The impact of size in fenestration design on the airflow and temperature in natural cross ventilation, case study: A two-bedroom Polish multifamily home

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This paper demonstrates the results of both thermal and airflow simulation of existing naturally ventilated in double-bedroom homes in Poland.

Due to climate change, the rise in temperature causes an increase for cooling demand to provide occupants' thermal comfort [1]. The increase in temperature, decreases the heating demand for buildings during winters [2], on the other hand, in summers energy consumption increase for cooling needs [2].

As over 40% of global energy use is accounted for by the building sector [3]; Application of architecture passive strategies, is more essential and crucial to undertake active cooling methods in order to provide thermal comfort [1]. The goal of passive design is to reduce the building's energy consumption. Also, as for passive cooling strategies, natural ventilation, solar shading and evaporative cooling, radiative cooling, and ground cooling [4] are the major studied strategies. This paper mainly focuses on natural ventilation during hot seasons in central European countries, especially Poland. Buildings consume roughly between 30–40% [3, 5, 6] of energy use in almost all countries around the world, while in Poland the precise number is among highest of 38% [7].

Utilizing large windows can minimize heating demand and allow for the use of solar heat gains in the cold season. Nonetheless, blinds should be installed for the summer months [8, 9]. But, the effect of large windows and the shading devices on hot seasonal thermal comfort and natural ventilation has never been studied before. While some researches [9] emphasize the need to study the effect of natural ventilation on environmental conditions and occupants' thermal comfort in future research. On the other hand, in Poland there are few design reviews or construction quality control for high-performance houses, including airtightness and ventilation [10]. Some good examples of these applied research in Poland are the Polish Ventilation Association [11] and the Polish Association of Wind Engineering (PAWE), which are mainly working on implementation of the ventilation and window standards in Polish construction regulations.

Natural ventilation (air currents without the use of fans) can be divided into two categories: wind-driven ventilation and stack or buoyancy-driven ventilation [4, 12]; The former relies on wind-induced pressure differentials and air inlets (fenestrations like windows and doors) in the building facade, while the latter results from convective flows originated by vertical temperature gradients [4]. Also as design point of view, it includes single-sided ventilation, cross ventilation, and stack ventilation [12] (fig. 1.).

Several research experiences have shown the potential of ventilation for cooling demand savings, ranging from 40% to 80%, depending on flow rates, climate context, and particularities of the building [13]. According to this research, Vertical Pivot window performs most effectively in terms of air velocity and airflow direction [14]. It should be noted that climate change and the importance of windows for better thermal comfort are global and many researchers investigated this issue all over the world [15], but this study tries to focus on large-scale apartments with real window sizes as well as their dimensions. This study addresses a research gap by investigating housing buildings with flat roofs and non-symmetric window placements. A detailed model is created, including internal walls and available windows in the Polish market. The study examines temperature and airflow in different areas of the house, considering solar radiation and worst-case scenarios for cooling.

Methodology

As the research process is shown below, this study includes 3 main steps: first theoretical framework and state of art second, input modeling and possible alternatives and analysis and finally Part 3: Analyzing the outcomes.

In the first stage, weather data in some important cities in Poland was examined. The

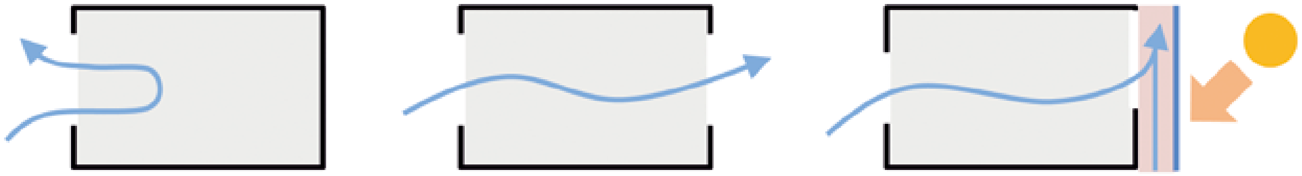

Fig. 1. Natural ventilation: single-sided ventilation (left), cross ventilation (middle) and stack ventilation (right); source: [4]

worst (hottest) scenario is for to July 2022. On this day, the air temperature of most cities in Poland are as for Warsaw 35,5°C, Poznan 37°C, Gdansk 35°C, and Krakow 36°C, the relative humidity is between 50–60% and the minimum wind speed is between 3–4 m/s (fig. 3.).

