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Multi-Objective Optimization of the Envelope of Building with Natural Ventilation

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Abstract: A properly designed house should provide occupants with the high level of thermal comfort at low energy demand. On many occasions investors choose to add additional insulation to the buildings to reduce heat demand. This may lead to overheating of the building without a cooling system in summer periods (these prevail in Poland). Additionally, it affects the deterioration of thermal comfort, which can only be improved by increasing ventilation. The paper presents the multi-objective optimization of the selected design parameters in a single-family building in temperate climate conditions. The influence of four types of windows, their size, building orientation, insulation of external wall, roof and ground floor and infiltration on the life cycle costs and thermal comfort is analyzed for the building without cooling. Infiltration changes during the simulation and is controlled by a special controller. Its task is to imitate the behavior of occupants in changing the supply airflow. Optimal selection of the design parameters is carried out using Non-dominated Sorting Genetic Algorithm II (NSGA-II) by coupling the building performance simulation program EnergyPlus with optimization environment. For the single-family house, optimal values of design variables for three different criteria are presented.

Keywords: multi-objective optimization; heating demand; genetic algorithms; building envelope; life cycle costs; thermal comfort

1. Introduction

Due to the population growth, urbanization and industrialization energy consumption is rapidly increasing. The building sector plays an important role in this regard. About 40% of all primary energy is used in buildings all over the world [1–5]. The largest contributors to high energy consumption in buildings are heating, ventilation and air conditioning (HVAC) systems [6–8]. While the heating demand can be effectively reduced by better thermal insulation of a building, cooling plays a more significant role in the overall energy demand of buildings [9]. On the one hand, this is due to the increase in comfort expectations in summer time and the gradual warming of climate. On the other hand, cooling is becoming popular not only in commercial buildings but also in residential buildings. Therefore the energy conservation in buildings has become an important part of national energy strategies in multiple countries [10]. This led to the development of building energy efficiency regulations. These regulations introduce a minimum of energy efficiency requirements that need to be met by all new buildings and retrofitted buildings [11,12].

Increasing a building's energy efficiency can be achieved mainly by increasing insulation thickness and installing high performance windows. Additionally, several other design parameters have a significant effect on heating and cooling demand in buildings, such as a building shape and orientation, wall and roof constructions, window sizes and shading, as well as characteristics of heating, ventilating, and air conditioning systems (type, efficiency, and operation settings) [13–18]. For that reason designers should take into account the best combination of these parameters, which can minimize energy use over the lifespan of a building. 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 [19]. Therefore the selection of a suitable optimization tool is very important.

A large number of techniques and algorithms have been developed for the optimum design of technical problems. Evolutionary algorithms, especially genetic algorithms (GAs) are popular and advanced optimization tools for a wide spectrum of structural problems [20]. The advantages of GAs, as well as population-based meta-heuristic algorithms, are: the ability to deal with discrete set of design variables, the global convergence and no need for derivatives of objective functions. 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 an advanced optimization tool for a wide range of problems. An optimization tool in studies is often connected with simulation program to find the best combination of design parameters. Simulation tools can predict the effects of design variables on building energy consumption [3]. The studies have been performed for residential buildings and for one or different climates using TRNSYS (University of Wisconsin, Madison, WI, USA) [21,22], EnergyPlus (U.S. Department of Energy's, Washington, DC, USA) [2,23,24], DOE-2 (Lawrence Berkeley National Laboratory, Berkeley, CA, USA) [17,18], eQUEST (Energy-Models.com, San Francisco, CA, USA) [25] simulation programs.

To perform the optimization analysis the simulation-optimization environment can consider a various objective functions, most often it is an energy demand. Gasparella et al. [22] 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. A similar problem, but with energy cost as the objective function, is analysed in the work by Ferdyn-Grygierek and Grygierek [21] (a detached house in Polish climate conditions). The effects of different types of glazing systems, windows orientation, windows size and wall insulation considering energetic point of view were studied for buildings in Spain and China in the works by Ruiz and Romero [24] and Yu et al. [25] respectively. Similar parameters and additionally some parameters of HVAC system were optimized for single family homes in five US locations from the economic point of view as described by Bichiou and Krarti [17] in their work. Energy-efficient solutions are often costly, therefore also economic factors were be introduced to determine the best configuration of building design features. The optimum balance should be found between the initial investment and the energy savings during the building life cycle. Life cycle cost (LCC) is the most popular economic factor as objective function in research [1,2,5,15,26].

Some investigations limit their optimization to a few parameters (e.g. one or two). For example, Ko [27] in his paper presented an optimization method to design a solar water heating system whereas Ferdyn-Grygierek and Grygierek [21] concentrated only on the optimization of windows. A lot of studies, however, have employed optimization algorithms to solve the multi-variable optimization problems. This was used in order to select optimal values of a comprehensive list of parameters associated with different envelope features [18,28,29] and main parameters of HVAC system [17].

In the articles cited above [17,21,22,24,25,27] one objective function is assumed (LCC or energy demand). Some researchers apply multi-objective optimization models. Multi-objective Evolutionary Algorithm (MOEA) enables to optimize more objectives simultaneously and is widely used in multi-objective optimization problems. It is based on Pareto-dominance. Unlike classical weighted-sum approach, MOEA gives more solutions than a single optimization problem. In the research of the built environment NSGA-II [30] is the most popular method. In the study conducted by Tokarik and Richman [31], a procedure combines EnergyPlus simulation and a genetic algorithm which was implemented to determine the best solutions for the HVAC system control in a residential building. The objective of this study was to minimize the primary energy demand and investment cost simultaneously. In this article Non-dominated Sorting Genetic Algorithm II (NSGA-II) was applied to optimize the parameters. In the article by Schwartz et al. [2]. NSGA-II was used to find optimal designs for a refurbishment of a residential complex case study, in terms of life cycle carbon footprint and life cycle cost. Azari et al. [32] utilized a multi-objective optimization algorithm to explore optimum building envelope design with respect to energy use and life cycle contribution to the impacts on the environment in a low-rise office building in Seattle. A hybrid genetic algorithm and artificial neural net-works was used for the optimization. The optimization of the insulation thickness of a house considering both economic and environmental (eco-indicator 99 methodology) concerns is presented by Carreras et al. [33]. The authors proposed a systematic framework for the design of buildings that combines a rigorous objective reduction method with a surrogate optimization model.

