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Residents' thermal comfort and energy performance of a single-family house in Poland: a parametric study

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Abstract. Building energy and environmental efficiency is presently one of the most important research subjects due to global climate change and the actual geopolitical situation. Residential buildings should provide a comfortable environment for the occupants while they spend up to 90% of their life indoors. Moreover, a comfortable indoor environment should be provided efficiently and affordably. Thus, the examination of the correlated factors of buildings' energy efficiency and occupants' comfort is highly anticipated. This field can be analyzed using various methods, where computational simulations are the most comprehensive technique. Unfortunately, buildings' simulated energy demands usually differ from the actual use. There are numerous uncertainties impacting buildings' energy demand, likewise, those parameters are usually strongly correlated. Therefore, parametric analyses are a valuable approach allowing us better understanding of various phenomena occurring in buildings. This article shows some preliminary results of the case study analysis for a residential building in Poland examining the impact of residents' thermal comfort on the buildings' energy performance. This study will be continued and expanded to fully understand the occupants' behavior impact on building energy performance. Studies like this are helpful for future building design, following the paradigm of sustainable development.

1. Introduction

People spend up to 90% of their life in buildings. Residential buildings should assure a comfortable environment for the occupants, provided in an efficient way. Building energy and environmental efficiencies are presently one of the most important research subjects due to the global climate change and the actual geopolitical situation. Buildings and their energy improvement are an essential part of the numerous long-term strategies for a more sustainable environment in the future, especially the ambitious EU strategies towards an environmentally neutral society by 2050 [1]. Yet, buildings consist of approximately one-third of energy demand and approximately 40% of total greenhouse gas (GHG) emissions [2]; thus, their impact on the ongoing global energy transformation is crucial.

Building energy performance, as well as occupants' thermal comfort can be analyzed using various methods, assuming different complexity of the applied model. Computational simulations (white-box modeling) are usually the most appropriate and comprehensive technique, while for some studies gray-box or black-box (e.g. Artificial Intelligence) modeling is found to be sufficient [3-6]. White-box modeling allows us to receive very precise outputs, which can be furtherly analyzed. The obtained outputs are not only assessing buildings' performance but also allow us to examine variable in time phenomena occurring in the examined objects, such as residents' comfort. Unfortunately, this method has several disadvantages. White-box modeling is always challenging, where detailed input data and expert knowledge are required. Also, computational simulations are time-consuming, and licenses of the applied software (e.g. Design Builder) are typically payable. Despite all the disadvantages, if performed appropriately, the computational simulations and parametric studies are a valuable source of knowledge on the examined field: the correlation between energy performance and occupants' thermal comfort [7-9].

Unfortunately, buildings' simulated energy demands usually differ from the actual energy use [10,11]. Out of numerous uncertainties impacting buildings' energy demand (e.g. its geometry, construction, systems applied, or weather data), the residents' impact seems to be usually neglected or underestimated. The role of occupants in the energy performance of buildings is still not fully investigated, let alone standardized. The occupants' impact on the building's energy efficiency has recently attracted much academic attention. It is highly probable, that occupants' impact, due to various feeling of thermal comfort, can be one of the main causes of the energy performance gap between predicted and actual building energy use [12]. The above-mentioned statement is especially valid for modern buildings, which are usually highly energy efficient and often with building management systems, where users can control the parameters of the indoor environment by adjusting the settings of HVAC and lighting systems.

