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OPTIMIZATION OF WINDOW SIZE DESIGN FOR DETACHED HOUSE USING TRNSYS SIMULATIONS AND GENETIC ALGORITHM

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Abstract

Heat gains from the sun affect the heat balance of building by reducing the energy demand at certain periods of the year and increasing it at others. Windows, especially the type of glazing, are a determining factor in the successful use of solar gains. The aim of the research presented in the paper is to analyse the effects of the type and size of windows on annual heating and cooling energy consumption considering the energy costs in Polish climate conditions. Additionally the influence of building orientation has been analysed. Optimal selection of these parameters for reduction of the energy consumption has been carried out. Genetic algorithms were used for the optimization, while TRNSYS program was used for energy analysis. The analyses were performed on an exemplary single family detached house. Self-adaptive genetic algorithm connected with energy building simulation successfully identifies the lowest energy costs. Optimal window type and size design and window orientation reduce the energy costs. The developed comprehensive energy simulation environment can also be used to optimize other building's parameters.

Streszczenie

Zyski ciepła od słońca wpływają na bilans cieplny budynku, zmniejszając jego zapotrzebowanie na energię w pewnych okresach roku i zwiększając ją w innych. Okna, a szczególnie rodzaj zastosowanego oszklenia są determinującym czynnikiem wpływającym na skuteczne wykorzystanie zysków od nasłonecznienia. Celem badań zaprezentowanych w artykule było przeanalizowanie wpływu typu i wielkości okien na roczne zapotrzebowanie na ciepło i chłód w odniesieniu do kosztów energii w polskich warunkach klimatycznych. Dodatkowo analizowane było usytuowanie budynku względem stron świata. Do optymalizacji wykorzystano algorytmy genetyczne, a do symulacji zapotrzebowania na ciepło i chłód zastosowano program TRNSYS. Analizy przeprowadzono dla przykładowego domu jednorodzinnego. Samoadaptacyjna metoda algorytmów genetycznych w połączeniu z energetyczną symulacją budynku skutecznie identyfikuje najmniejsze koszty energii. Optymalny dobór typu i wielkości okien i ich rozmieszczenie względem stron świata ogranicza koszty energii. Opracowane pełne środowisko symulacyjne może być wykorzystane do optymalizacji również innych parametrów budynku.

Keywords: **Genetic algorithms; Optimization; Energy consumption; Building simulation; Window size.**

1. INTRODUCTION

Simulation tools are increasingly used nowadays in the design of buildings and analysis of their performance. If the designer decides to improve the building envelope and/or HVAC system parameters, he usually makes a guess at the values of the design variables to be modified and runs the simulation many times, trying to find the effect of changes on the simulation output and to conclude a relationship between studied parameters [1]. Such numerical analyses are used in many cases to predict the energy consumption for heating and cooling in buildings. For example, multi-variant analyses are conducted to find energy-saving strategies for HVAC systems [2-7]. This is an inefficient procedure in terms of time and labour. To overcome such difficulties, it is possible to perform automatic simulation-based optimization using search techniques that require little effort and time [1].

Selection of suitable optimization tool is very important. The energy performance of a building depends on the large number of parameters. External conditions and internal gains also have an impact on it. Taking into account the number of variables that can be combined, we have an enormous number of combinations, even in the case of a not very complicated building [8].

A large number of techniques and algorithms has been developed for the optimum design of technical problems. Popular and advanced optimization tools for wide spectrum of structural problems are evolutionary algorithms, especially genetic algorithms (GA) [9]. The advantages of GAs, as well as population-based meta-heuristic algorithms, are the ability to deal with discrete set of design variables, no need for derivatives of objective functions, and the global convergence. GAs are search algorithms based on ideas of natural selection and genetics (selection, crossing and mutation). Although GAs do not guarantee finding the global optimum, they have become advanced optimization tool for a wide range of problems. For example, in terms of indoor environmental engineering and civil engineering, GAs are used to optimize electricity consumption[10], total energy consumption in a building [11] and renewable energy system in low/zero energy buildings [12]. Optimization of chiller operation is presented by Čongradac and Kulić [13], and the energy costs of air conditioning system by Mossolly et al. [14].