Some articles take thermal comfort as an objective function into account. For example in the study by Wright et al. [34] MOEA search method was applied in the identification of the optimum parameters for the work of HVAC system taking into account the energy cost and the occupant thermal discomfort. In this work the zone comfort criteria were represented by the "predicted percentage of dissatisfied" (PPD). Maximum value of PPD and daily energy cost have been chosen as the objective function. The same function was implemented in the study by Ascione et al. [35] where the HVAC hourly set point temperatures were optimized, with a day-ahead planning horizon, based on weather forecasts and occupancy profiles. Ascione et al. [36] proposed a new multi-stage framework for cost-optimal analysis by multi-objective optimization and artificial neural networks, called CASA. A genetic algorithm and EnergyPlus simulation allowed to select recommended retrofit packages by minimizing energy consumption and thermal discomfort. The same energy simulation software and a heuristic algorithm was used by Mostavi et al. [37]. The effect of 65 different building construction materials was analysed by the authors. The multi-objective design optimization model to minimize life cycle cost and life cycle emission, and maximize occupant satisfaction level in a typical commercial building was developed.

The optimized buildings in all the articles were equipped with both heating and cooling systems. Such assumptions provided for good thermal comfort even in well-insulated buildings, where the passive cooling was hardly used. Some works [34–36] introduced thermal comfort index as an extra objective function. All the articles described above assume constant infiltration rates during simulations (occasionally selected from the set of discrete values). There are no studies where the building parameters with natural ventilation only are optimized. The previous research [28] showed that from the economic and energetic point of view, the insulation as well as type and size of windows optimization excluding cooling gives poor results due to thermal comfort in rooms (too high temperatures during most of the year). The constant infiltration rate assumed in the simulations further contributes to poor thermal comfort.

2. Research Problem Definition

Poland is located in transitional climate (between continental and Atlantic climates) with relatively cold winters and warm summers. Throughout a year external temperature varies from approximately −20 °C to over +30 °C. Low outdoor temperatures in winter pose a major problem. Every building designed for regular occupancy is equipped with adequate heating systems. Consequently, heating is of vital importance when it comes to total energy consumption. It is the purpose of research, therefore, to optimize the building external partitions (thermal insulation of building envelope, the proper choice of windows) and heating systems in order to reduce heating demand [28,29]. Polish investors argue that high initial investment (above the required standard) pays off in the long run when using a building. On the other hand, in most cases, the existing and newly built buildings, lack any cooling systems and consequently too high temperatures in summer seasons create poor thermal conditions. A poor indoor climate, especially indoor temperature may contribute to the occupants' discomfort, and in some cases increase the risk of illness. So thermal comfort and occupant thermal satisfaction should be absolutely vital for investors and building designers. Air conditioning, which improves thermal comfort, is a costly investment. It is used in residential buildings in Poland only in summer months. Ventilation by open windows is another method used to improve thermal comfort in summer. A natural ventilation that uses ambient air to cool a building when the outdoor temperature is low can improve thermal conditions in a room during the warmer periods of the day, as the building´s structure can be used as a heat sink. Free cooling by ventilation is one of the most effective techniques for cooling since the ambient cool air is directly used to reduce the inside air temperature. Direct ventilation to cool a building is often applied during the night period and is referred to as night cooling [38,39].

The paper presents the multi-variable and multi-objective optimization of chosen design parameters (types of windows, their size, building orientation, insulation of external walls, roof and ground floor) in a single-family building with natural ventilation in Polish climate conditions. A building was modelled using EnergyPlus where natural ventilation changes during the simulation time. The ventilation is controlled by a special controller that is supposed to reproduce the occupants behavior in controlling air change rate. Certain parameters were optimized in the controllers in order to improve thermal performance in zone. NSGA-II was used for parameter optimization, taking into account economic aspect and thermal comfort as an objective function. A comparison was made of the optimal results for the buildings with the assumed constant and variable natural ventilation rate during the simulation.

3. The Ventilation Controller

Accepting constant infiltration in buildings with natural ventilation in simulations is a big simplification that can affect the results. In this type of buildings, occupants usually control the supply airflow by opening windows. In the transitional periods of the year and in summer, the supply outdoor airflow reduces the room temperature. The occupants experience allows the proper control of airflow and prevents over-cooling, which would require additional heating. Natural ventilation is hardly predictable and dependent on temperature difference and wind speed. Effectiveness of passive cooling using natural ventilation will also depend on the design of external walls, because the temperature change in the building in the non-heating period will be affected by the mass and thermal resistance of the partitions. A well-insulated building, desirable from the point of view of heat demand, will be much slower to cool down during warm periods of the year. Therefore, in buildings without cooling, the optimization of external partitions (thermal insulation, type and size of windows) should take into account the variability of infiltration and thermal condition for occupants.