The Polish housing is classified based on four archetypes: single-family houses, terrace houses, multi-family houses, apartment blocks [10], but the Polish residential building is dominated by two types: multi-family houses in dense urban regions by 37% and single-family houses in rural and low-density areas by 36% [17, 18]. This study includes the study of more than 25 residential complexes in different regions of Poland. These are based on library study mainly Polish architecture magazines, books and reports called ARCHITEKTURA (1945–2022). In total, more than 300 types of housing studios (no bedroom), one-bedroom, two-bedroom, three-bedroom and four-bedroom residential unit plans were included. This information categorized by the location, size (bedrooms), year of construction/design, type of possible ventilation (cross ventilation or single-sided ventilation), and organization along the façade as shown below.

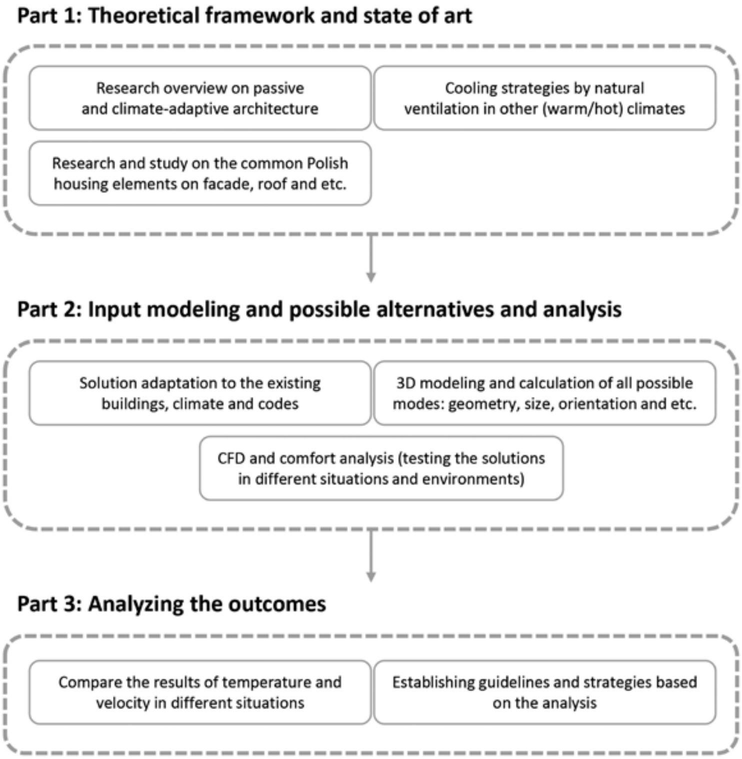

Fig. 2. The research processes

The graph shows that two-bedroom housing units have cross ventilation potential, while single-bedroom and flats typically have single-sided ventilation potential. Based on interviews with architects and experts, the most commonly used types of windows in Poland were selected, with two different sizes: 120 cm wide by 150 cm high and 150 cm wide by 150 cm high. A 3D model was generated, considering the fenestrations such as window size and solar protection. Test models were created with different window protection options, including base model, horizontal louvres, and overhangs (fig. 4.).

To facilitate the presentation of results, each model has been named briefly as shown in the table 1.