Bichiouo and Krarti [15], Tuhus-Durow and Krarti [16], Magnier and Haghighat [17] and Znouda et al. [8] developed models with the use of genetic algorithm method to select the best combination of several components of the building envelope to optimize the energy consumption and life cycle costs of building. In turn, Król and Białecki [18] applied genetic algorithm to optimization of a window frame.

Thermal energy demand of a building is determined by the need to compensate for the transfer of heat through the building envelope and thermal bridges, and the effects of air infiltration, ventilation and domestic hot water systems. Heat gains from the sun affect the energy balance by reducing the energy demand at certain times and increasing it at other times [19]. Windows with low solar heat gain coefficient allow to control solar gains in the summer period and to reduce demand for cold. However, on the other hand, the reduction of solar gains causes an increase in the heat demand of the rooms during the winter season. Apart from the solar radiation transmittance, also the orientation and size of the windows influence the heat consumption of the building [20].

Therefore, building design must take into account the need to create energy and cost-efficient solutions for windows. Well-designed building glazing can reduce the energy consumption for heating and cooling. The size of the windows is also an important psychological parameter because of providing daylight [21].

The problem of optimizing the type or size of the windows in residential buildings is widely undertaken in the literature. Gasparella et al. [20] studied the impact of different types of glazing systems (two double and two triple glazing), window size and the orientation of the main windowed façade on winter and summer energy demand of a well insulated residential building in four different central and southern European climates. Ruiz and Romero [22] presented energy saving in a detached house in Spanish climate due to the size of the windows and the building orientation, taking into account the sum of the heating and cooling needs of the building. In turn, the influence of windows' size due to the cooling demand is shown in the works of Filippin et al. [23] and Cheung et al. [24]. The influence of the building's envelope, including the windows' size and type, on the electricity consumption by the air conditioning system during hot summer season and cold winter season in China were also analysed by Yu el al. [25]. Kapsalaki et al. [26] and Jaber and Ajib [27] searched for the optimal size of windows in detached houses in various climates (cold, temperate and hot). Fitness function was the life cycle costs of the building and the payback time of investment.

The above-mentioned studies show that the maximum use of solar gains allow to reduce the cost of the energy consumption for heating in the winter. In the summer the situation is reversed – higher gains from the sun generate the need for cooling the rooms. Therefore, in climates where both heating and cooling throughout the year are required, the optimization of the size of the windows in buildings should take into account the cost of both heating and cooling.

The paper presents the optimization of the size and type of windows in a single-family building in Polish climate conditions. 50.1% of the population in Poland live in detached houses and 5.3% – in semi-detached houses. Although the amount of energy consumed in detached houses built nowadays is much lower than in older ones, they still consume a considerable portion of energy for heating. In Poland it is about 37% [28].

The influence of four types of windows, their size and building orientation on annual cost of the energy consumption for heating and cooling is analysed in the paper. Optimal selection of these parameters for reduction of the energy consumption was carried out by the tool which combines the optimization method (genetic algorithms) and the dynamic building simulation program (TRNSYS), in which both internal and external loads were taken into consideration.

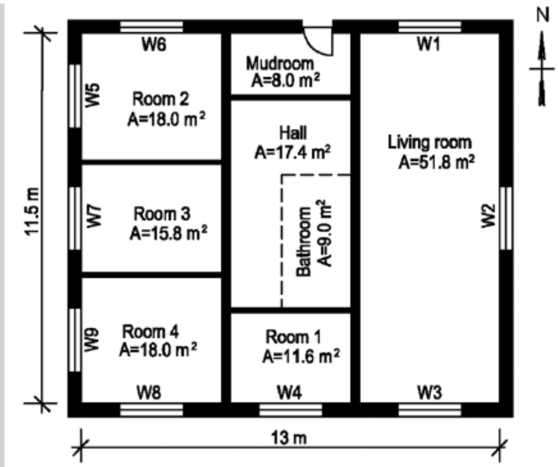

Figure 1.
Ground floor view

Table 1.
***U*-value external partitions of the building**

Partition	U, W/(m^{2}K)
Ground floor	0.27
External wall	0.23
Ceiling to unheated attic	0.17
External door	1.50

2. BUILDING DESCRIPTION

The single-family detached house without a cellar and with unusable attic was chosen for the research. The total area of rooms is 150 m^2 and the height of rooms is 2.6 m. Ground floor of the building is shown on Fig. 1. It was assumed that the walls were brick construction with polystyrene insulation, the ceiling was ferroconcrete construction with mineral wool insulation and the roof was covered with ceramic tiles and uninsulated. Heat transfer coefficients of external partitions (Tab. 1) were according to Polish requirements for thermal insulation for newly designed buildings [29].