The energy modelling tool EnergyPlus [40], which allows integrated calculations of the transfer of mass and energy inside the building, was used for the simulation and calculation of the energy demand and thermal comfort. The EMS (Energy Management System) module of this program enables the users to program their own functions to develop custom control and modelling routines. This module was used to program the ventilation controller, which is to imitate the control of ambient airflow supply by the inhabitants. The controller based on "if-then" rules is proposed here. It was assumed that input data for the infiltration controller (IC) can only be temperature. The IC does not take into account all the information about weather (e.g. speed and wind direction) that have occupants before changing the window opening. Consequently, it was assumed that the controller will calculate the air change rate (ACH), not the degree of window opening. In the program, it was modelled as a change in infiltration rate.

The following constraints are assumed in the IC work:

- minimal air change rate (ACH) is 0.3 h^{-1},
- infiltration may be increased if the outside temperature (T_{out}) is less than the inside room temperature (T_{in}),
- infiltration may be increased if the inside zone temperature is above 22.2 °C (it was assumed that 22 °C is heating set point),

- infiltration may be change only four times during day (8 am, 12 am, 5 pm, 10 pm).

It was assumed that the input data for the calculation of the additional instantaneous air change rate (ACH—local factor, calculated for each room separately) are:

- trend of outside temperature during last two hours (tT_{out}),
- the temperature difference between indoor T_{in} and outdoor temperature T_{out} at the time step (dT_{in_out}),
- the temperature difference between indoor T_{oin} and comfort operative temperature T_{otc} (dT_{in_tc}). Comfort operative temperature was calculated according to EU Standard EN15251:2007 [41]. Schematic diagram of the IC is shown in Figure 1.

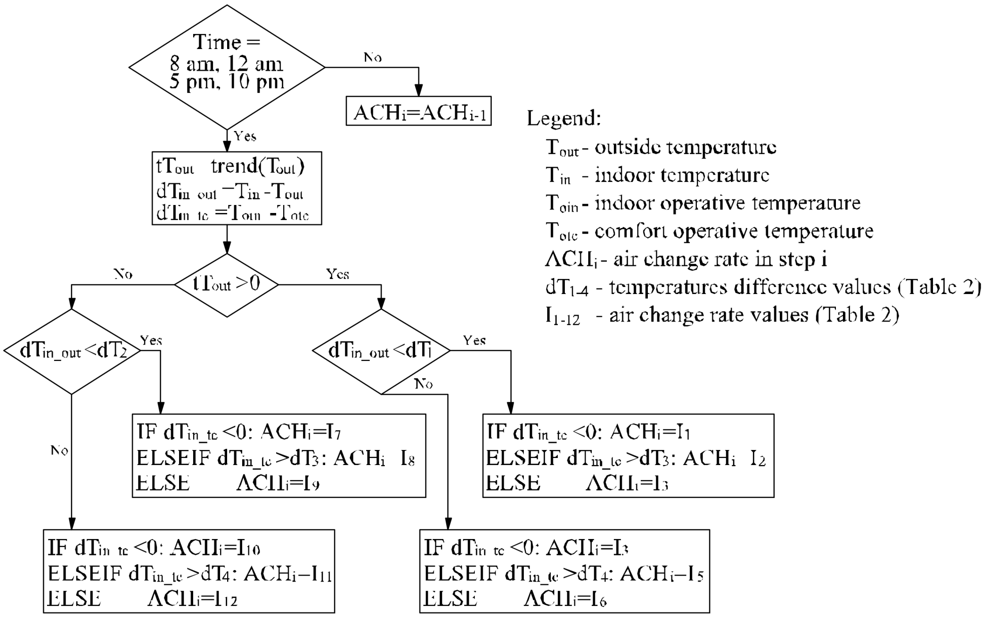

Figure 1. Flowchart diagram of the infiltration controller.

Sixteen parameters (difference between temperatures: from dT_1 to dT_4, air change rate: from I_1 to I_{12}) have been entered into the controller. In our work, the appropriate selection of these parameters should provide a compromise between two objective functions: the minimization of life cycle costs of building and the maximization of thermal comfort for occupants. The values of the parameters depend on the envelope of building, which is optimized. Therefore, it was assumed that the parameters will also be optimized. Their values will be chosen from discrete set.

4. Optimization Methodology

This study considers optimization of chosen design parameters in a single-family building with natural ventilation in Polish climate conditions. The first step to solve this problem is the definition of decision variables, the definition of objective functions and the selection of an appropriate computation technique.

4.1. Decision Variables

In optimization analysis the most common design options available for the envelope of a building in Poland are chosen as design variables. This options have a great impact on the life cycle energy performance of buildings. Four types of decision variables are defined as the alternative choices:

- four glazing types (Table 1) characterized by three parameters of the glazing, i.e.: heat transfer coefficient (U), solar heat gain coefficient (SHGC) and visible transmittance (T_{vis}),
- windows area (glazing + frame) defined by the sixteen discrete value of windows size (Table 2),
- insulation of external walls, ground floor and ceiling to the unheated attic defined by the thickness of polystyrene or mineral wool. Six options for all types of external partitions are considered,
- building orientation defined by the azimuth angle between the north and the front of the house. Sixteen options for the orientation are considered (Table 2).

Table 1. Visible and solar energy parameters of the glazing.

Type of Glazing	U_{glass}, W/m²K	U_{frame} *, W/m²K	U_{window} **, W/m²K	SHGC	T_{vis}
Glazing G10	1.00	1.35	1.13	0.49	0.72
Glazing G07	0.68	1.35	0.90	0.61	0.73
Glazing G06	0.61	1.35	0.85	0.51	0.74
Glazing G05	0.52	1.35	0.78	0.43	0.65

* taking into account U-edge of window ** for window 1.5 × 1.5 m.