In this article, we try to estimate the influence of some parameters, which affect both occupants' thermal comfort and building energy performance. This analysis is performed using white-box modeling, executed by means of parametric simulations obtained out of Energy Plus software. This study is performed for a case study designed as a prototype moveable single-family house. In total, 6600 computational simulations were performed, each with the hourly calculation step. A comprehensive outputs database was obtained, allowing us to examine the impact of exterior climate conditions (6 scenarios: 3 locations, 2 weather files each), building orientations (4 scenarios), and its' thermal insulation (11 scenarios), as well as set-point temperatures for heating and cooling purposes (5 scenarios each). Building energy performance was examined based on the calculated annual energy demands, while thermal comfort was evaluated based on discomfort hours obtained following the ASHRAE 55 standard [13]. Those types of studies might be helpful for future buildings design, considering sustainable development basis, focusing on the social, environmental, and economic aspects of buildings operation. Additionally, some of the obtained results might be helpful in terms of explanation for the potential performance gap between the predicted and actual energy use of buildings.

Figure 1. The examined portable residential house: (**a**) design visualization and (**b**) floor plan view in Design Builder.

2. The transportable portable house

The examined building is a transportable prototype house, which can be easily moved from one place to other. It has no basement, and its placement is usually performed on concrete blocks/frame, limiting contact with the ground. It is an energy-efficient building, providing all residential conveniences and various zones. The prototype building was in depth examined in 2022 to assess its energy efficiency, as well as users and environmental friendliness.

The examined building has a 78.3 m^2 useable floor area, consisting of a large living zone with a kitchen (46.1 m^2), two bedrooms (12.7 m^2 and 14.8 m^2), and a bathroom (4.7 m^2), as well as an unoccupied attic. The total glazing area is 10.8 m^2, distributed on two opposite walls. The building enclosure is designed with highly energy-efficient sandwich panels (R-value equals 5.58 m^2K/W) with an additional XPS layer (thermal conductivity λ=0.032 W/mK) as thermal insulation. An additional

5 cm of XPS was added to external walls, and 10 cm to ceilings and ground floor providing thermal transmittance (U-value) of 0.13 W/m^{2}K and 0.11 W/m^{2}K, accordingly for both ceilings and ground floor. This building has a complex HVAC system, consisting of electric radiators, split units, as well as supply and exhaust fans with heat recovery. Air conditioning is provided for all zones excluding the bathroom. It also has an energy-efficient lighting system with LEDs and standard housing appliances. The hot water system was not analyzed. All the above-mentioned information are based on the measurements of the prototype building. Within the performed measurements, the blower door test, thermography imaging, the U-value evaluations, as well as thermal and lighting comfort assessments were done following the national regulations and standards. Additionally, despite the fact, that this building is designed to be a moveable house, it fulfills all the Polish regulations for residential buildings.

