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Impact of Passive Cooling on Thermal Comfort in a Single-Family Building for Current and Future Climate Conditions

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Abstract: Today, there is a great deal of emphasis on reducing energy use in buildings for both economic and environmental reasons. Investors strongly encourage the insulating of buildings. Buildings without cooling systems can lead to a deterioration in thermal comfort, even in transitional climate areas. In this article, the effectiveness of natural ventilation in a passive cooling building is analyzed. Two options are considered: cooling with external air supplied to the building by fans, or by opening windows (automatically or by residents). In both cases, fuzzy controllers for the cooling time and supply airflow control are proposed and optimized. The analysis refers to a typical Polish single-family building. Simulations are made with the use of the EnergyPlus program, and the model is validated based on indoor temperature measurement. The calculations were carried out for different climate data: standard and future (warmed) weather data. Research has shown that cooling with external air can effectively improve thermal comfort with a slight increase in heating demand. However, to be able to reach the potential of such a solution, fans should be used.

Keywords: building simulation; thermal comfort; climate change; passive cooling; EnergyPlus

1. Introduction

The overheating of buildings is becoming more common, especially in newer residential buildings. The heat transfer and air exchange are limited in such buildings and the indoor temperature can often be too high. This may lead to a significant reduction in thermal comfort, especially during the summer months. This can be both detrimental to people and the building itself. It affects the durability of building construction and materials and causes the appearance of the Sick Building Syndrome (SBS). SBS is a combination of health ailments that people can experience when living in poor environmental conditions. People sick with SBS often complain about ailments such as headaches, shortness of breath, and coughs. Unfortunately, with SBS the serious medical conditions are also associated with issues such as bronchial asthma, conjunctivitis, and cancer [1]. The main cause of overheating is the high insulation and airtightness of such buildings. In Poland, the heat transfer coefficient of external walls may not be bigger than 0.23 W/(m^2·K) [2] in ordinary buildings. However, in passive buildings, this may not exceed 0.15 W/(m^2·K) [3]. This approach to the design of buildings is justified when heating demand is greater than the cooling demand during the year. However, due to the warming climate, the range of days that demand heating is decreasing. Therefore, much more attention should be focused on building cooling. In residential buildings, such as a single-family house, methods to provide cooling often involve the usage of air conditioners. This is a simple solution but requires additional investment costs and ongoing operating costs through the consumption of additional electricity. This solution is also not

ecological. Energy use by air-conditioning devices might exceed half of the total electricity in a single flat in a country with a warm climate [4]. In the current Polish climate, the energy consumption costs for mechanical cooling may be as much as a third of the heating costs in single-family houses, especially in buildings with high insulation [5]. A much more environmentally friendly solution is the conscious use of ventilative cooling.

Ventilative cooling (VC) is an energy-saving way to cool the building. It relies on the use of the natural cooling capacity of outdoor air instead of mechanical cooling, while still maintaining ideal thermal comfort conditions. The airflow driven can be natural or forced by fans, or it can be a combination of the two. Detailed information about VC is described in ANNEX 62 of the IEA Energy in Buildings and Communities program [6]. The main aims of this program are to develop a design method and tools related to the prediction, assessment, and elimination of the need for cooling and the risk of overheating of buildings, as well as to develop energy-saving VC solutions [7]. One of the tasks was to analyze and evaluate buildings with VC systems. In Denis et al. [8], the overview of the VC systems and design method for 14 case studies were presented. Different types of buildings were analyzed: residential, educational, office buildings, one kindergarten, and one mixed-use. They were located in various climates, for example, Norway, Belgium, Great Britain, Japan, and China. The cheapest solution of VC is using only natural ventilation using open windows. This has been the topic of discussion of numerous scientific papers [5,9–13]. Sorgato et al. [10] analyzed the impact of occupant behavior in relation to the window opening on residential building consumption. A number of scenarios were considered: opening windows from morning to night, night ventilation, and automated opening control. The various thermal capacity of buildings was taken into account and simulations were made in the EnergyPlus program. The best thermal comfort conditions were obtained for a building with medium thermal capacity and automated ventilation control. Grygierek et al. [12] suggested the optimal window opening times, with the windows being opened to provide comfortable conditions for the greatest number of hours during the year with the lowest possible heat demand. The thermal comfort was estimated according to the adaptive model [14]. The simulations were carried out in EnergyPlus, combined with MATLAB (R2017a, The MathWorks Inc., Natick, MA, USA). In Grygierek and Ferdyn-Grygierek [15], the authors present a way to improve the thermal comfort conditions in a detached house using passive cooling which was based on mechanical ventilation using ambient air. Mechanical ventilation was controlled by a fuzzy logic controller, and the optimization of the controller was based on the genetic algorithm method. The calculations were carried out in EnergyPlus for the transitional climate prevailing over Poland. The use of optimally controlled mechanical ventilation allows for increasing thermal comfort, with the number of discomfort hours being just 2% during the year. Psomas et al. [11] described an advanced VC algorithm of a window system and prepared building performance simulation (BPS) tools in order to reflect the work of the algorithm in the real world. The simulations were carried out on coupled BPS environments (ESP-r and BCVTB tools) and for a single-family house in Denmark. The research analyzed the influence of various opening steps of roof windows on overheating and thermal comfort and used their algorithm to investigate the window systems for other building types and climatic conditions. Stazi et al. [13] analyzed the automatic window control system in two adjacent school classrooms. Two indicators of thermal comfort (PMV and PPD) were used to evaluate the system. In Sarna et al. [5], the heating and cooling consumption were simulated for different types of single-family houses with current and passive insulation standards, and for two cooling systems using air conditioners and ventilative cooling through the use of windows. The research has shown that cooling by outdoor air can be used in single-family houses in the current climate conditions experienced in Poland.