3. METHODS AND SIMULATION MODEL

Multi-criteria simulations of the heating and cooling demand were performed with the use of integrated energy modelling tool TRNSYS (TRaNsient System Simulation program) [30], which allows integrated calculations of the transfer of mass and energy inside the building, taking into account heating and air-conditioning systems and the strategy of control. The building is described in the program as a macro-scale model represented as the series of idealized zones with constant parameters of the air within the limits of the entire zone.

The multi-zone model containing all the rooms on the ground floor and unheated attic was built in TRNSYS program. To simplify, the hall and the bathroom (rooms without external walls) were joined into one zone, adopting internal temperature the same as for the rest of the ground floor rooms.

GAs were used to solve optimization problem. Due to their stochastic nature, GAs are faced with two problems: the optimizing capability and convergence speed. To improve the efficiency of GAs, self-adaptive genetic algorithm method (SGA) based on fuzzy arithmetic was applied. SGA was applied simultaneously in the selection of chromosomes and to control basic parameters of genetic algorithm. More information is presented in papers by Grygierek [31, 32, 33]. SGA and all procedures to exchange data between simulation and optimization tool were implemented in MATLAB language. Fig. 2 shows the structure of the simulation and optimization environment.

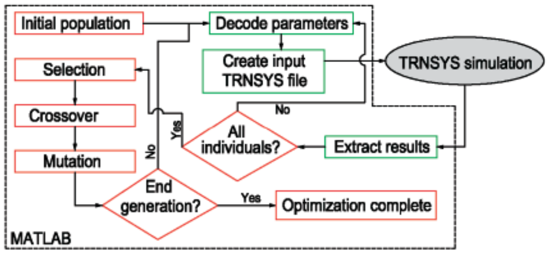

Figure 2.
Flowchart diagram for the developed simulation/optimization tool

3.1. Energy simulation and optimization assumptions

For the energy simulation the following assumptions were adopted:

- Internal heat gains: four occupants, two computers, TV set and kitchen equipment (value of heat gains according to literature [34, 35]) and lighting (10 W/m^2); an hourly schedule for the presence of occupants and for the use of lighting and equipment was adopted in each room; the duration of the lighting operation was additionally dependent on the solar radiation (according to climatic data);
- Heating and cooling: ideal heating and cooling controlling, set-points 20 and 24°C respectively;
- Weather data: the reference weather data for Katowice; EnergyPlus weather file was downloaded from the website [36] and converted to TRNSYS compatible weather file;
- Simulation time step: 1 hour.

The purpose of the optimization tool was to choose the type and size of windows and the orientation of the building to minimize the energy costs. It was assumed that the heat source was a condensing gas boiler and a source of cooling was split system air conditioning units. The objective function in the genetic algorithm method was described by the equation:

$$C = \frac{Q_H}{\eta_H} \cdot P_{H(gas)} + \frac{Q_C}{\eta_C} \cdot P_{C(el.)} \qquad (1)$$

Where:

Q_H – annual heat demand, kWh,

Q_C – annual cold demand, kWh,

η_H = 0.78 – efficiency of heating system,

η_C = 3.79 – efficiency of cooling system,

$P_{H(gas)}$ = 0.1694 PLN/kWh – price of energy from natural gas, according to the applicable tariffs,

$P_{C(el.)}$ = 0.5565 PLN/kWh – price of electrical energy, according to the applicable tariffs.

Thirty individuals and twenty five populations were assumed in the simulations. Relatively small number of individuals and populations is a compromise between the simulation duration and the quality of the obtained results.

Optimization was performed for four different types of window glazing. Windows differed in the type of glass. Table 2 presents parameters of the glazing, i.e.: heat transfer coefficient (*U*), solar heat gain coefficient (*g*) and visible transmittance (*Tvis*).