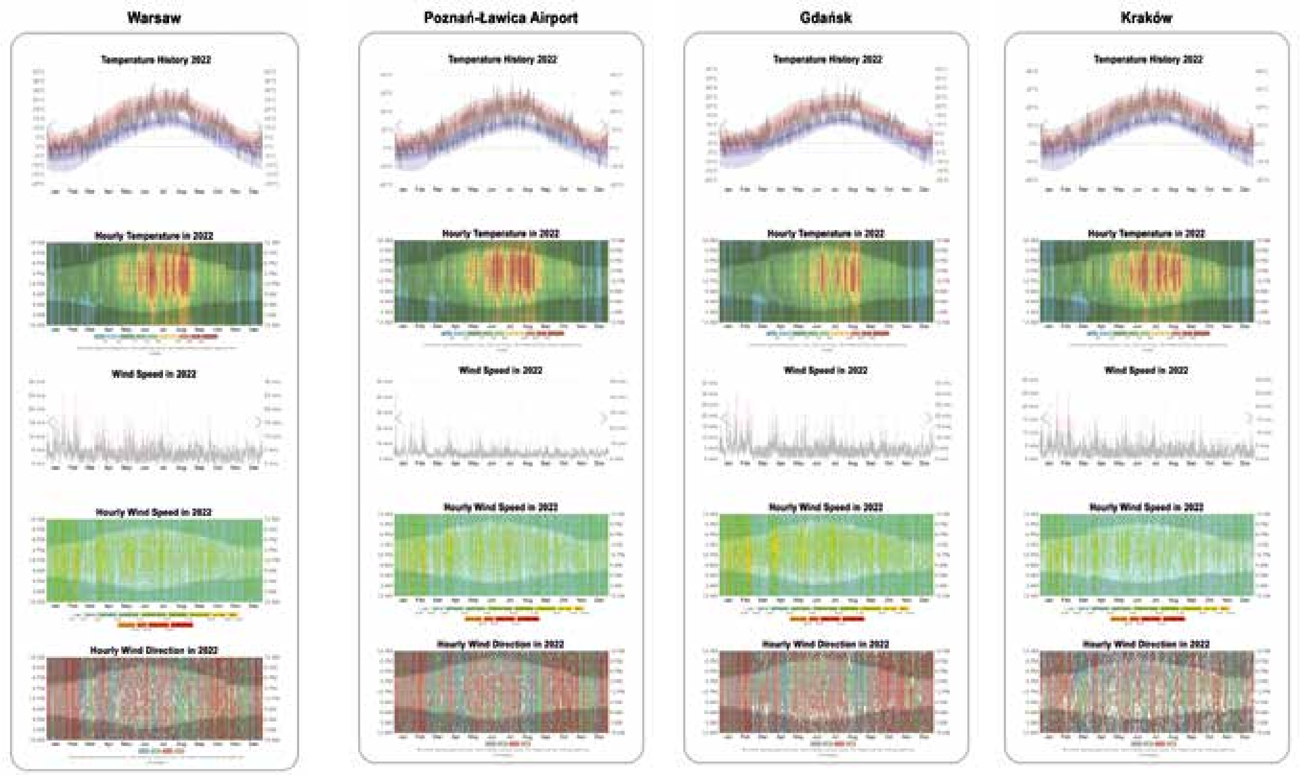

Fig. 3. Climate data for main Polish cities (Warsaw, Poznan, Gdansk and Krakow); source: [16]

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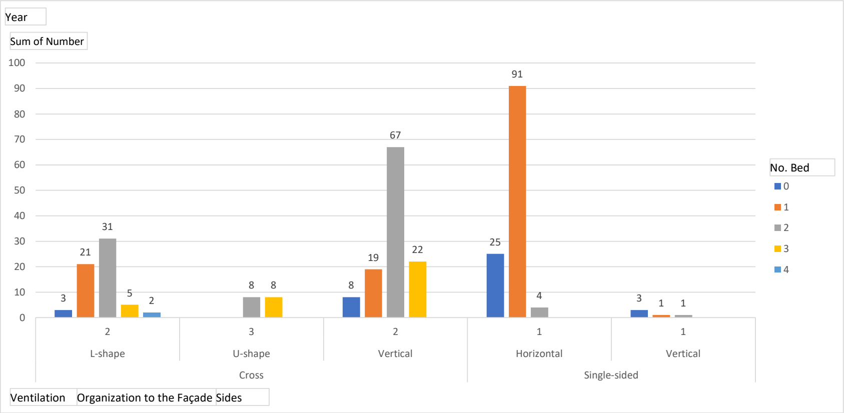