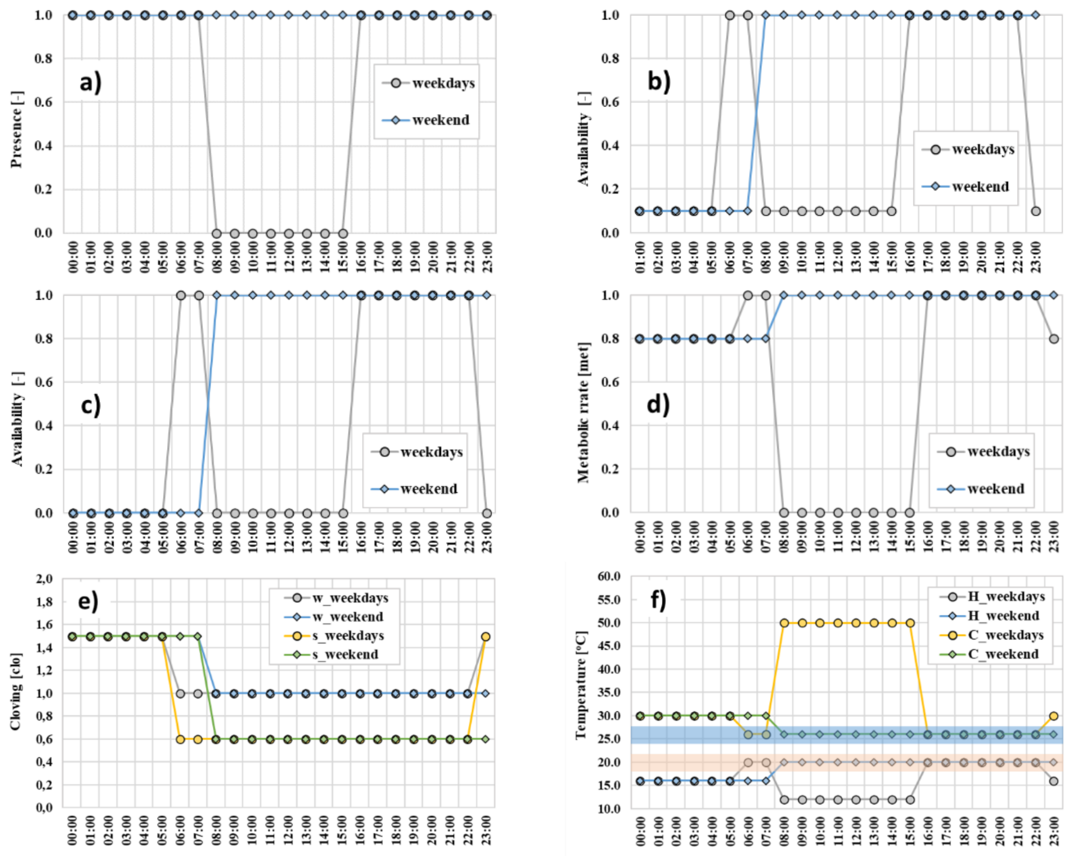

Figure 2. The assumed schedules for the examined house: (**a**) occupancy, (**b**) equipment availability, (**c**) lighting availability, (**d**) metabolic rate, (**e**) occupants' clothing, and (**f**) temperature setpoints for living zones.

The examined house was modeled using Design Builder software providing high conformity with the actual building (see Figure 1). Building enclosure, as well as the HVAC system were input in detail. Additionally, the nominal capacity of heating and cooling coils, as well as provided air flows and fan efficiencies were assumed respectively for each zone. The air infiltration rate was simplified as constant throughout the whole year, with the n_{50} index equal to 0.76 1/h (the result of the performed blower door test). The examined building enclosure is highly airtight (thermal bridges impact is marginal according to the performed thermography). The lighting system (power density and target illuminance) was assumed out of the performed measurements, adequately for each zone. Moreover, in the performed computation analyses, detailed hourly operation schedules were assumed (see figure 2) in order to precisely define the occupants' presence. It was set, that the family of 4 has a regular weekly schedule, assuming working/school on weekdays from 8:00 AM to 4:00 PM. The housing equipment is used following the people's presence, with marginal demands during nights and working hours. A similar schedule was assumed for the availability of the lighting system; it is controlled based on the natural lighting, by the 3-step control/switch (off/half-on/on). The human-related factors, in particular, metabolic rate and clothing were assumed precisely, with high consideration of the daytime, where 0 represents the time that people are outside. The metabolic rate considers occupants' activity throughout the day: light activity during daytime (equals 1.00 met), and relaxation during nighttime (sleeping, equals 0.80 met). The thermal resistance of the cloths depends on the day period, as well as the time of the year. The winter outfit was set as 1.00 clo, and summer as 0.60 clo, while throughout the whole year in the nighttime, it was set as 1.50 clo (occupants under the duvet).

Finally, schedules for heating and cooling setpoints were set for each zone. The default temperatures for all living zones were set as 20/16/12ºC for heating and 26/30/50ºC for cooling, accordingly for occupied/sleeping/unoccupied periods. The temperature management for the bathroom is much more limited: there is no air conditioning (no cooling setpoints), while heating setpoints differ only for occupied/unoccupied periods, with 24/12ºC temperatures.

3. Methods applied

The performed analyses were made using a computational simulation approach. The white-box model approach was considered the most appropriate for this study due to the needs and requirements of designers, as well as the availability of a large set of input data.