Table 2.
Visible and solar energy parameters of the glazing

Type of glazing	*U*, W/m^2 K	*g*	*Tvis*
Glass 1 (G11)	1.10	0.609	0.782
Glass 2 (G08)	0.81	0.632	0.749
Glass 3 (G05)	0.52	0.585	0.741
Glass 4 (G04)	0.40	0.408	0.625

The energy cost optimization was performed for two variants of infiltration: air change rate 0.5 h^{-1} (I05) and 0.3 h^{-1} (I03). It was assumed that there must be at least one window in each of the rooms and two windows in the living room. It was assumed in the simulations that minimum glazing area is at least 1:8 of the floor area in the room (according to Technical Conditions [29]) and the glazing area accounts 65% of the total area of the window.

It is assumed that windows' area and building orientation are a design variable and they are selected from a discrete set (Tab. 3).

Table 3.
Allowable values of design variables

Window area, m^2	0 and 1.125–6.375 with step 0.375
Orientation, angle between North axis and building North (clockwise), deg	0–337.5 with step 22.5

3.2. Model validation

Prior to main research (optimization), numerical verification of the constructed model was performed. The hourly heat demand and the annual heat demand for building without internal heat gains were verified. The results obtained in TRNSYS program for basic building were compared to the results obtained in an alternative energy simulation program: ESP-r [37]. The ESP-r software and energy multizone models were validated with experimental

Table 4.
Optimal results of window area and building orientation

Type of glazing (optimal case**)	Window area, m^2									Building orienta- tion, deg*	Sum of windows area
	W1	W2	W3	W4	W5	W6	W7	W8	W9		
Infiltration 0.5 h^{-1}											
G11(A05)	2.625	1.125	6.375	2.250	2.250	1.500	3.375	4.500	0	337.5	24.000
G08(A05)	2.625	1.125	6.375	2.250	2.250	1.500	3.375	4.500	0	337.5	24.000
G05(B05)	6.000	2.250	1.875	2.250	6.000	0	6.000	0	5.250	270.0	29.625
G04(C05)	6.000	2.625	1.500	2.250	6.375	0	6.000	0	6.375	247.5	31.125
Infiltration 0.3 h^{-1}											
G11(A03)	2.625	1.125	6.375	2.250	2.625	1.125	3.375	3.750	0	337.5	23.250
G08(A03)	2.625	1.125	6.375	2.250	2.625	1.125	3.375	3.750	0	337.5	23.250
G05(B03)	5.250	3.750	1.125	2.250	6.000	0	6.000	0	4.500	270.0	28.875
G04(C03)	6.000	2.625	1.500	2.250	6.375	0	6.000	0	6.375	270.0	31.125

* clockwise
** number of optimal case of window area and building orientation

Table 5.
Total energy cost (heating + cooling) in each optimal case of design variables

Type of glazing	Energy costs, PLN					
	Infiltration 0.5 h^{-1}			Infiltration 0.3 h^{-1}		
	A05	B05	C05	A03	B03	C03
G11	**2191.8**	2204.5	2221.7	**1800.6**	1825.1	1845.7
G08	**2189.1**	2205.7	2224.6	**1800.4**	1828.2	1850.5
G05	2046.2	**2021.1**	2027.3	1658.8	**1646.4**	1652.7
G04	2115.5	2075.7	**2066.9**	1698.8	1670.5	**1664.7**

data by authors repeatedly [5, 6, 38]. The correlation coefficient of hourly values is 0.99 and the difference in annual heating demand calculated in both programs is 1.3% (ESP-r: 13143 kWh, TRNSYS: 12978 kWh). TRNSYS is used in this research, because the optimization program and TRNSYS run on Windows, and the latest versions of ESP-r operate under Linux.

4. RESULTS

The optimal results for four window types and two infiltration cases are shown in Table 4. It can be seen that for glazing cases G11 and G08, the same values for design variables were obtained. Exactly the same windows and orientation of the building were chosen.

For further analyses, to distinguish considered infiltration variant, the obtained optimal cases of design variables (windows' area and orientation) were marked as A, B and C, and 03 and 05. Taking into account optimal case of design variables, thermal simulations were performed for each case of the window.

Table 5 lists total energy costs for optimum results of design variables and for each glazing type. The optimal results for each window type are bolded.

The results obtained for glazing G11 in each infiltration variant (I05 and I03) were taken as reference.

For the best case (glazing G05), the energy costs for infiltration variants 0.5 h^{-1} and 0.3 h^{-1} decreased by 7.8% and 8.6% respectively. With less infiltration, the share of windows in the building's thermal balance increases, therefore improving their thermal properties has a greater impact on reducing the energy costs.