The situation with overheating of buildings may worsen if scientists' forecasts about global warming come true. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature may rise by a range of 1.5 to 4.5 °C in the 21st century [16]. The IPCC is "the United Nations body for assessing the science related to climate change" [17]. The scientists of IPCC published the Special Report on Emissions Scenarios (SRES) in

2000 [18]. The scenarios included in SRES are used as the baseline to predict possible future climate change. There are six families of scenarios: A1FI, A1B, A1T, A2, B1, and B2. They differ in their focus on environmental or economic growth and an integrated (globalization) or divided (regionalization) world. Global warming forecasts are regularly updated by the IPCC. The probability of each of the scenarios is largely the same. All can be used to create estimates of future climates by using specially designed tools. These developments allow for the possibilities to predict and generate models of the future climate, and there are more and more scientific publications in the field of thermal comfort and energy demand for the different scenarios of warming climates. Heracleous and Michael [19], for example, compared the indoor conditions in educational buildings in Cyprus (Southern Europe) for the current and future climatic conditions. The impact of using only natural ventilation to provide the thermal comfort conditions was investigated and checked to examine to what extent the buildings would be overheated. The A1B scenarios were chosen to generate the future climates of 2050 and 2090. It was shown that it would be possible to use night ventilation to improve thermal comfort and reduce overheating. However, the period of discomfort conditions would be longer for residents (more than 50% of the time with people in 2050 and more than 70% in 2090). Artmann et al. [20] investigated the use of night ventilation to passively cool a building for current and future climates. The potential of passive cooling was compared in different climates in Europe. The most optimal results were obtained in Northern Europe, however, in other parts of Europe, even the Southern regions could experience improved thermal comfort through the application of night cooling (but not all of the time). Bienvenido-Huertas et al. [21] examined the possibilities to use an adaptive comfort model for current and future climates in various regions in Japan. The research showed that the adaptive comfort model is a good application in both climates. Jentsch et al. [22] analyzed the two groups of models to generate a future climate. The first groups were freely available general circulation models (GCM): six GCMs under AR3 [23] and 23 GCMs under AR4 [24]. The second was a more detailed regional climate model (RMC). Existing weather data were transformed into future data by using the 'morphing method'. It was found the results of the simulation using the GMC 'morphed' data were similar to the results of the RMC data. However, the authors predict that in the future, the differences would be more significant and whenever possible, RMC models should be used. Hosseini et al. [25] examined the energy demand of buildings with various roof designs. They took into account the current and future climate and used the General Circulation Model (HadCM3) to create future weather data. All these studies show that there is a need to take climate change into account when designing buildings.

Research Gap and the Purpose of Study

Today, investors are deciding to invest in insulating their buildings more and more. Currently, in a transitional climate, this can mean cost savings on heating buildings, and globally, it can lead to a reduction in environmental pollution. Unfortunately, the occupants of such buildings (without cooling systems) more and more often experience the problem of building overheating and thus deteriorating thermal comfort. It turns out that traditional window opening in order to lower the temperature in rooms is insufficient. The progressive warming of the climate may lead to the necessity to install mechanical cooling installations in such buildings. Assuming a slight increase in temperature, mechanical cooling devices will be used only in summer, however, the overall energy demand in buildings is increased.

The purpose of this study is to analyze the potential of natural ventilation (passive cooling, window opening—automatically or by the occupants) in providing proper thermal comfort. The second method under consideration (for cooling the building) is passive cooling based on mechanical ventilation (fans) with the use of colder outside air. This is a cheaper solution to invest and operate than a mechanical cooling system.

Research in the field of passive cooling with mechanical ventilation mainly considers office buildings, where night cooling is increasingly used to support cooling installations. There is little research analyzing the use of such systems in residential buildings, where there is no possibility of

overcooling (due to the comfort of residents staying in the building at night). Research on the problem of overheating of buildings and the demand for cooling is carried out mainly for Mediterranean countries. There is little research for colder climates where this problem is exacerbated and it is not possible to directly translate the results between different climates. There is also a lack of research for naturally ventilated buildings, which are more difficult to model, and in most studies, the authors mainly analyze buildings with mechanical ventilation.

The authors dealt with the issues described above to a certain extent in previous articles [12,15]. In this article, the research has been extended to include new methods of controlling passive cooling systems. Additionally, the effectiveness of such systems for the future (warmed) climate was also tested.

In this study, research was carried out for a selected single-family building. The building and cooling systems were modeled in the EnergyPlus program. Fuzzy controllers have been proposed to control passive cooling systems. The controllers have been optimized with the use of genetic algorithms. The results obtained in this way show the potential and limitations of individual methods in cooling the building.

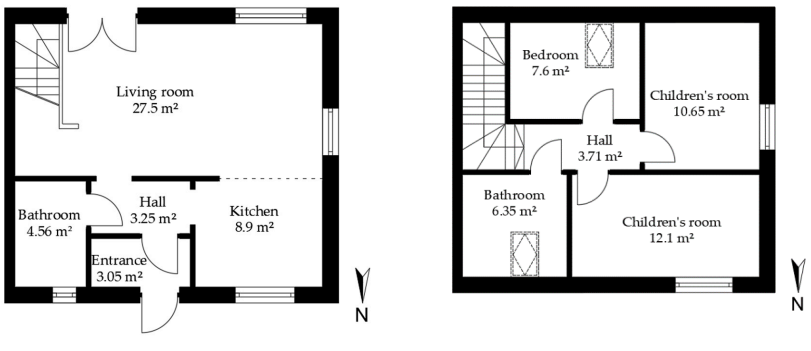
2. Methods

2.1. Research Object

The research object was a single-family house with a usable area of 92 m^2 (Figure 1). It was in the right part of a whole semi-detached house. The building was located in the southern part of Poland in Skoczów and was built in 2018. Three stories have been designed in the building: a ground floor, a usable attic floor, and an unheated attic floor. Figure 2 shows the building plan. The building was designed for a 2 + 2 family. The walls of the building were made of brick and insulated with polystyrene. The ceilings were made of reinforced concrete. The insulation of external partitions has been designed and made in accordance with the requirements of 2017 standards [2].



Figure 1. Project building [26].



(**a**) (**b**)

Figure 2. Plan of (**a**) ground floor; (**b**) usable floor.

2.2. Thermal Model

The building thermal model was prepared in the OpenStudio program [27]. This program is integrated with the SketchUp program [28], in which it is relatively easy to create building geometry. This model has been transformed into the EnergyPlus 9.3 program (EP) [29]. All simulations were carried out in EP. This program can be combined with other programs, which was necessary for the analyses realized in this study.