Firstly, the examined portable house was defined by means of Design Builder software, in accordance with the technical documentation, as well as measurement data (see more in section 2). The complex input data, as well as information from numerous consultations with designers, were used. Next, computational outputs were validated with all the available data. Finally, the obtained model was accepted, considering it sufficiently accurate.

Secondly, the simulation file was exported into Energy Plus format (IDF file) and then furtherly used for parametric calculations. The process was automatic, performed using a script written in Python language, allowing for looping the EP-launch software. The original IDF file was constantly overwritten, assuming a set of the examined parameters (see more in subsection 3.1). Comprehensive outputs out of each simulation were saved, focusing mostly on energy demands and occupants' thermal comfort. Saved results can be furtherly used in future studies, considering especially their granularity (hourly calculation step).

Thirdly, the obtained results were sorted considering their proper data management. This post-processing was performed using additional scripts written in Python language. The sorted outputs allow us to analyze the impact of the examined parameters on the buildings' energy performance, as well as occupants' thermal comfort.

The applied method is an effective approach allowing for complex assessment of various phenomena occurring in buildings. This method can be easily modified, as well as furtherly developed considering the current needs. Unfortunately, advanced computational simulations are time-consuming and require considerable computing power. Furthermore, the simulation outputs cover significant space on a hard drive, thus the range of performed calculations should be well-planned at the early stage.

3.1. Examined parameters

The first of the examined variables is the exterior climate. 3 different localizations were examined: Gdansk (a representative city at the Polish seaside), Lodz (a city located directly in the geographical center of Poland), and Krakow (probably the most tourist city of Poland, located in the South-Eastern part of Poland). This selection covers the most representative climates of Poland, excluding extreme conditions like in mountain regions. For each city, two EPW files [14] were used: the traditional weather files (obtained based on data from years 1970-2000), as well as more recent data (from years 2001-2020). The used EPW files can be found on the web [15]. The distribution of Dry Bulb Temperature (DBT), as well as total monthly solar radiations can be seen in figure 3. It can be seen, that for the all examined localizations the annual average temperature is higher now than in the past. Additionally, the annual amplitude of the temperature is generally shifting upward, observing warmer winters. Solar radiation is now usually greater than in the past. For the examined localizations the solar radiation growth was as high as approx. 14%. Surprisingly, the total solar radiations decrease for Krakow. Additionally, the sunny hours (a time when solar radiation occurs) for Gdansk increase by up to 15%.

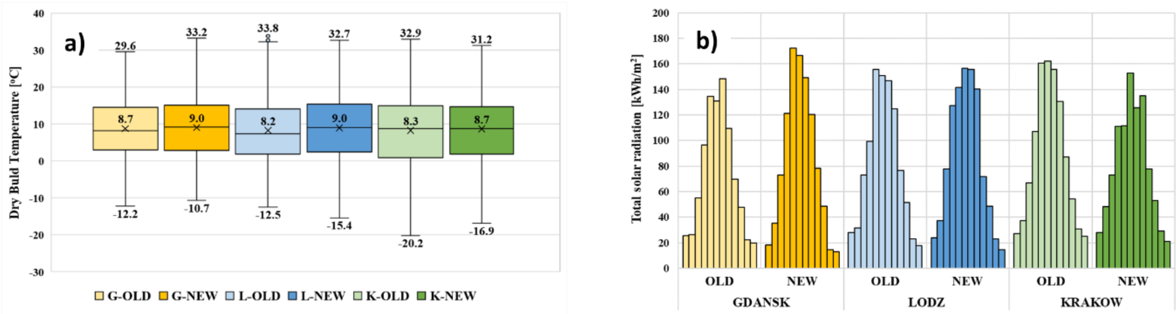

Figure 3. Comparison of the examined exterior climate conditions for the examined locations: (**a**) DBT distribution and (**b**) total monthly solar radiation during consecutive months.