Graph 1. The frequency of each type according to the type of natural ventilation

Table 1. The given names of each model

	Small window (S)	Big window (B)
Base model (BA)	S-BA	B-BA
Shading devices (overhangs and side fins) (SH)	S-SH	B-SH
Louvers (LO)	S-LO	B-LO

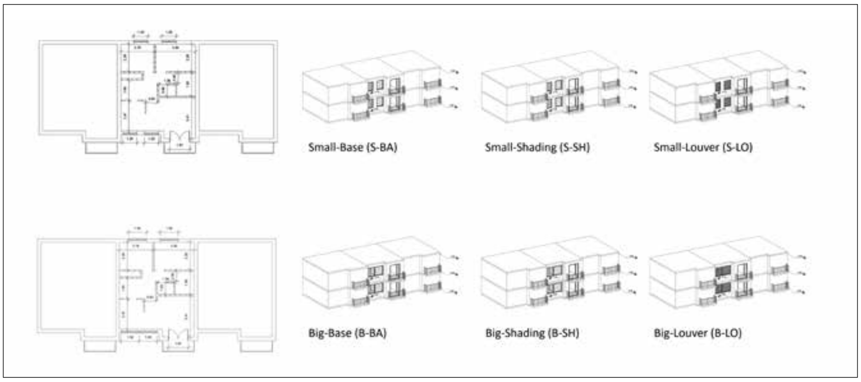


Fig. 4. Plan and 3D model of the 2-bedroom house with the potential of cross ventilation

Model geometry and boundary conditions

For the design and evaluation of cross-ventilation in buildings, a reliable CFD simulation of combined external wind flow and indoor airflow is required [19]. Cross-ventilation, may be modeled in two basic ways: the decoupled method and the coupled method. A decoupled approach necessitates the use of two sets of CFD models: one for external space and one for internal space. After calculating the outdoor airflow field, the second stage involves performing an indoor CFD simulation by using the outdoor pressure profiles at the opening positions as boundary conditions for the indoor model [12, 19]. As a result, current research replicates cross ventilation across wide openings using a coupled technique. Because the coupled CFD simulation includes both indoor and outdoor regions in the same computational domain.

Simulation process has been taken place using a CFD software from Autodesk (Autodesk CFD 2019). After modeling cases, a typical city block should also be modeled. All the building blocks have the height of a two-story building. The top floor represents the highest floor of residential buildings that receive solar heating from the roof, and the ground floor represents other normal floors of the building. The whole block including the neighbors is located in a model of an urban area, which simulated based on a high-density city standard.

Model features (boundary condition and materials)

The cases were modeled on a boundary with a domain size of 6d, 5w, 3h, where d is modeled length, and h and w are the height and width, respectively. The dimensions were selected following former studies and Autodesk recommendations (fig. 5. and 6.).

The ratio of the building height to the street canyon width has been set by the Polish code of residential buildings like considering the minimum distance between the wall with windows and/or doors from the plot border/neighbor blocks in the worst-case scenario. The second parameter that was taken into consideration was the building aerodynamic standard, where the distance between the building blocks should not considered greater than their height. This causes more static flow behind the building and the worst ventilation conditions. Then, the model has been placed inside a volume of air with the inlet air velocity of 3 m/s with the temperature of the hottest day (37°C) and relative humidity of 50%, the outlet gauge pressure has been set to 0Pa and the other four faces of the boundary condition has been set to be slip/symmetry. The simulation has been executed to 6 types in 8 different orientations (0=N, 45=NE, 90=E, 135=SE, 180=S, 225=SW, 270=W, 315=NW). Glass material was used for the windows, and UPVC material for the window frames. For balcony railings, wood material and concrete construction elements were applied for the rest.

Results and discussions

Here the results are presented based on the wind direction toward the model. The final results include the evaluation which is the presenting of the accuracy the data measured by CFD comparing with the other CFD simulations or experimental data [21]. In this research evaluation is done by repeating the simulation on DesignBuilder software and comparing the results related to air temperature, wall temperature, and the airflow rate.