The investigated building was divided into 10 thermal zones. The simulations were conducted with 15-min steps. The thermal model included:

- heat gains of equipment in accordance with ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards [30]
- human heat gains (the schedule of occupied people was prepared based on the behavior of a traditional Polish 2 + 2 family, divided into working days and weekends. Heat gains were assumed to be 126 W per person)
- interior blinds, which were covered if the intensity of solar radiation on the glass was greater than 27 W/m^2
- lighting, which was switched on if the lighting intensity was less than 300 lux
- an ideal heating model; the heating set point was assumed to be 21 °C during the day, and 18 °C at night (11 p.m.–5 a.m.).

The simulations were carried out for two variants of the building insulation. The first one was the current state of the building, which fulfills the requirements of the current 2017 standard [2]. The second variant fulfills the requirements of a passive building [3] in terms of thermal insulation. Both cases of the thermal models differed only in the thickness of thermal insulation. Table 1 presents the comparison of the values of the heat transfer coefficient for two variants. The requirements of values of heat transfer coefficient for passive buildings are significantly higher than standard buildings, especially for ground floor heat transfer which is three times smaller.

Table 1. The values of the heat transfer coefficient for building partitions.

Building Partition	Heat Transfer Coefficient, U, W/(m^2·K)	
	Current Standard	Passive Standard
External wall	0.23	0.15
Ground floor	0.30	0.10
Internal ceiling to the unheated attic	0.18	0.15
Roof	0.18	0.15
Window	0.6 [1]	

[1] Solar heat gain coefficient of 52%.

The simulations were carried out for two different climates, which are described in the next section.

2.3. Current and Future Weather Data

The building performance simulation allows for a prediction and analysis of different cases of cooling. The weather data are needed to perform reliable simulations. The common file format of weather data is the EPW weather file (Energy Plus Weather) due to the popularity of EnergyPlus [31]. Other popular weather files are TMY2, TMY3, TRY, and IWEC which were described in a study by Herrera et al. [32]. Weather files can be prepared for one calendar year or are averaged from 20–30 years for a given location—the so-called standard weather data. The weather data can be generated for future years and can take into account climate change scenarios by using different tools and ways. One popular method to predict the future climate is the so-called morphing method. Numerous scientists [22,25,33–36] use and develop this method. In their study Escandón et al. [33] use the

CCWorldWeatherGen [37] software to generate future data. This is a generally available tool that can be run in Microsoft Excel [38]. EPW weather files with current data and climate change scenario data are required to transform the weather files to future data. The creation of future data is based on the morphing of historical observation. The changed files are EPW or TMY2 weather files. An alternative tool to generate a weather file can be WeatherShift, which is based on two of the representative concentration pathways RCP emission scenarios described in the fifth assessment report, AR5 [16]. Moazami et al. described and compared both sets of tools: CCWorldWeatherGen and WeatherShift. Dias et al. [39] presented a comparison of the two methods to generate future weather data: morphing and typical meteorological year of future climate (F-TMY). It has been shown that morphing methods create weather files with similar accuracy to F-TMY, and this can be used to simulate the future climate. Yassaghi et al. [40] compared the outputs for three various weather generators: The Advanced Weather GENerator, the CCWorldWeatherGen, and Meteonorm. Their main limitations are indicated.

In this study, the simulations were carried out for two different climates. In the first case, the standard climate was used, and in the second case future (warmer) climate for 2050 was generated based on the A2 scenario. Both were prepared for Katowice in the CCWorldWeatherGen program. The comparison of these climates is presented in Figure 3.

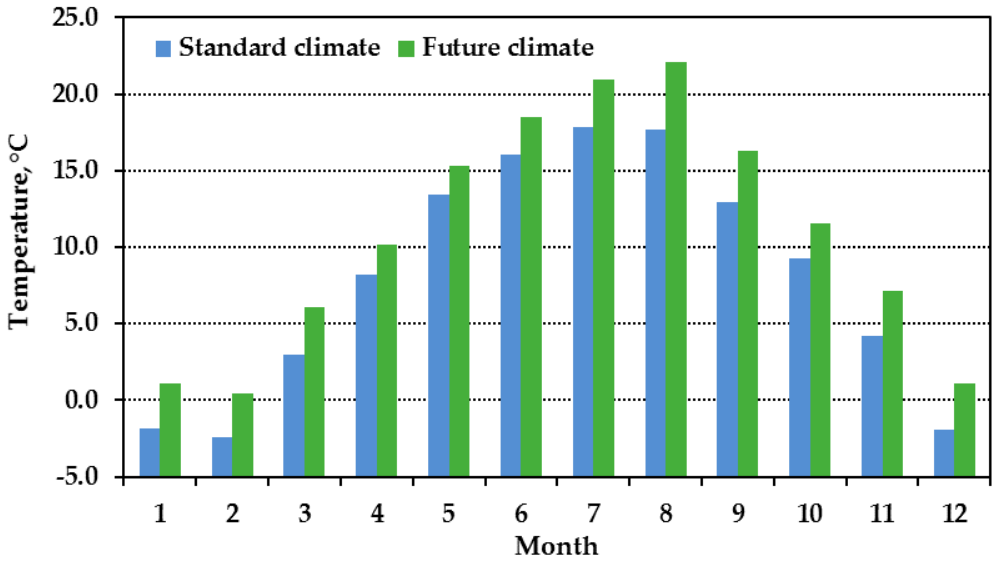


Figure 3. The comparison of average monthly exterior temperature for standard and future climate.

2.4. Thermal Comfort

The main aim of this work is the analysis of thermal comfort in rooms depending on the insulation of the building and the climate. In the investigated building there was natural ventilation. Therefore, the adaptive model, implemented in the EP program, was selected for thermal comfort analysis. As there is central heating in the building, it was assumed that during the heating season, the heating temperatures would be set to ensure thermal comfort for the occupants. It was also assumed that the inhabitants did not feel any thermal discomfort during the scheduled night hours of the reduced heating temperature. It was decided that the parameter describing the thermal comfort would be the number of discomfort hours H_{dis} (the lower number of H_{dis} = the better thermal comfort). The H_{dis} is defined as the sum of hours in rooms for the permanent stay of people (living room, bedroom, child rooms), where the thermal comfort is outside the 2nd category of climate in the adaptive model. Only hours with occupants in the rooms were taken into account in the calculations. Therefore, during the week, the total number of hours in which the thermal comfort is checked is 280 h.