The second examined parameter is building orientation. The original one (the same as for the building prototype) had facades with windows oriented East and West. 4 scenarios were assumed, considering the base orientation, as well as 3 positions rotated by 90, 180, and 270 degrees.

The third of the examined parameters is related to the thermal insulation of the main components of this moveable house. All these components (exterior walls, ceilings, ground floor) are based on the prefabricated sandwich panels, with PUR core (the R-value equals 5.6 m^2K/W). The examined variability of thermal insulation thickness is related only to the supplementary layer of the XPS added to each component: 5 cm for exterior walls and ground floors, and 10 cm for ceilings. The thickness was analyzed with 1 cm increment, providing 11 different scenarios of the thermal performance of the building enclosure.

The fourth and fifth parameters are temperature setpoints for heating and cooling respectively (see figure 2). For each set of temperatures, only the setpoints (temperatures during the occupied periods) were analyzed, considering the following ranges (changeable by 1°C): for heating in the range from 18°C to 22°C, and from 24°C to 28°C for cooling purposes. Thus, 5 scenarios for heating and 5 scenarios for cooling management were examined.

In total, 6600 parametric simulations were executed, each with an hourly calculation step. Out of all the outputs, the following parameters were collected for further analyses: heating, cooling, fans, and lighting demands (hourly and annual), as well as PMV index (hourly) and hours of discomfort (annual, based on [13]). Moreover, each of the simulated scenarios assumed the detailed schema corresponding to the occupants' behavior, in particular, their activity and how they are dressed; those assumptions are shown in figure 2.

4. Results

Firstly, the obtained results were examined considering the exterior climate conditions; a short summary can be seen in table 1. Energy consumption by lighting system (which maintains relatively constant for all the examined scenarios), as well as fans (depending on ventilation system efficiency, as well as air conditioning usage), are not examined individually. The total energy demand, i.e. heating, cooling, lighting, and fans supply combined (**T** in table 1) varied significantly, regardless the examined localization. The obtained results showed demand as low as 3894 kWh/a (the best thermal insulation, and less demanding setpoint values) and as high as 7065 kWh/a (building without additional thermal insulation and the most demanding setpoint values). The outputs varied even more for heating and cooling demands separately. The cooling demand (**C**) was as low as 256 kWh/a and as high as 1199 kWh/a, while heating demand (**H**) varied in the range of 776 kWh/a and 2621 kWh/a. The best comfort (**COM**) for the occupants was provided with only 1042 dissatisfied hours (out of 6672 occupied hours throughout the year) for the scenario assuming the best thermal insulation and 22°C and 24°C setpoint temperatures accordingly for heating and cooling purposes.

All the above-discussed outputs are also shown in figure 4. Those figures show that the exterior climate conditions have a huge impact on the obtained outputs. It can be concluded that higher comfort can be provided now rather than in the past: the mean and minimal values of dissatisfied hours are lower for outputs with the usage of present weather data (NEW) compared with older ones (OLD). Conclusions for energy demands are not so evident. Heating demands are lower for outputs using present climate data for all the analyzed localizations. Surprisingly, cooling demand for Krakow is lower for outputs with the present climate data, despite the noteworthy increases for Gdansk and Lodz. Additionally, an interesting comparison can be observed for total energy demands. A visible reduction in the observed outputs is noticed for Krakow, while for Gdansk and Lodz, the outputs are maintained at similar levels.

Table 1. Summary of the obtained results: impact of the exterior climate conditions on buildings' energy demand and occupants' comfort.