Wind angel 0:

Among the 6 different modes examined on the ground floor, the cases with large windows generally had the better performance. The base model with big windows (B-BA) has the most stable temperature behavior between 36°C and 36,5°C. With the addition of the overhangs (B SH), the maximum temperature reaches slightly more than 36°C, with the difference in some areas, in which

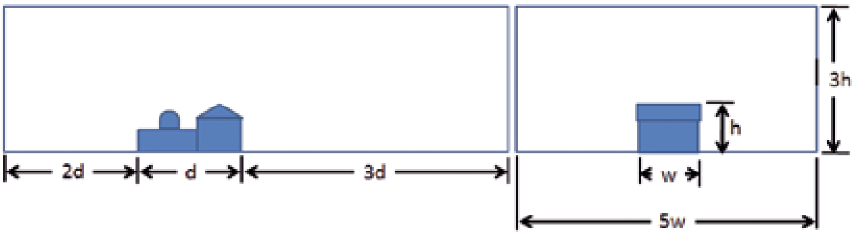


Fig. 5. Relation between built environment geometry and boundary condition size using recommended relative dimensions and proportions by Autodesk CFD; source: [20]

the temperature drops to about 34,5°C. While all the models with small windows had a temperature above 37°C (outdoor temperature). Even in some areas, the temperature rises to 39°C. In the living room, the graphs show that the use of a larger window reduces the temperature by more than 2°C, i.e., to about 33–35°C. Among these three models, louvered windows (B-LO) performed better for the minimum temperature.

In terms of airflow in rooms, small windows had also the worst performance. Only in front of the window in the rooms with small windows model (S-BA), the air speed reaches about 0,7 m/s, and in the rest of the room, the airflow speed is about 0,1 m/s. In general, large windows have relatively more stable performance, the best example of which is windows without solar protection (B-BA). After that, there are cases with louvers and then with shadings. In the living room, except for the small shaded window model, which has a more balanced air distribution but with low velocity, and the small louvered window model have the worst performance; Other models convey similar behavior, with an unbalanced airflow of 0,2–0,35 m/s (very low) in the kitchen, and maximum between 0,6–0,8 m/s in the living room to a minimum of 0,05 to 0,1 m/s.