2.5. Ventilation

The "Infiltration by Effective Leakage Area" method [41] was used in EP in order to model the infiltrating airflow. The factor of the Effective Leakage Area (ELA) in rooms was calculated based on the airtightness tests [42,43] regarding residential buildings in Poland and ASHRAE guidelines [44]. The results obtained in the validation (Section 3.1) of the building model allow us to conclude that these values were correctly selected.

The infiltrating airflow is small and therefore, the rooms might be overheating in the summer. The most effective way to deal with this problem is the installation of refrigeration devices, for example, split air-conditioners. However, this comes with high investment costs and ongoing utility costs due to continuous energy consumption. In Poland, such systems are installed in only a small number of buildings, as most cooling is obtained by opening windows.

In this article, several methods of ventilation have been tested and the extent to which they are effective depending on the level of building insulation and the climate is considered. The first group of methods relied on the installation of extra supply fans, while the second group relied on controlling the window opening (automatically and manually).

In the case of supply fans, it is assumed that the air change rate (ACH) cannot exceed 3 h^{-1} in the room. The fans can be turned on and off at each simulation step. The two types of fans were analyzed:

- with variable air volume. In simulations, the operation time of fans and supply air was optimized. The flow rate depends on the parameters described in Section 2.6 and can have different values at each simulation step.
- with constant air volume. The fan operation time and efficiency have been optimized. In this case, it is a constant value at each simulation step. The optimal fan efficiency was calculated as the product of the searched parameter (constant for all rooms) and the room volume.

Automatic window opening can be realized with a special actuator with a constant degree of opening. Theoretically, such an actuator could change the setting (on-off) at each simulation step. However, a wide-open window, in the absence of occupants, can be dangerous to the property (and could lead to flooding or allow opportunities for theft). Hence, some restrictions have been introduced into the two cases of automatic windows opening:

- the widow setting can be changed at each simulation step. However, it is only possible to tilt the widow slightly (2 cm). The moment of changing the window setting (on-off) is optimized.
- windows can only be opened if the residents are in the building. The windows on the ground floor are closed at night (10 p.m.–6 a.m.). While people are at home, changing the window setting can be done at each simulation step. In the simulations, the moment of opening (or closing) the window and the degree of its opening were optimized. The window opening area is calculated as the product of the searched parameter (constant for all windows) and the window area.

The last considered case was manual window control. It was assumed that there are two possible degrees of a window opening. The area of the open window was calculated as the product of the parameters sought (the same for all windows) and the total area of the window. Windows can be opened as in the second case of an automatic window opening. Due to the manual window adjustment, it was assumed that the change of window settings is possible only at certain times (approximately every 2 h when people are in the building during the day, for example, on working days at 6 a.m., 7 a.m., 4 p.m., 6 p.m., 8 p.m., 10 p.m.). Between these hours the window remains in a fixed position. In practice, possible rainfall may affect the decision of residents to open the window. In the ".epw" climate files, however, relevant data are missing, so this aspect was omitted from the calculations. Such a simplification will not have a large impact on the obtained results because of the analyzed climate, where the temperature drops significantly along with rain. In this case, overheating of the rooms will very rarely occur.

The "Wind and Stack Open Area" method built into the EP was used to model the window opening. The methods presented above are intended to cool the indoor air, therefore they are used when the outdoor temperature is at least 1K lower than the temperature in the room.

2.6. Fuzzy Logic Controller of Ventilation

For all the ventilation cases described in Section 2.5, a controller was used. This controller determines when a change in the settings of fans or windows will occur. In the case of fans with variable supply airflow, an additional controller has also been introduced to determine the supply airflow by fans. These values may change as the simulation runs.

Due to the fact that the controller, in one of the methods, is used to imitate the behavior of people in opening/closing a window, it was decided to use the Takagi—Sugeno—Kang zero-order controller [45,46] (TSK controller) for all analyzed cases. Fuzzy logic (on which such a driver is based) describes imprecise phenomena and concepts that are understandable to a human in everyday speech. A fuzzy controller can turn inaccurate information given by an expert into a specific action. In this paper, it was decided that the role of an expert would be replaced by controller optimization.

All controllers used in this study have two inputs and one output. Inputs are described by three membership functions: triangular and two trapezoidal on sides. For this case, there are nine rules in the controller. There is one output for each rule. The final output value is the weighted sum of outputs of individual rules.

With the exception of the controller "imitating" the control of the window by people, it was assumed that the input data can only be temperature (easy to measure).

Additional ventilation (by fans or windows) was activated if the internal temperature in the room (T_{in}) is higher than the calculated "ventilation" temperature (T_{vent}) and the assumptions described in Section 2.5 are met. T_{vent} is calculated as the sum of the comfort temperature T_{comf} (calculated as in the adaptive comfort model) and the dT value (output from the controller—takes values in the range [−3, 3] K): $T_{vent} = T_{comf} + dT$.

Input data of controllers calculating dT for each ventilation method are:

- fans with variable air volume: T_{avg} (weighted average of maximum outdoor temperatures for the last three days) and T_{out} (outdoor temperature)
- windows controlled by people: the difference between indoor and outdoor temperature ($dT_{in_out} = T_{in} - T_{out}$) and the difference between operative room temperature and comfort temperature ($dT_{ot_comf} = T_{ot} - T_{comf}$)
- remaining methods: T_{avg} and dT_{in_out}.

In the method of fans with variable air volume, the supply airflow is additionally calculated. This value is calculated by the controller whose input data are dT_{in_out} and the difference $dT_{in_vent} = T_{in} - T_{vent}$.

The window area which is opened by people can take two values. They depend on the wind speed. It was assumed that the occupants open their windows to a different extent depending on the wind speed. It was also assumed that occupants do not open their windows when the wind speed exceeds a certain value. The window surface areas and the limit wind speeds have been optimized.

In the controller, seven values describing the assignment of each input and nine outputs of each rule should be defined. In the article, this was done in the optimization process.