Table 2. Cost data for design variables and options used for the optimization analysis.

Design Variable	Options	Cost *
Glazing type for window	**G10**, G07, G06, G05	34.4 €/m², 64.7 €/m² 53.5 €/m², 57.9 €/m²
Windows Area	Height: 1.5 m Width: 0 and 0.75 m–4.25 m with step 0.25 m	0 € for all options
Insulation		
Ground floor: polystyrene (λ = 0.031 W/mK)	**5**, 6, 8, 10, 12, 15 cm (thickness)	51.9 €/m³
External wall: polystyrene (λ = 0.031 W/mK)	**12**, 15, 18, 20, 22, 25 cm (thickness)	46.0 €/m³
Ceiling to unheated attic: mineral wool (λ = 0.038 W/mK)	**20**, 22, 25, 28, 30, 35 cm (thickness)	0.3 €/m² for 1 cm of thickness
Azimuth (orientation of the building relatively to the north)	**0**–337.5 with step 22.5	0 € for all options
Temperatures difference in the IC (from T_1 to T_4)	0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0 K	0 € for all options
Values of the air change rate in the IC (from I_1 to I_{12})	0.3, **0.5**, 1.0, 2.0, 3.0, 4.0, 5.0 h^{-1}	0 € for all options
Additionally included the costs of window frame and installation and cost of external wall construction.		

* 1 € = ~4.30 PLN.

All possible values of the design variables are summarized in Table 2. Glazing systems were prepared using Window 7.4 software [42]. Glass types were chosen from Saint Gobain Glass library [43].

As mentioned in the previous section, also some parameters of the IC are optimized:

- temperatures difference at which the appropriate actions are activated. Eight options were assumed,
- values of the supply airflow, chosen from seven options (Table 2).

4.2. Objective Functions

Objective functions are the selected simulation results which vary depending on the parametric input combinations, and are the values to be minimized by the optimization algorithm. The simulation-optimization environment can consider a various objective function to perform the optimization analysis. In this study, the cost function is selected as the life cycle cost (LCC) and thermal comfort function as number of hours with thermal discomfort (H_{dis}) over the period of optimization. The formal definition of the problem is as follows:

$$\text{Min}\{F_1(x) = \text{LCC}, F_2(x) = H_{dis}\}, \quad \mathbf{x} = [x_1, x_2, \ldots, x_n], \tag{1}$$

where **x** is the vector of the design variables.

4.2.1. Life Cycle Cost

In terms of economic benefits of energy retrofits, life cycle cost analysis is one of the most common tools used to compare the initial investments and the future benefits of retrofit alternatives in building energy efficiency. LCC, which sums all costs during a certain period of time, provides a criterion for finding the best solution, when the LCC is as low as possible [44].

In the study life cycle cost was defined by Equation (2). The investment costs of the analyzed design variables have been used for the calculations. The remaining investment costs are equal in each case and do not affect the optimization result. Only extra investment costs involved in the reference building that result from the changes introduced in each optimization option have been analyzed.

$$LCC = dIC + a(r_e, N) \cdot EC, \tag{2}$$

where: dIC–the differences between sum of investment cost for implementing all the design and operating features in the reference and optimized case of the building. In this study it is the cost (material and labour) of external walls, ceiling and floor insulation, cost of windows and external walls structural material. Table 2 provides the cost data for various design and operating options, a–discount factor which takes into account the effect of inflation and escalation of energy price (r_e is the real interest rate, N is the number of years under study (it assumed 30 years)). It our work a = 20. More information on how this parameter was calculated can be found in the paper by Ferdyn-Grygierek and Grygierek [28], EC–the annual heating energy from Equation (3).

$$EC = \frac{Q_H}{\eta_H} \cdot P_{H(gas)}, \tag{3}$$

where: Q_H–annual heating demand, kWh, η_H–annual efficiency of heating system (η_H = 0.78 [45]), $P_{H(gas)}$–price of energy from natural gas, according to the applicable tariffs ($P_{H(gas)}$ = 0.0394 €/kWh as of 1 February 2018).

4.2.2. Thermal Comfort

Thermal comfort means satisfaction with the thermal environment. The appropriate mathematical models make it possible to evaluate the thermal environment quality and determine the percentage of the dissatisfied with the thermal conditions [41,46,47]. Adaptive comfort model based on EU Standard EN 15251:2007 [41] is used to assess thermal comfort in this study. The model, intended for use in naturally ventilated buildings, determines the acceptability of indoor conditions. The model includes occupant adaptation to outdoor conditions and people's clothing adaptation in naturally conditioned spaces. The model defines three comfort regions: Category I (90% acceptability), Category II (80% acceptability), and Category III (65% acceptability). Values outside the criteria for the above categories belong to the category IV. Category II is assumed as the acceptability limit of indoor conditions. In order to optimize thermal comfort, the number of hours with discomfort H_{dis} (category III and IV) over the whole year is used as objective function.

4.3. Multi-Objective Evolutionary Algorithm

Simultaneous reduction of LCC and H_{dis} involves conflicting objectives. Since these two functions are nonlinear and additionally discrete values of design variables, it was assumed the global multi-objective optimization method (genetic algorithms) is used in order to obtain optimal results. As this study involves two objective functions for optimization, a multi-objective genetic algorithm (MOGA) was used. It is based on Pareto-dominance. Unlike classical weighted-sum approach, MOGA gives more solutions. NSGA-II is applied in this work. This method is the most widely used in environment engineering research.

Fifty individuals and eighty populations were assumed in the simulations. A relatively small number of individuals and populations is a compromise between the simulation duration and the quality of the obtained results.