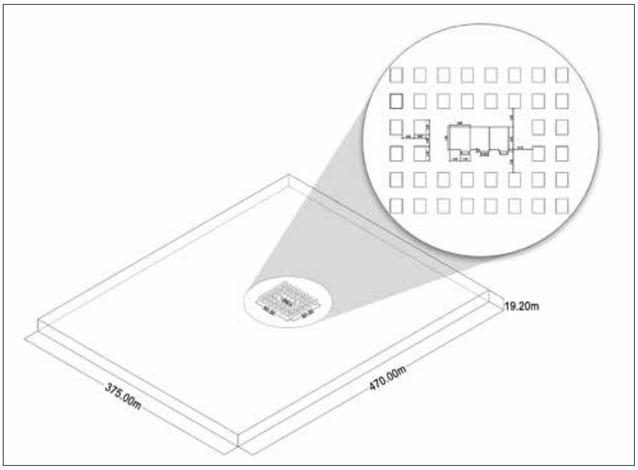
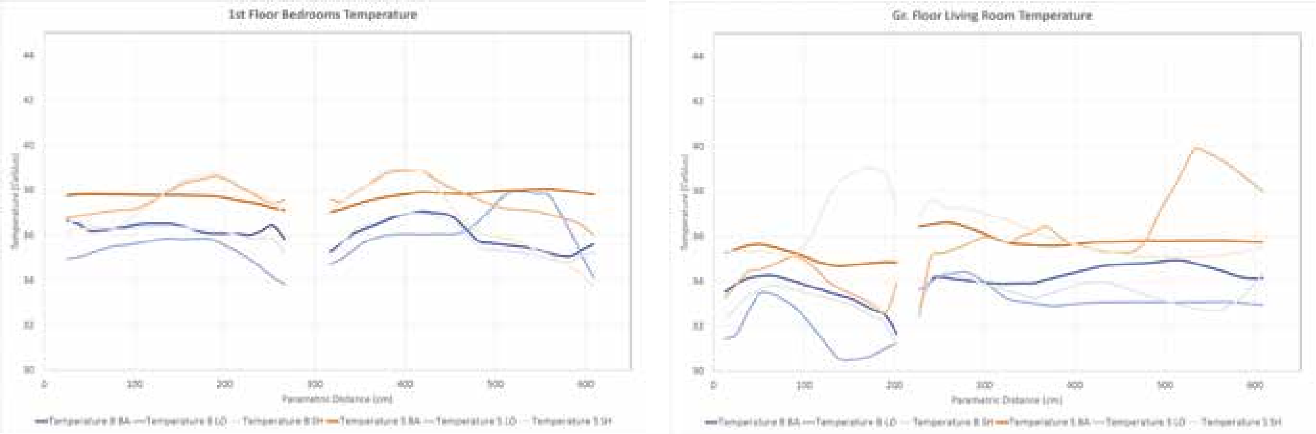
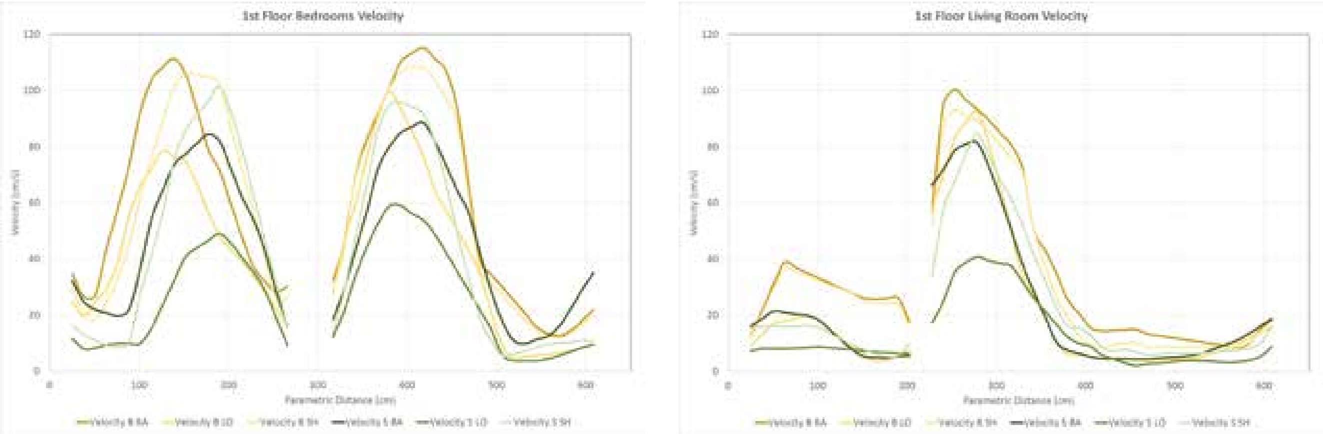


Fig. 6. Boundary condition and neighborhood units and how to place the model in dense urban space



Graph 2. and 3. Temperature data for the rooms (left) and the living room (right) located in ground floor



Graph 4. and 5. Velocity analysis for the rooms (left) and the living room (right)

On the first floor, in front of the windows, there is a significant increase in temperature caused by the entry of outside air. Except this, the increase in temperature can be seen in the part of the room with a louvered big window (B-LO) model. In other cases, temperature changes are almost stable. Among the 6 modes, the models with large windows with louvers, shadings, and without sun protection (B-LO, B-SH, and B-BA) respectively have a relatively lower temperature (about 36°C), while models with small windows experience higher temperatures (37–39°C) than the outdoor temperature.

In the living room, the situation is the same, the louvered sample with a large window (B-LO) recorded the lowest temperature of 33°C, and other options with a large window (B-BA and B-SH) have a temperature of 34–36°C. All small window models reach the outside temperature in this scenario.