2.7. Optimization

Building ventilation should be used in such a way as to improve the thermal comfort of the occupants. However, too much ventilation (especially in intermediate seasons) may cause a situation when additional heating is required. This situation is undesirable. When occupants open their windows, their experience helps them to make a decision on how to control the windows so that

the building does not cool down excessively. In this paper, it was decided that the role of occupants (experts) would be replaced by optimization.

In the optimization of the parameters described in Section 2.6, it was decided to minimize two objective functions:

- H_{dis}, h (described in Section 2.4)
- Q_{heat}, kWh—heating demand.

Such optimization guarantees that an improvement of H_{dis} is obtained with a minimal increase of Q_{heat}.

A multi-criteria method of genetic algorithms was selected for optimization. The NSGA-II method, the most popular in engineering applications, was used. As a result of multi-criteria optimization, the Pareto front was obtained (a set of non-dominated solutions, these are optimal solutions). The solution with the smallest H_{dis} which achieved the conditions of the specified number of hours H_{dis} (described in Section 3.2) would be compared.

The optimization process was carried out by combining three programs (Figure 4). In the MATLAB program, which has embedded the NSGA-II method, the process of optimization and preparation of *.idf input files to the EP program and *.py to the Python 3.7 program was carried out. Python is added to the EP (from version 9.3). In Python, functions extending the operation of the EP program can be written. TSK controllers have been programmed in Python. In Python, the values that were passed to EP were calculated at each time step of the simulation. EP for the defined thermal model (*.idf file) computed the objective functions that were passed to MATLAB.

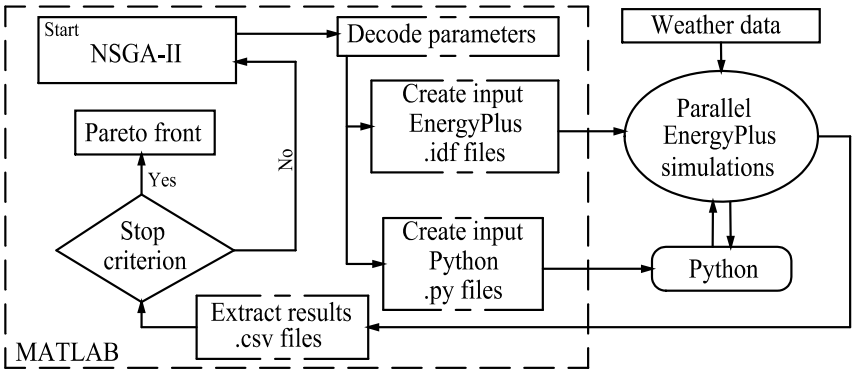


Figure 4. Flowchart diagram for the optimization tool.

3. Results

3.1. Measurement and Model Validation

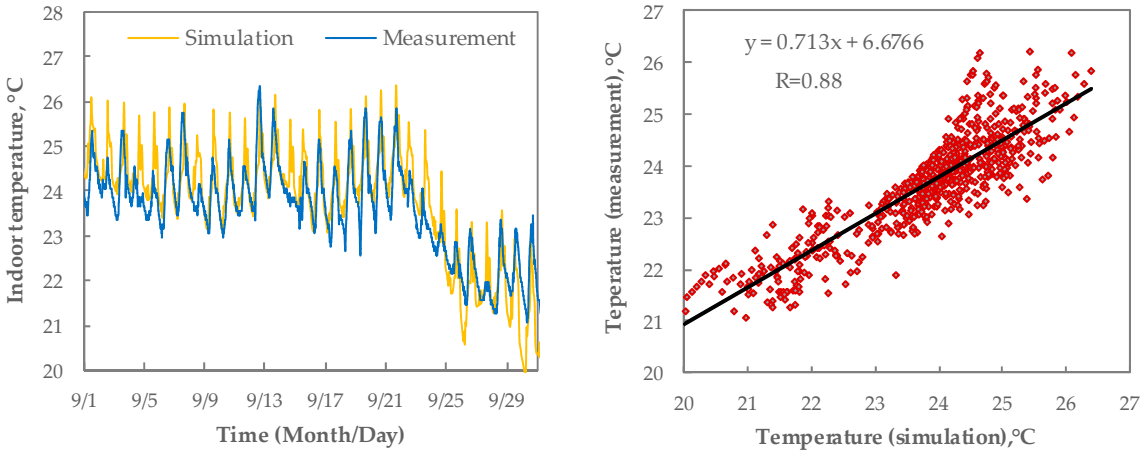
Before carrying out the simulations, the model was validated and calibrated. The detailed description of the process of model validation and calibration was presented in the previous paper by Sarna et al. [47]. In September 2018, the measurements of outdoor and indoor air temperature were conducted by using Apar235 recorders (measuring range: −30–80 °C, measuring accuracy: ±0.5 °C in the range 20–30 °C and ±0.5–1.8 °C in the remaining range). The recording of the measurement values was done with a 15-min time step. The indoor air temperature was measured in four rooms: living room, children's room, bathroom on the first floor, and unheated attic. In addition to the air temperature measurement, a register of occupants' presence (two adults and a one-year-old child) in the research object was also kept, so as to be able to take into account the appropriate heat gains for the model verification. The outdoor temperature was also measured in order to verify the climate. After the measurements, preliminary simulations were carried out and the thermal model has been tuned to reflect the actual building conditions. Next, a four-steps-calibration was conducted, which included the adaptation of the infiltration model and a proper estimation of internal and solar gains. Figure 5a

presents the comparison of indoor temperature obtained by measurements and simulations for the living room. The variability of simulated and measured temperatures was similar. In accordance with the recommendations given in the ASHRAE guide [48], the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of Root Mean Squared Error (CVRMSE) were adopted for model verification. These indicators should be calculated on the basis of Equations (1) and (2).

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(M_i - S_i)}{n \cdot \overline{M_i}} \times 100 \quad (1)$$

$$\mathrm{CVRMSE} = \frac{1}{\overline{M_i}} \sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n}} \times 100 \quad (2)$$

M_i—measured value, S_i—simulated value, n—number of compared values, $\overline{M_i}$—mean of the measurement values.



