A_{\text{Sol,C}} = \alpha_{\text{S,c}}R_{\text{S,C}}U_\text{C}A_\text{C}. \qquad (21)$$

g_{gl} - permeability factor of solar radiation; F_F - frame factor; A_W - the surface of the window; $\alpha_{\text{S,C}}$ - the emissivity of the outer surface of the wall; U_C - conductivity coefficient of the wall; $R_{\text{S,C}}$ - resistance of heat transfer for the outer side of the wall; AC - area of the wall.

After calculating the annual energy requirement for heating, we can get the specific energy necessary for heating via the form:

$$Q_{H,an} = \frac{Q_{H,nd}}{A_\text{F}}. \qquad (22)$$

B. Symplification method

The process described above could be simplified by removing elements of the analysis that are not necessary to get the effectiveness of common interventions on the building. Our implementation does not calculate losses to the ground and to the unheated space, but these losses are approximated based on the average percentage of participation of these positions in the heat loss of the particular building type from [16]. These positions are not calculated because they are less significant in terms of energy loss, because they are rarely repaired during the modifications to the building and because they use different calculation methods that require additional information which is not easy to find. Calculation of the water vapour diffusion and building's thermal stability in the summer were also excluded.

Within the statistical analysis, the buildings listed in [16] were processed. These buildings are taken for the analysis because they represent the typical buildings in Serbia, they were analysed in detail in the field of energy efficiency (studies, passports, thermovision snapshots), and the information source is reliable. The fact that those buildings are typical is very important because the averages will represent most buildings in Serbia. Division according to the type of the buildings before the averaging values process makes the average values to be in narrow range and provides smaller: standard deviation, deviation from the average value and median. In this way software imprecision was reduced. Lamellas and buildings in series will on average have more transmission losses in the walls of the dilatation, in comparison with the free-standing buildings. Skyscrapers will have fewer losses to the ground than other types of buildings. Simplification of the calculation by obtaining the average values appears twice: when considering the share of transmission heat loss, and when considering the surface area of individual elements of the building.

Prerequisite for statistical analysis is data collection. The data can be a population or samples. In our case, the samples are taken from [16]. Samples analysed show that it is possible to approximate the share of transmission heat loss and surface areas of the facade walls, windows and roof, and the share of the other parameters. That is achieved considering building types independently. In our implementation, we calculate the influence of transmission heat loss and surface areas of the facade walls, windows and roof. The influence of the other parameters was approximated using values from [16], by averaging values for specific building types. In the end, values are rescaled according to shares, and added up. Those approximations fill the gaps in the formula (10) for calculating the coefficient of transmission heat loss. To be more specific the area approximation is used to calculate a part of thermal bridge losses. These approximations seem

reasonable because the calculated share is much greater than the approximated share. Also, the deviation from the mean values is very small, in the approximated part.

III. SOFTWARE IMPLEMENTATION

Our software implementation is straight forward coding of equations discussed in the simplified method. Graphic interface consists of 1 main and 3 additional windows: additional information, energy estimate and financial estimate. The main window (Fig. 1) accepts general information about the building – layers of the facade wall and the roof, as well as the type of windows. In the main window there is elementary feedback information about the thermal and financial characteristics of the elements of the building envelope. Through the main window, we can access the additional windows, and enter detailed information about the building's windows positions, facade wall and roof. There are also fields for general information about the building.

Fig. 1. Main window of software implementation

The additional information window, which is shown in Fig. 2, is used to create other positions of facade wall and roof, for precise inputs regarding orientation and surface area, to define shading factor, pause in heating and type of energy used for heating. None of the data which can be adjusted in this box is mandatory for the calculation of the energy and economic characteristics of the building, but by setting adequate values user improves the accuracy of the calculation.

Fig. 2. Additional information window of software implementation

Energy estimate window provides results from conductivity of individual elements of the thermal envelope to the annual emissions of carbon dioxide (CO_2) due to energy consumption for heating the building. Information about the coefficient of transmission loss of thermal bridges, total coefficient of transmission losses, coefficient of ventilation losses, intern and solar thermal gains, annual energy demand for heating and compensation of losses of heat are displayed. There is also information about specific annual energy demand for heating systems that work with or without any interruption in heating, energy class of the current state and the proposed modification options. As the final result in this window, there is information about energy requirements before and after modifications, and corresponding CO_2 emissions.