The lowest energy costs for heating and cooling (glazing G05) were achieved for larger window area in relation to the case of glazing G11 by 23.4% (I05) and 24.2% (I03).

The increased share of solar gains in relation to the heat loss for windows with lower *U* coefficient causes that windows with larger area give better optimal results in total heating and cooling consumption. This work did not take into account the impact of the initial investment cost (window purchase) on the optimum result. High price of these windows (G05) and their increased area may cause a low profitability of such investments.

Table 6.
The sum of window area facing main directions of the world

Optimal case	Window area, m^2			
	S	W	N	E
A05	13.125	5.625	4.125	1.125
B05	17.250	6.000	2.250	4.125
C05	18.750	6.000	2.625	3.750

Technical Conditions [29] specify the minimum ratio of glazed area of the windows to the floor area of the rooms they are located in. Such minimum glass area in the analysed building is 14.4 m^2. Considering the infiltration case I05, glazing area values for G11, G08, G05, G04 are: 15.6 m^2, 15.6 m^2, 19.25 m^2 and 20.23 m^2 respectively. When analysing the above results, it can be observed that it is not right to cling on to the minimum value given in Technical Conditions. Reduction of the energy costs is obtained by proper location of the windows in the building, not by reducing their area. Table 6 contains window areas facing the directions close to main directions of the world for optimal solutions for the infiltration case I05. Reduction of the energy costs is obtained by increasing the area of windows facing south at the expense of the eastern and northern directions. With the decreasing *U* coefficient, the ratio of the area of south-facing windows to the other windows is larger. Increasing the area of windows and directing them to the southern side increases the demand for cooling and reduces the demand for heat. In the Polish climate, the effect of cooling consumption on total energy costs is small (Tab. 7), hence such home design is beneficial in view of the energy costs.

Table 7.
Heating and cooling cost for case of infiltration I03

Type of glazing	Heating cost, PLN	Cooling cost, PLN
G11	1627.9	172.7
G08	1618.3	182.1
G05	1439.8	206.6
G04	1541.9	122.8

As a result of the optimization, the building was rotated by similar angles for two glazing units with higher *U* coefficients (G11 and G08) and for two glazing units with lower *U* coefficients (G05 and G04). When designing the house, the selection of windows cannot be based solely on the *U* coefficient, but the attention must also be paid to the solar heat gain coefficient. The analysis of the results for windows G05 and G04 shows that the building with windows with higher *U* coefficient (G05) and higher values of *g* and *Tvis* coefficients has lower energy consumption than the building with windows with lower *U* coefficient (Tab. 2). In the case of G11 and G08, despite large difference in *U* coefficients, similar costs of the energy consumption in building were obtained due to other window properties.

5. CONCLUSIONS

Proper selection of windows should prevent excessive heat loss in winter as well as too high heat gains from the sun in summer. The location and climate of Poland determine the need to heat buildings for most of the year, i.e. from September to May. The demand for cooling is a much smaller share of total energy demand. In the analysed cases, the demand for cooling is about 10% of the heat demand. Simulations show that the cheapest way to reduce the energy consumption for heating and cooling is to locate windows on the southern side of the building. This applies especially to rooms with smaller internal gains. In the optimal case, the area of windows facing south is about 60% of the area of all windows.

Windows with better thermal properties cause less energy demand for heating and cooling in the building. However, in order to use their potential and to get minimal demand for cooling and heating, their area should be significantly increased, which obviously affects the cost of their purchase. For windows with the smallest heat transfer coefficient, this area is significantly larger than the minimum area required by Technical Conditions [29]. Research also showed that selecting windows should not be based solely on the *U* coefficient (which is common to investors). Solar optical properties of windows also significantly affect the cost of the energy consumption.

The paper presents the methodology and the tool aimed at supporting the choice of economically effective building solutions. In many works on this subject, the size of the windows is determined by the ratio of their area to the façade area [15]. The window optimization tool built in this study analyses each window separately and allows to remove windows that overstate the energy consumption.

The paper presents the optimization of window size, window type and building orientation only. The developed simulation environment can also be used to optimize other building parameters, such as construction of external partitions, insulation thickness, and used HVAC system parameters, i.e. the type of system or control system. The simulation environment can easily be extended to other types of buildings.

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