(**a**) (**b**)

Figure 5. Variation of instantaneous value (**a**) and correlation (**b**) of measured and calculated indoor temperature for the living room zone.

Empirical verification regarding indoor temperature makes the results of the simulation calculations reliable—relative error is small. According to the guide [43], the model is well-validated if, for the hourly data, the maximum values of the NMBE and CVRMSE are 10% and 30%, while for the average monthly data the NMBE and CVRMSE is 5% and 15%. In the case of this model, the indicators' values were within this range (Table 2).

Table 2. Values of Normalized Mean Bias Error (NMBE) and Coefficient of Variation of Root Mean Squared Error (CVRMSE) indicators after the model calibration.

	NMBE, %	CVRMSE, %
Living room	1	3
Children's room 1	2	3
Bathroom on 1st floor	2	3
Unheated attic	10	11

In order to determine the interrelationship between the measured and simulated variables, the correlation of the results was performed. The correlation is considered strong if Pearson correlation coefficient R is greater than 0.7 [49,50]. This requirement was met for all calibrated rooms. The correlation

for the living room zone was presented in Figure 5b. Therefore, it was found that the model could be used for further simulations.

3.2. Analysis of Simulation Results

Simulations were carried out for two types of building insulation, two climates, and various methods of passive cooling. The symbols used in the following sections are summarized below:

Building insulation:

- B_{std}—building insulation according to the 2017 standard [2],
- B_{pass}—building insulation according to the standard of passive building [3].

Climates:

- Kat—standard climate for Katowice,
- Kat_{A2}—future climate for Katowice, generated according to the A2 IPCC scenario.

Cooling by fans:

- F—with variable airflow (variable air volume),
- F_{const}—with constant airflow (constant air volume).

Cooling by automatic window opening:

- W_{Aall} –adjustment and opening of windows all day long,
- W_A (W_{A20})—adjustment and opening of windows allowed during the hours of living in the building, unlimited supply airflow—any window opening area ensuring an optimal solution (W_{A20}—in optimization solution in which ACH exceeds 20 h^{-1} are rejected).

Cooling by opening windows by occupants:

- W_{O10} (W_{O20})–adjustment and opening of windows allowed during the hours of living in the building, (Section 2.5), the degree of window opening must not exceed the ACH 10 h^{-1} (20 h^{-1}) (implemented in the optimization process).

As a result of two-criteria optimization, the Pareto front of optimal solutions was obtained. Exemplary solutions of B_{std}-Kat-W_{O10} and B_{pass}-Kat_{A2}-W_{O10} are compared in Figure 6. The solutions on the Pareto front differ in the parameters of the controller (cooling time) and in this case, the window opening area. In all the cooling systems analyzed in the work, the reduction in the number of thermal discomfort hours (H_{dis}) causes an increase in heating demand (Q_{heat}) in the building. In transitional periods, cooling the building during the warmer midday hours causes the need for increased heating during the evening and night hours.

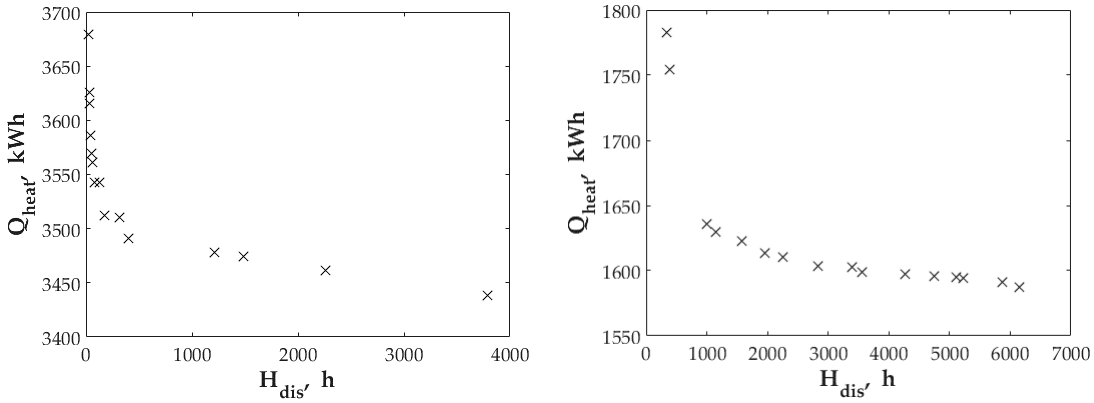


Figure 6. The comparison of Pareto front for W_{O10}-B_{std}-Kat- and W_{O10}-B_{pass}-Kat_{A2}.

The solutions with the highest H_{dis} correspond to buildings without passive cooling systems that depend only on the climate and the building insulation. The solutions with the highest H_{dis} are summarized in Table 3. Although it is a theoretical solution, it shows perfectly how H_{dis} increases with better building insulation and climate warming. In the further part of the article, the heating demand will be expressed in relation to that obtained in these solutions (difference, percentage). It will be treated as the base.

Table 3. Results for the solution with the greater H_{dis}.

	H_{dis}, h	Q_{heat}, kWh/m^2
B_{std}-Kat	3785.8	37.4
B_{std}-Kat_{A2}	4994.0	27.7
B_{pass}-Kat	5503.3	24.5
B_{pass}-Kat_{A2}	6143.7	17.3

The solution with the smallest H_{dis} illustrates the potential of the individual passive cooling systems. In Table 4, the results for this solution are summarized. These are H_{dis}, dQ_{heat} (the difference in relation to the solution from the largest H_{dis}), the maximum and average number of ACH in rooms, hours in which the number of air changes exceeds 10 h^{-1} and the total operation time of the passive systems cooling in all rooms.

Table 4. Results for the solution with the smallest H_{dis}.