		GDANSK		LODZ		KRAKOW	
		OLD	NEW	OLD	NEW	OLD	NEW
C [kWh/a] [1]	min	277.6	256.1	342.1	363.9	418.5	315.8
	max	945.9	1103.5	1047.6	1193.0	1199.9	1108.3
H [kWh/a] [2]	min	837.5	776.4	964.6	943.9	1117.1	850.8
	max	2154.2	2025.9	2441.5	2307.6	2621.8	2239.7
T [kWh/a] [3]	min	3966.5	3894.6	4177.6	4207.8	4407.4	4091.6
	max	6376.0	6308.4	6721.1	6714.1	7065.1	6582.6
COM [h] [4]	min	1333	1042	1573	1437	1770	1512
	max	4765	4884	5033	4911	5029	4723

[1] Annual cooling demand [kWh/a]. [2] Annual heating demand [kWh/a].
[3] Annual total energy demand (heating, cooling, fans, and lighting combined) [kWh/a].
[4] Discomfort hours according to ASHRAE 55 standard [h].

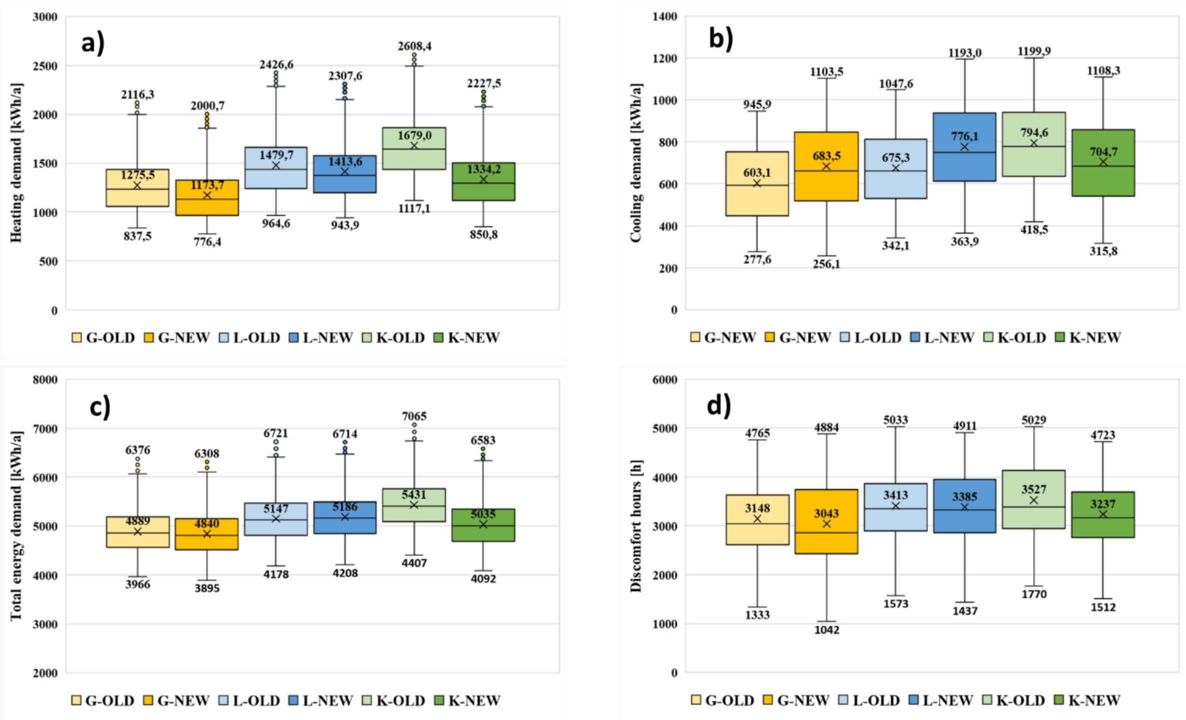

Figure 4. Summary of the obtained results comparing exterior climate conditions: (**a**) heating demand, (**b**) cooling demand, (**c**) total energy demand, and (**d**) discomfort hours.