The final goal of the optimization process is the Pareto front, which represents the set of non-dominated solutions. The last step is to select a solution that represents the best configuration. This process is called Multi-Criteria Decision Making (MCDM). Different criteria can be adopted for the MCDM. In our study the three methods are used:

- the utopia point criterion (UP): the best solution is the closest to the ideal point (point that minimizes both objective functions). As stated in the study by Nguyen et al. [48] this approach has already been used in many engineering applications,
- the thermal comfort criterion (TC): H_{dis} for this solution is minimal,
- the cost-optimal criterion (CO): LCC for this solution is minimal.

4.4. Employed Tools

The NSGA-II optimization algorithm is implemented in MATLAB and it is automatically coupling with energy simulation tool. EnergyPlus was used for the simulation and calculation of the objective functions: LCC and H_{dis}. All procedures to exchange data between the simulation and the optimization tool were implemented in MATLAB. Due the fact that the IC has been programmed in interior module of EnergyPlus (Energy Management System) it was possible to carry out parallel simulations and consequently to accelerate the optimization process. Figure 2 shows the structure of the simulation and optimization environment.

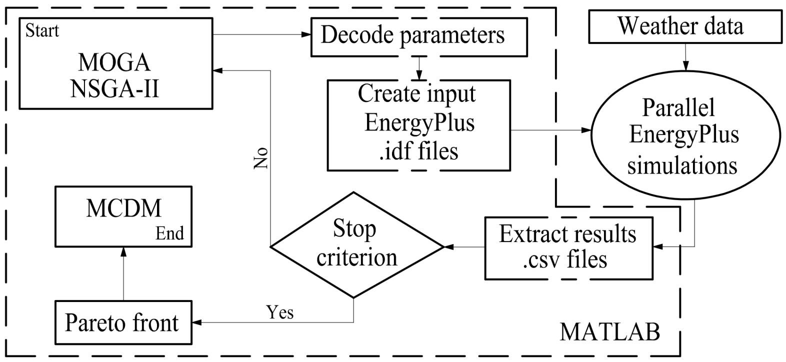

Figure 2. Flowchart diagram for the developed simulation/optimization tool.

4.5. Application of the Optimization Methodology: A Residential Building

A single-family detached house without a cellar and with an 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. The ground floor of the building is shown in Figure 3. The selected building form enables different positioning of windows, which is the assumption of this study. The walls are of brick construction with polystyrene insulation (U = 0.22 W/m^2K), the ceiling is a ferroconcrete structure with mineral wool insulation (U = 0.18 W/m^2K) and the roof is covered with ceramic tiles and is uninsulated. This building structure is typical of single-family buildings in Poland. Parameters of the materials and acceptable options are presented in Table 2. The building is naturally ventilated and equipped with a hot water central heating system. A natural gas boiler is utilized to generate hot water supplied to radiators. The heating set point is kept at 22 °C [41], but between 10 pm and 5 am night time decreases of 3 K have been assumed. The windows have blinds that are drawn when the indoor temperatures and solar radiation are too high.

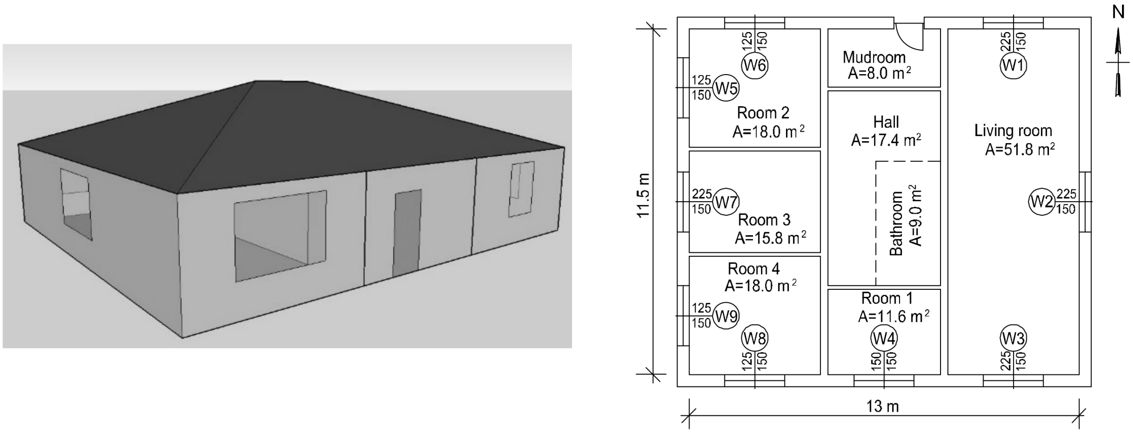

Figure 3. View of the building and ground floor view (widow dimensions are in cm).

The newly-constructed buildings in Poland must meet Technical Conditions [49]. The external partitions' structure (Table 2) in a reference building (RB) (which will be used in the comparison) was determined so that heat transfer coefficients of external walls, ground floor, ceiling and windows (type and size) would be according to these requirements. The details of insulation thickness in the external partitions in the reference building are specified respectively in Table 2 (bold values). In the reference building the windows area amounts to 23.3 m^2 (including glazing area 15.7 m^2). Figure 3 shows the windows' dimensions in the building (they are the overall dimensions with a frame). A constant infiltration (ACH = 0.5 h^{-1}) is assumed in the reference building.

The simulations were performed on a multizone model with a 15-minute time step using the reference weather data for Warsaw [50]. Internal heat gains were introduced into the model: four occupants, two computers, a TV set and kitchen equipment (heat gains values according to the literature [51,52]) and lighting. An hourly schedule for the presence of occupants and for the use of equipment was adopted in each room. The duration of the lighting operation (10 W/m^2) was additionally dependent on the solar radiation (according to climatic data). The detailed schedule of internal heat gains is presented in the study by Ferdyn-Grygierek and Grygierek [28] and it is assumed that at least one person stays at home all the time.