			H_{dis}, h	dQ_{heat} kWh/m^2, (%)	ACH, h^{-1} Max, (avg)	Time ACH > 10, h	Passive Cooling Working Time, h
F	B_{std}	Kat	0	1.3 (3.5)	2.6 (2.4)		3319.5
		Kat_{A2}	8.5	3.1 (11.0)	3.0 (2.9)		5095.3
	B_{pass}	Kat	1.5	2.2 (9.0)	3.0 (2.9)		5570.8
		Kat_{A2}	4.0	3.4 (19.9)	3.0 (2.9)		7382.3
F_{const}	B_{std}	Kat	0.3	2.9 (7.7)	1.3 (1.3)		6904.8
		Kat_{A2}	15.0	3.1 (11.4)	2.4 (2.4)		7941.0
	B_{pass}	Kat	2.2	4.0 (16.5)	2.0 (2.0)		7031.8
		Kat_{A2}	17.3	4.8 (27.7)	2.8 (2.7)		7466.0
W_{Aall}	B_{std}	Kat	3.5	4.5 (11.9)	12.7 (2.2)	3.8	4486.5
		Kat_{A2}	61.5	4.7 (17.1)	13.3 (2.2)	5.0	7654.8
	B_{pass}	Kat	3.7	5.4 (22.2)	12.4 (2.2)	6.0	5625.8
		Kat_{A2}	98.3	4.9 (28.6)	13.5 (2.2)	4.3	7428.5
W_A	B_{std}	Kat	3.7	5.8 (15.4)	24.8 (4.3)	81.5	2256.8
		Kat_{A2}	21.5	11.5 (41.7)	48.4 (8.5)	736.8	2458.3
	B_{pass}	Kat	14.5	9.9 (40.5)	31.3 (5.6)	254.5	2692.3
		Kat_{A2}	50.3	21.3 (123.3)	53.0 (9.5)	1236.8	3359.3
W_{A20}	B_{std}	Kat	7.7	4.2 (11.2)	19.3 (3.5)	30.3	2459.5
		Kat_{A2}	60.5	3.7 (13.5)	19.5 (3.4)	44.0	3941.5
	B_{pass}	Kat	20.8	6.0 (24.3)	16.2 (2.9)	19.0	3795.5
		Kat_{A2}	181.0	7.2 (41.7)	18.2 (3.2)	42.3	4932.8
W_{O10}	B_{std}	Kat	26.5	2.6 (7.0)	8.8 (2.2)		3667.0
		Kat_{A2}	158.5	2.7 (9.8)	7.5 (2.3)		5196.0
	B_{pass}	Kat	145.2	2.4 (9.7)	10.0 (2.4)		3957.0
		Kat_{A2}	358.5	4.8 (28.1)	9.6 (2.7)		6232.0
W_{O20}	B_{std}	Kat	21.0	2.7 (7.2)	9.6 (2.7)	0	3061.0
		Kat_{A2}	102.7	2.4 (8.6)	14.7 (3.8)	27.5	4559.0
	B_{pass}	Kat	52.5	5.8 (23.6)	15.5 (3.5)	21.8	3872.0
		Kat_{A2}	241.5	6.3 (36.7)	19.7 (4.6)	78.3	4115.0

When analyzing H_{dis}, it should be borne in mind that the maximum number of such hours in one week is 280 h. Except in one case of W_{O10}-B_{pass}-Kat_{A2}, the number of hours in all passive cooling solutions does not exceed one week.

Fans are effective in both cases of building insulation and climate warming. This applies to passive cooling by fans with variable and constant airflow. In the case of cooling with fans, providing a high

level of thermal comfort has little effect on the increase in heating demand (compared to the solution without passive cooling). A better solution (in terms of increasing heating demand) is to use fans with variable airflow, where the increase in heating demand is from 3.5% to 19.9% (Table 4). The same value for F_{const} is from 3.3% to 16.1%. Due to the assumed limitations as to the maximum supply airflow by the fans, fans work for the largest number of hours compared to other solutions. The use of fans involves additional electricity consumption. This aspect was not analyzed in the paper.

Taking into account all results obtained for passive cooling realized by automatic window opening, the W_{Aall} version turned out to be the best. However, it is associated with the risk that occupants might have the window opened slightly when they are not at home. The main problem faced with the use of automatic windows opening was the size of the blown airflow. In this paper, it was assumed that the controller was based on values that are easy to measure (temperature). Wind speed was not taken into account. Therefore, in the case of $W_{Aall,}$ ACH exceeds 13 h^{-1}. For the method where the open window area (W_A) is not limited, the worst-case ACH (W_A-B_{pass}-Kat_{A2}) is 53 h^{-1}. The number of hours when the ACH exceeds 10 h^{-1} is 1236.8, which is related to a 123.3% increase in energy for heating the building. In the W_{A20} method, a limit was imposed on the maximum allowable ACH, which may not exceed 20 h^{-1}. It was implemented in the optimization process by imposing a penalty function on solutions that do not meet this constraint. This method (W_{A20}) is effective in providing thermal comfort, except in warmer climates where the H_{dis} was 181 h. The number of hours with ACH greater than 10 h^{-1} does not exceed 45 h. In this method (W_{A20}), the number of hours when the window is opened was smaller than the W_{Aall} method.

In terms of H_{dis}, the worst results were obtained for passive cooling achieved by residents opening windows. These results are associated with a lower increase in heating demand compared to the automatic window opening. This is a constant trend for all methods: greater H_{dis}—less Q_{heat}. In the case of opening windows by occupants, the wind speed and two degrees of opening windows were taken into account. Unfortunately, when analyzing H_{dis}, only the results for the W_{O10}-B_{std}-Kat and W_{O20}-B_{std}-Kat cases do not differ significantly from other methods. For the B_{std} building and the Kat climate, ACH does not have to exceed 10 h^{-1} to ensure good thermal comfort. When analyzing the results for W_{O10} and W_{O20}, it should be taken into account that the results are obtained with a strong window handling regime. In simulations, this is done by a controller that imitates human behavior. In fact, the results with this method may turn out to be worse.

Getting the best H_{dis} solution does not have to be an occupants' priority. Occupants may accept a certain number of discomfort hours in a room. In Table 5 for selected methods, the increase in heating demand in relation to the base demand (dQ_{heat}) for cases where H_{dis} = 140 h (half of the week) and H_{dis} = 280 h (one week) is shown. In these cases, the heating demand is linearly interpolated from two adjacent Pareto front solutions. These values can tell the investor what the heat demand will be for a given H_{dis}. Additionally, in Table 5, H_{dis} was compared for energy consumption higher than the base by 10% (dQ_{heat} = 10%).