Financial estimate window is used to enter values for annual savings and annual maintenance costs, or to choose the type of heating followed by entering the cost of energy source. Cumulative net savings for the initial state and both variations are displayed. It is possible to select which variation will be described in detail. There is also a table of profitability calculations for a period of 20 years which contains information about investment costs, annual savings, annual maintenance costs, net savings, the present net savings value and cumulative net savings.

IV. RESULTS AND DISCUSSION

In this chapter results obtained using KnaufTERM2 PRO [17] and our software implementation (named T5000) was compared. KnaufTERM2 PRO is used in Serbia for this kind of calculations. Concrete data from location studies were used. That information was taken from [16].

In Table I and Table II results for two cases were displayed. First one is a free-standing family house built between 1919 and 1945, and the second one is a residential skyscraper built between 1961 and 1970.

TABLE I
FREE-STANDING FAMILY HOUSE

	KnaufTERM2 PRO	T5000 precise info	T5000 basic info
R windows	0,28571	0,29	0,29
U windows	3,5	3,5	3,5
R facade wall 1	0,90334	0,97	0,97
R facade wall 2	/	/	/
U facade wall 1	1,107	1,04	1,04
U facade wall 2	/	/	/
R roof 1	1,53609	1,29	1,29
R roof 2	/	/	/
U roof 1	0,651	0,78	0,78
U roof 2	/	/	/
H_{TB}	26,969	26,59	26,59
H_T	246,553	242,11	242,11
H_V	30,69	30,69	30,69
Q_{Int}	713,223	713,22	713,22
Q_{Sol}	1688,1	1660,5	1624,05
$Q_{H,ht}$	16767,416	16498,59	16498,59
$Q_{H,nd}$ (without pause)	14366,1	14124,87	14161,32
$Q_{H,nd}$ (with pause)	/	/	/
$Q_{H,an}$	243,91	239,81	240,43

TABLE II
RESIDENTIAL SKYSCRAPER

	KnaufTERM2 PRO	T5000 precise info	T5000 basic info
R windows	0,28571	0,29	0,29
U windows	3,5	3,5	3,5
R facade wall 1	1,33869	1,34	1,34
R facade wall 2	2,5	2,52	/
U facade wall 1	0,747	0,75	0,75
U facade wall 2	0,4	0,4	/
R roof 1	1,43885	1,5	1,5
R roof 2	2,32019	2,3	/
U roof 1	0,695	0,67	0,67
U roof 2	0,431	0,43	/
H_{TB}	480,335	436,71	436,71
H_T	8143,281	7338,47	7656,18
H_V	3495,51	3495,51	3495,51
Q_{Int}	63699,94	63699,97	63699,97
Q_{Sol}	157153,9	158640,2	161004,98
$Q_{H,ht}$	703913,85	655239,02	674453,71
$Q_{H,nd}$ (without pause)	483060	455132,86	449748,75
$Q_{H,nd}$ (with pause)	/	/	/
$Q_{H,an}$	137,74	129,78	128,24

The first example for analysis is the simplest real building, with a single type of construction of the facade wall, one type roof construction and one type of window. It is important to note that values of $Q_{H,an}$ in our implementation differ from KnaufTERM2 PRO for just −1.68% in case that precise information was entered, and −1.43% in case that just basic information was entered.

The second example is more complex than the first one. It is a building that has 3 types of the facade walls, 2 types of roof construction. Once again, it is possible to note that values of $Q_{H,an}$ in our implementation differ from KnaufTERM2 PRO for just −5.78% in case that precise information was entered, and −6.90% in case that just basic information was entered.

Thus small deviations in both examples show that the approximations used in our implementation are justified. On the other hand, entering data in KnaufTERM2 PRO requires a professional user, while our implementation does not require professional user. Also, to insert information in KnaufTERM2 PRO it takes at least one hour. Our implementation requires 5 minutes to insert basic information, and about 10 minutes to enter detailed information. Generation of results is almost immediate in both applications.

There are a lot of possibilities to improve this software implementation. Web application would provide simple communication with databases. That would provide more options, and more precise results. Graphical display of the results would simplify interpretation. Possibility to save models of buildings would simplify and speed up the use of the software tool.

V. CONCLUSION

This paper presents the implementation of a simplified method for calculating the energy efficiency of buildings. The simplification is done by approximating the less important parameters. Also, values of those parameters are not easy to find. In this way, we allowed non-professional user to insert required information. Besides that, we reduced the time required for collecting needed information and its insertion. That caused slight deterioration of precision. Deviation is about 1.5% for free-standing houses and about 6% for residential skyscrapers. There are some possibilities to improve this solution: graphical display of results, possibility to save templates, connecting with databases.

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