5. Results

Simulations were conducted for five cases. Table 3 presents the optimized design variables for each case. The result analysis will be carried out for individual cases.

Table 3. Optimization cases.

Case Study	Controller	Type and Windows Area	Insulation	Azimuth
1	+			
2		+	+	+
3	+	+		
4	+		+	
5	+	+	+	+

+ means that variable is optimized.

5.1. Case 1 (Optimization of Natural Ventilation Controller)

In this case, only the natural ventilation controller was optimized. It was checked how much ventilation is affected by the H_{dis} and LCC values in case of the unchanging building structure, and to what extent thermal comfort conditions for the reference building with constant and variable ventilation can be met. The Pareto front, which shows the non-dominated configurations of the FLC is presented in Figure 4. The points marked with a triangle are the selected solutions based on the criteria: UP, TC and CO (MCDM solutions). Values of objective function, heating demand and ACH for this solutions and for the RB are shown in Table 4. In case of H_{dis} the calculation did not take into account hours with night temperature decreases.

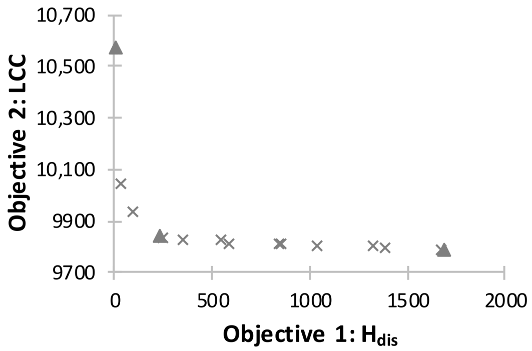

Figure 4. Pareto front for case 1 (triangle–MCDM solutions).

Table 4. Optimal results for case 1.

MCDM	RB	UP	TC	CO
H_{dis}, h	740	237	9	1692
LCC, €	11,863	9842	10,570	9787
Heating demand, kWh/m^2	78.3	65.0	69.8	64.6
All year average ACH, h^{-1}	0.50	0.44	0.71	0.38
Sumer average ACH, h^{-1}	0.50	0.60	1.43	0.38
Max value ACH, h^{-1}	0.5	2.0	4.0	1.0

RB-reference building, UP-utopia point criterion, TC-thermal comfort criterion, CO-cost-optimal criterion.

Lower LCC values than in the RB with constant ventilation air flow rate were obtained for all assumed criteria. It was influenced by the assumption that in the RB in winter the minimum ACH value is 0.5 h^{-1}, while the optimized IC allowable minimum value is 0.3 h^{-1}. Hence, the significantly higher heating demand is achieved for the RB (Table 4). An important information for investors is that in such a building, properly controlling natural ventilation, it is possible to obtain very good thermal comfort (for TC, H_{dis} = 9 h). However, it requires greater ventilation of the building during summer periods. In the hottest days the maximum ACH equals 4 h^{-1} (summer average ACH is 1.43 h^{-1}). Different results were obtained for the CO criterion, where the average annual and summer air change rates are the smallest, but H_{dis} values high. The LCC value in this case is the smallest. A slightly larger LCC was obtained for the UP criterion, but with significantly better thermal comfort (H_{dis} = 237 h). For this criterion, the H_{dis} values and summer average ACH values in the rooms are summarized in Table 5. Almost 80% of the number of hours with thermal discomfort occur in the living room, which is connected with the kitchen and has large internal heat gains. Therefore, in the summer the highest ACH value was obtained in the living room. High ventilation rate is also needed in room 1, with the south facing window.

Table 5. H_{dis} for case 1-UP (utopia point criterion).

	Living Room	Room 1	Room 2	Room 3	Room 4
H_{dis}, h	186	17	9	12	13
Sumer average ACH, h^{-1}	0.88	0.76	0.57	0.45	0.50

5.2. Case 2

In this case, the optimization of windows and insulation thickness of the external partitions for building with the constant airflow (ACH = 0.5 h^{-1}) was carried out. In Poland, such an airflow is assumed for calculating the heat demand for newly designed residential buildings. The Pareto front for this case is shown in Figure 5.

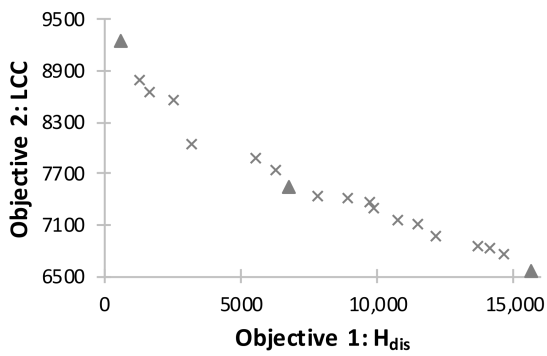

Figure 5. Pareto front for case 2 (triangle–MCDM solutions).

The minimum H_{dis} value is 636 h, which is close to the H_{dis} value for the RB. Too low ventilation in the summer causes the overheating of the building and thermal discomfort. The right side of the Figure 5 (max H_{dis}) shows the aberrant values that we receive assuming constant ventilation for the optimization of buildings without cooling. We get huge savings in heat demand, but the building has too high temperatures in each room for an average of 36% of the year. A comparison of the detailed results for case 2-UP, with the results for case 5 is shown later.