Secondly, detailed analyses were performed to investigate each of the examined parameters. The impact of additional thermal insulation on energy demand and occupants' comfort is shown in figure 5, for all the examined localizations. The impact of thermal insulation on building energy demand is obvious, yet the outputs show, that despite the same parameters of building operation it impacts occupants' comfort as well. The above-mentioned shows the importance of other parameters related to building enclosures, such as thermal mass or temperature distribution on surfaces. The dependencies between occupants' comfort and energy demand are shown in figure 6, based on setpoint temperatures for heating and cooling purposes. It might be seen that the higher temperature for heating, and the lower for cooling, the better the occupants' comfort obtained. The best results, in terms of occupants' comfort, are obtained for setpoint temperatures of 22°C and 24°C respectively for heating and cooling.

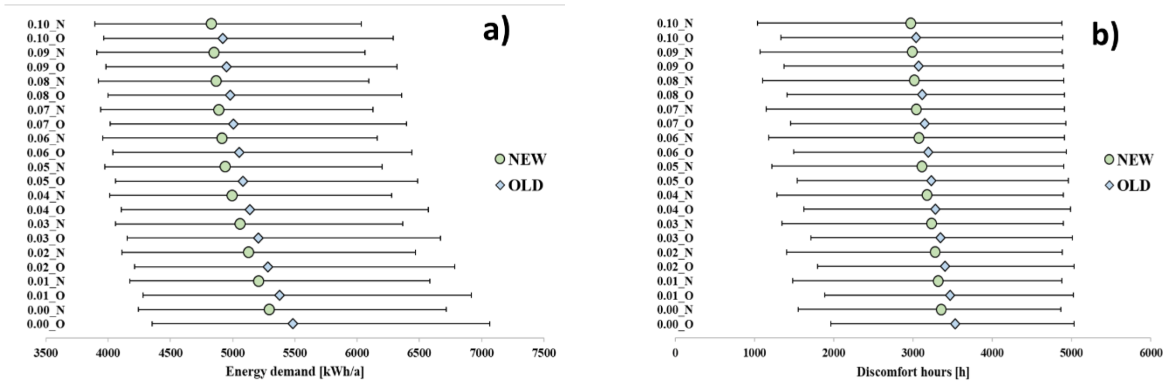

Figure 5. Impact of the additional thermal insulation of building enclosure components on (**a**) energy demand and (**b**) occupants' comfort.

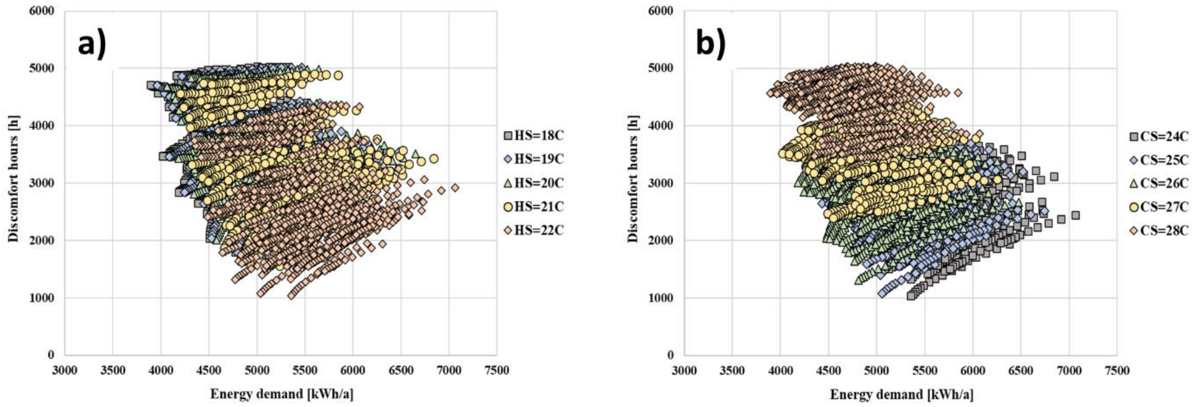

Figure 6. Impact of the setpoint temperatures of (**a**) heating (HS) and (**b**) cooling (CS) on energy demand and occupants' comfort.