By analyzing the results of Table 5, it can be seen that achieving H_{dis} = 140 h (280 h) for B_{pass}-Kat_{A2} requires a significantly greater increase in energy for heating than in other cases. The case of B_{std}-Kat_{A2} and B_{pass}-Kat shows similar increases in energy in all methods. For the F method (except for B_{std}-Kat), H_{dis} = 140 h, similar absolute increases in heating energy was obtained. In most cases, the improvement of H_{dis} (from 280 h to 140 h) requires a dQ_{heat} lower than 5% (in the F method it does not exceed 1%). In the cases of W_{A20}-B_{pass}-Kat_{A2} and W_{O10}-B_{pass}-$Kat_{A2,}$ such improvement comes at the cost of greater dQ_{heat}. In these methods, the cooling of the rooms must be carried out by larger areas of an open window, which in the transition period leads to too much cooling and the need for heating. For B_{std}-Kat in order to obtain H_{dis} = 180 h, the increase in heating, depending on the method is in the range of 1–8.4%, where the same range for B_{pass}-Kat_{A2} is 5.1–42%. This clearly shows that obtaining a similar thermal comfort for buildings that are very well insulated in a warmer climate requires greater investment.

Table 5. Increase in heating demand dla H_{dis} = 140 h and H_{dis} = 280 h. H_{dis} for heating increase dQ_{heat} = 10%.

			dQ_{heat}, kWh/m^2 (%)		H_{dis}, h
			H_{dis} = 140 h	**H_{dis} = 280 h**	**dQ_{heat} = 10%**
F	B_{std}	Kat	0.4 (1.0)	0.3 (0.9)	0
		Kat_{A2}	0.8 (2.7)	0.4 (1.3)	24.88
	B_{pass}	Kat	0.8 (3.4)	0.7 (3.0)	3.7
		Kat_{A2}	0.9 (5.1)	0.8 (4.4)	18.1
F_{const}	B_{std}	Kat	1.2 (3.3)	1.1 (2.9)	0.3
		Kat_{A2}	2.0 (7.4)	1.9 (6.7)	40.7
	B_{pass}	Kat	1.8 (7.4)	1.6 (6.7)	66.7
		Kat_{A2}	2.8 (16.1)	2.2 (12.6)	381.5
W_{Aall}	B_{std}	Kat	3.1 (8.4)	3.1 (8.3)	7.5
		Kat_{A2}	3.0 (10.9)	2.9 (10.4)	384.9
	B_{pass}	Kat	3.7 (15.1)	3.7 (14.9)	940
		Kat_{A2}	4.3 (25.2)	3.5 (20.2)	2500
W_{A20}	B_{std}	Kat	1.6 (4.3)	1.3 (3.5)	17.5
		Kat_{A2}	2.9 (10.6)	2.2 (7.9)	156.2
	B_{pass}	Kat	2.7 (10.9)	2.1 (8.6)	192.9
		Kat_{A2}	7.2 (42.0)	3.9 (22.7)	1071
W_{O10}	B_{std}	Kat	1.1 (2.8)	0.8 (2.1)	26.5
		Kat_{A2}	2.7 (9.9)	1.2 (4.2)	83.7
	B_{pass}	Kat	2.4 (9.7)	1.5 (6.3)	145.2
		Kat_{A2}	6.1 (35.4)	4.9 (28.5)	560.66

Except for the B_{pass}-Kat_{A2} case, a 10% increase in dQ_{heat} achieves H_{dis} within the limit for one week (280 h). This limit was not reached for B_{pass}-Kat_{A2} with all passive cooling methods except F. The W_{Aall} method is characterized by an exceptionally flat Pareto front. Small changes in dQ_{heat} made big changes in H_{dis}.

4. Summary and Conclusions

In this paper, the effectiveness of several passive cooling methods (based on supplying cooler exterior air by fans or open windows) was analyzed in providing thermal comfort. The effectiveness of these methods has been tested for the current and future (warmed) climate. The tests were carried out for a building with two types of insulation: standard and passive building.

The analyses were carried out for an existing single-family building. Fuzzy controllers have been optimized and optimal results were obtained, which allowed for the analysis of the effectiveness of cooling methods.

The results of the analyses allow for the formulation of the following general conclusions:

- in the future, in a transitional climate due to global warming, in very well insulated buildings not equipped with mechanical cooling systems, there will be problems with the overheating of rooms over longer periods of time. In the analyzed building, with limited ACH, thermal discomfort in the most favorable case occurs for about 360 h (about 1.3 weeks), and in the worst case for 6140 h (about 22 weeks).
- a comparable number of hours of thermal discomfort occurs in a building insulated in a passive standard in the current climate and in a building insulated in a standard from 2017 in a warmed climate calculated according to the A2 scenario.
- currently, an effective method (in a transitional climate) of cooling rooms with cooler outside air by opening widows by occupants in a building with a passive standard will not be sufficient in the future to maintain thermal comfort. In the analyzed building, in the best solution in terms of thermal comfort, in a warmed climate compared to the current climate, there are twice as many thermal discomfort hours.

- automatic opening of the windows in order to lower the temperature in rooms, in the case of a simple controller based on the measurement of temperature, can cause drafts at high wind speeds. In this passive cooling method, the wind speed must also be taken into account when controlling the windows. In practice, this will require the installation of additional wind measurement devices. Such a system will be more complicated than fan-based systems.
- an effective method of ensuring thermal comfort is the application of fans with variable supply airflow. Such a solution, combined with proper control, provides very good thermal comfort with a slight increase in building heating demand, even for buildings with a passive insulation standard.
- in a warmer climate, in a building with a passive insulation standard, passive cooling by opening windows causes a significant increase in heating demand. This is due to the fact that in transitional periods, cooling the building during the warmer midday hours causes the need for increased heating during the evening and night hours.

The above conclusions show that in the future in a warmer climate, most problems associated with the overheating of buildings will occur in very well-insulated buildings. Therefore, the conclusion is that in the process of designing the thickness of insulation in new buildings, scientists' forecasts regarding climate warming should be taken into account. In an extreme case, it may happen that the current heating savings will be absorbed to pay for the future cooling of the building.

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