5.3. Cases 3, 4 and 5

In these cases, the natural ventilation controller and the envelope of building were optimized. In cases 3 and 4, only the windows (type and size) and only the thickness of the insulation were optimized, respectively. It was assumed that the H_{dis} value in the optimized building can not be larger than in the 1-CO case (1692 h). In the algorithm, this was done by introducing a penalty function. In Figure 6 and in Tables 6 and 7, the Pareto front and the results of the adopted MCDM for cases 3 and 4 are shown, respectively.

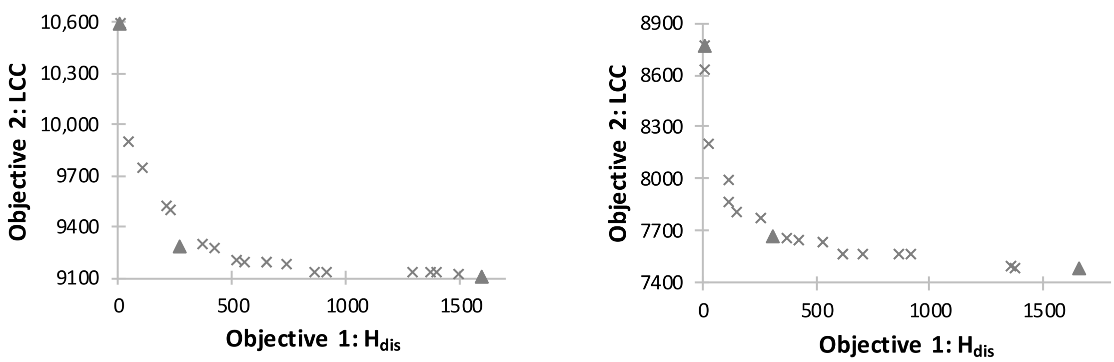

Figure 6. Pareto front for case 3 (on the left) and for case 4 (on the right).

Table 6. Optimal results for case 3.

MCDM	UP	TC	CO
H_{dis}, h	267	5	1591
LCC, €	9294	10,586	9112
Heating demand, kWh/m^2	57.8	65.7	55.8
All year average ACH, h^{-1}	0.51	0.74	0.52
Sumer average ACH, h^{-1}	0.84	1.43	0.84
Max value ACH, h^{-1}	2.0	3.0	2

UP-utopia point criterion, TC-thermal comfort criterion, CO-cost-optimal criterion. .

Table 7. Optimal results for case 4.

MCDM	UP	TC	CO
H_{dis}, h	309	10	1659
LCC, €	7670	8764	7482
Heating demand, kWh/m^2	39.9	48.0	39.3
All year average ACH, h^{-1}	0.71	0.67	0.57
Sumer average ACH, h^{-1}	1.36	1.24	0.96
Max value ACH, h^{-1}	4.0	5.0	3.0

UP-utopia point criterion, TC-thermal comfort criterion, CO-cost-optimal criterion.

Due to the fact that we analyze the two objective functions for each solution in the study, quantitative (percent) comparison of results without introducing additional parameters is difficult. However, when comparing the Pareto front (Figure 6) for case 3 with the Pareto front for case 1, it can be concluded that window optimization does not produce a great improvement in the optimal results. Solutions with the small H_{dis} (to the left of the UP in Figure 6) have a similar LCC in both cases. The results improvement can be achieved for the large H_{dis}. The similar H_{dis} values (CO criterion) but reduced LCC were obtained in case 3 (in RB-CO: H_{dis} = 1692 h, LCC = 9787 €, and in case 3-CO: H_{dis} = 1591 h, LCC = 9112 €). For all MCDM, there is a reduction in the heat demand: from 6% for TC criterion to 13% for CO criterion. However, the higher initial cost (window purchase) means that it does not translate into a significant decrease in LCC. Summing up case 3, it can be concluded that if the priority is to improve thermal comfort with reduced LCC, the type and size of windows have little effect on improving these parameters.

A significant improvement of LCC with the similar H_{dis} is obtained in case 4, where the insulation of the building is optimized, not the windows (Table 7). In relation to case 1, LCC savings amount to: UP–22%, TC–17%, CO–24%. However, ensuring good thermal comfort in the insulated building requires a large ventilation airflow in the summer. In the optimized controller, maximum permissible air change rate values of 5 h^{-1} for TC were obtained.

In the case 5, all the parameters summarized in Table 2 were optimized. The Pareto front is shown in Figure 7. Values of objective function: heating demand and ACH are shown in Table 8. Optimal values of design variables are presented in Table 9. In comparison to case 4, a slight improvement in the values of H_{dis}, LCC and heating demand for UP and CO criterions was achieved. However, in case 5, the lowest H_{dis} value (from all optimized cases) for TC criterion (only 3 h) was obtained. This was obtained with LCC increased by 5% compared to case 4. Additionally, the highest average ACH for all MCDMs was obtained in the summer period (compared to the remaining cases). However, in no MCDM the maximum ACH value has reached the maximum allowable value (5 h^{-1}). For all MCDMs, similar insulation thicknesses and the total area of glass were obtained (Table 9).

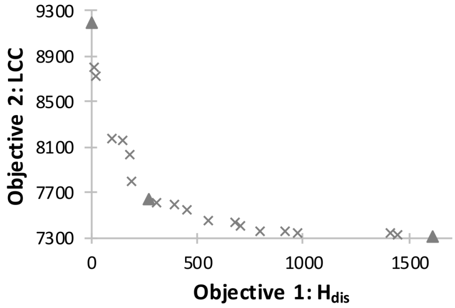

Figure 7. Pareto front for case 5.

Table 8. Optimal results for case 5.