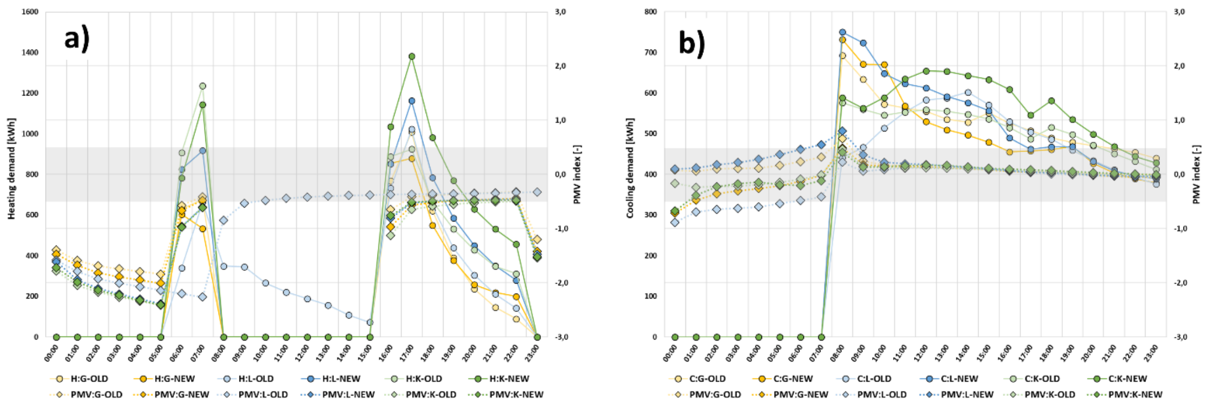

Figure 7. The PMV index distributions for the most demanding days in terms of (**a**) heating and (**b**) cooling demands.

Thirdly, the hourly distributions of the PMV-index are shown in figure 7, for the scenarios with the best results in terms of annual discomfort hours (best thermal insulation and 22ºC and 24ºC setpoint temperatures accordingly for heating and cooling purposes). The PMV values are shown with hourly heating and cooling demands, for a single day period. The selected day is the most demanding day throughout the year in terms of energy consumption (the highest observed demand) for the examined purpose. The range of the 2nd class of thermal comfort, according to [16], is shown in the gray range, screening the PMV values in the range from -0.5 to +0.5. It can be easily concluded, that 24ºC during the summer is a perfect temperature for the occupants of this study. Additionally, the 22ºC seems to be slightly too low for the occupants during winter with a given activity and outfit. Moreover, during the heating season in the nighttime, the occupants' comfort is not provided, despite the made assumptions. Finally, the ASHRAE standard [13] seems to be less restrictive in terms of occupants' comfort rather than the ISO [16].

5. Conclusions

The presented analyses were performed using computational parametric simulations. The moveable residential building was analyzed, considering several parameters affecting building energy demand as well as occupants' comfort. The above-mentioned parameters include exterior climate conditions, building orientation, and its enclosure parameters, as well as operational schemas. The obtained results show the preferable conditions to provide thermal comfort for the occupants, with the setpoint temperatures of 22ºC and 24ºC for heating and cooling accordingly. It also showed which parameters can be changed to improve occupants' comfort, simultaneously considering buildings' energy demand. Yet, this study also showed, that the examined field is much more complex, and it is affected by much more variables.

This article should be considered a preliminary analysis of a very comprehensive research subject. Building energy efficiency is now important more than ever, while occupants' thermal comfort is continuously gaining greater attention and importance. Authors will continue this topic throughout their upcoming analyses to examine more parameters and factors related to this subject, in particular, focusing more on occupant-related information, especially the operation patterns variability in order to evaluate the impact of occupants' behavior on the energy performance of a residential building, represented by a single-family house. Those types of studies can help to understand the residents' behavior impact on their thermal comfort and building energy performance.

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