MCDM	UP	TC	CO
H_{dis}, h	275	3	1609
LCC, €	7650	9205	7312
Heating demand, kWh/m^2	39.0	51.4	37.3
All year average ACH, h^{-1}	0.81	0.82	0.78
Sumer average ACH, h^{-1}	1.58	1.62	1.53
Max value ACH, h^{-1}	3.0	4.0	3.0

UP-utopia point criterion, TC-thermal comfort criterion, CO-cost-optimal criterion.

Table 9. Detailed results for cases 5 and 2-UP.

MCDM		UP	TC	CO	Case 2-UP
Type of glazing		G06	G05	G07	G06
Window area, m^2	W1	3.000	3.375	2.250	3.750
	W2	3.000	2.625	3.375	1.875
	W3	4.875	3.750	4.125	4.125
	W4	3.750	3.750	3.750	2.625
	W5	3.000	3.375	3.375	2.250
	W6	3.375	2.625	3.000	1.500
	W7	4.125	4.500	3.750	3.750
	W8	3.375	3.000	3.375	2.625
	W9	2.250	2.250	2.250	2.250
Building orientation, deg *		337.5	0	315	0
Insulation, cm	external walls	20	18	18	15
	ground floor	10	8	12	5
	ceiling	28	28	28	25
Sum of windows area, m^2		30.75	29.25	29.25	24.75
Sum of glazing area, m^2		20.85	19.60	20.05	16.73

UP-utopia point criterion, TC-thermal comfort criterion, CO-cost-optimal criterion. * clockwise.

In Poland Technical Conditions [49] specify the minimum ratio of glazed area of the windows to the floor area of the rooms they are located in. It should be minimum 1:8. Such a minimum glass area in the analyzed building is 14.4 m^2. In optimal cases, the glass area is from 136% (TC) to 145% (UP) of this value. It can therefore be concluded that investors are convinced that a smaller window area affects smaller life cycle costs. Taking into account only the heat transfer coefficient when choosing windows is wrong. As shown in Table 9, different types of windows were obtained for three different MCDMs. The smallest heat demand and LCC (CO criterion) were obtained for the most expensive windows, which have the largest solar heat gain coefficient (Glazing G07). In terms of the U-value, these windows are only in the third place. This shows how important the solar heat gains are in the

Polish climate. The contrary is for the TC criterion, where the window with the smallest solar heat gain coefficient is optimal, which is to protect the rooms from excessive overheating. This window has the smallest U coefficient. For the UP criterion, the optimal glasses are G06, whose U and SHGC coefficients are between the coefficients for glasses G05 and G07.

In order to show differences in the results obtained (variable and constant ventilation), Table 9 presents the optimal values of design variables for the 2-UP case. The direct comparison of results is not possible, but large differences can be noticed. In the case 2-UP, a much smaller glass area and smaller insulation thicknesses were obtained. This is to limit solar heat gains (through windows), and less insulation on the ground floor is to increase the impact of this partition on lowering the temperature in summer. This comparison shows that the assuming the constant ventilation in the thermal calculations leads to incorrect optimal results.

6. Summary and Conclusions

The article presents the methodology of optimal selection of the envelope of the building with natural ventilation. As the objective function, the heat demand and thermal comfort of occupants have been assumed. A special controller has been proposed, whose task is to imitate occupants in controlling the natural ventilation airflow. The controller reduces and increases the supply airflow in the periods of low and high temperatures in the rooms, respectively. NSGA-II was used to optimize the ventilation controller as well as the envelope of building.

In simulations of heat demand, a constant air exchange is often taken into account. The analysis showed that it significantly affects the results obtained. The optimal values of the insulation thickness of the external partitions are in this case smaller in relation to the optimal thickness of the insulation in the building with variable ventilation airflow throughout the year. A well insulated building, without additional ventilation using ambient airflow, will be cooling much slower during the summer, extending the period of thermal discomfort. Therefore, due to the criterion of thermal comfort, the building with constant infiltration was additionally slightly insulated.

In real cases of buildings with natural ventilation, the airflow varies throughout the year. In this case, the optimal insulation thicknesses, from the point of view of both the life cycle costs and thermal comfort, are significantly higher compared to the minimum requirements (RB): depending on the case by 6–8 cm for exterior walls (U = 0.14–0.16 W/m^2K), by 3–7 cm for the floor on the ground (U = 0.17–0.21 W/m^2K), by 8 cm for the ceiling (U = 0.13 W/m^2K). Upon full optimization of the building envelope (case 5), the heat demand for the utopia point (UP) criterion decreased by 40% and the life cycle costs by 22%. A much larger share in reducing the heat demand is due to an optimal selection of external partitions construction compared to the optimal selection of the windows type and size.

Analyzes have shown that striving for a maximum reduction of window area due to their higher heat transfer coefficient in relation to opaque external partitions is not a good solution. In a moderate transitional climate, the heating period is about 2/3 of the year. In this case, larger windows give the opportunity to use more solar heat gains in the cold periods of the year. It affects the reduction of heat demand. In hot periods of the year, such windows can be covered with blinds as in the case considered in the work, limiting solar heat gains. The determined optimal total window area is even 33% higher in relation to the size of windows in the reference building. The window area has increased most in the corner rooms 2 and 4, by as much as 80%. In the living room the southern window area increased, the north and east ones remained the same or were reduced depending on the criterion of TC or CO.

After the optimization, the orientation of the building for the criterion of thermal comfort (TC) has not changed and for the criterion of the optimal cost (CO) the building has been rotated by 45°. Thus, the windows in rooms 2, 3 and 4 were oriented to the south-west.

The simulations also show that expensive cooling systems are unnecessary in detached houses located in transitional climate. Using additional ventilation in the summer can effectively improve thermal comfort.

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