Regarding the airflow, in the rooms, the large window base model (B-BA) and shaded one (B-SH) have the better performance with a speed of 1,0 to 1,1 m/s. The worst performance in terms of speed and airflow is related to the small louvered window (S-LO), which both provides a lower air speed and affect less space in the room with natural ventilation. Living room airflow Improved in large window cases. The best is the base model and the shaded model with a difference of 0,1 m/s.

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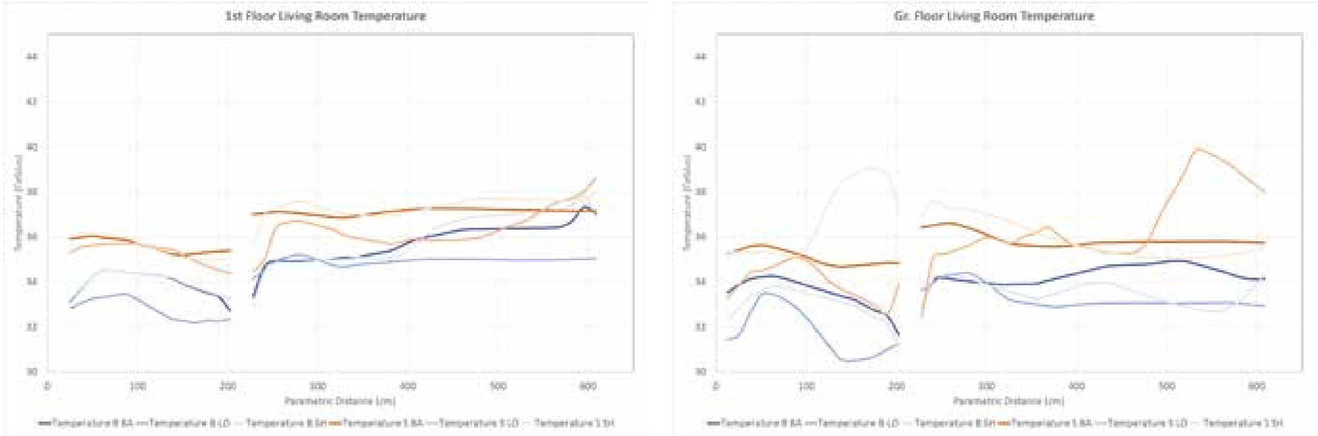
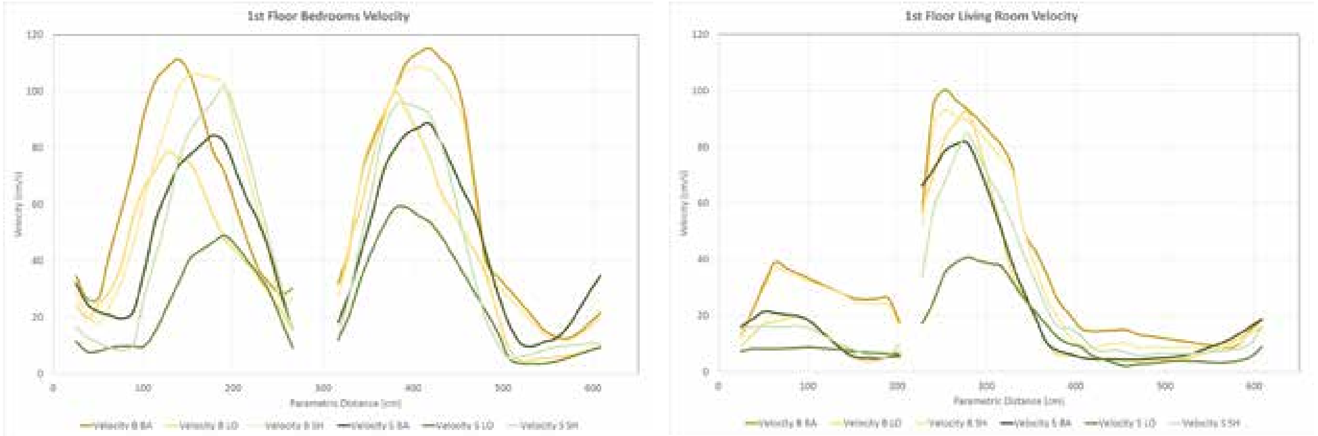
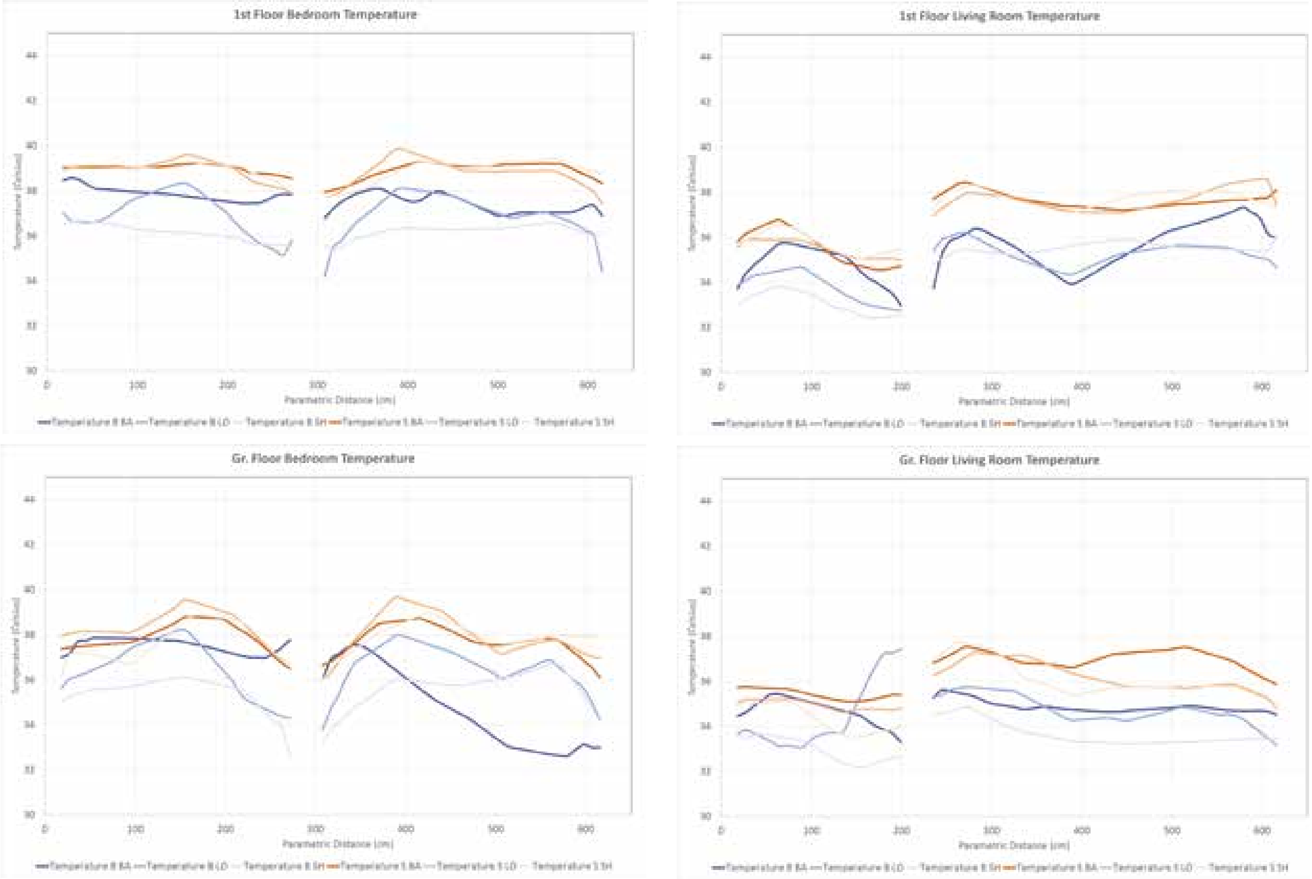


Graph 6. and 7. Temperature data for the rooms (left) and the living room (right) located in 1st floor



Graph 8. and 9. Velocity analysis for the rooms (left) and the living room (right) in 1st floor

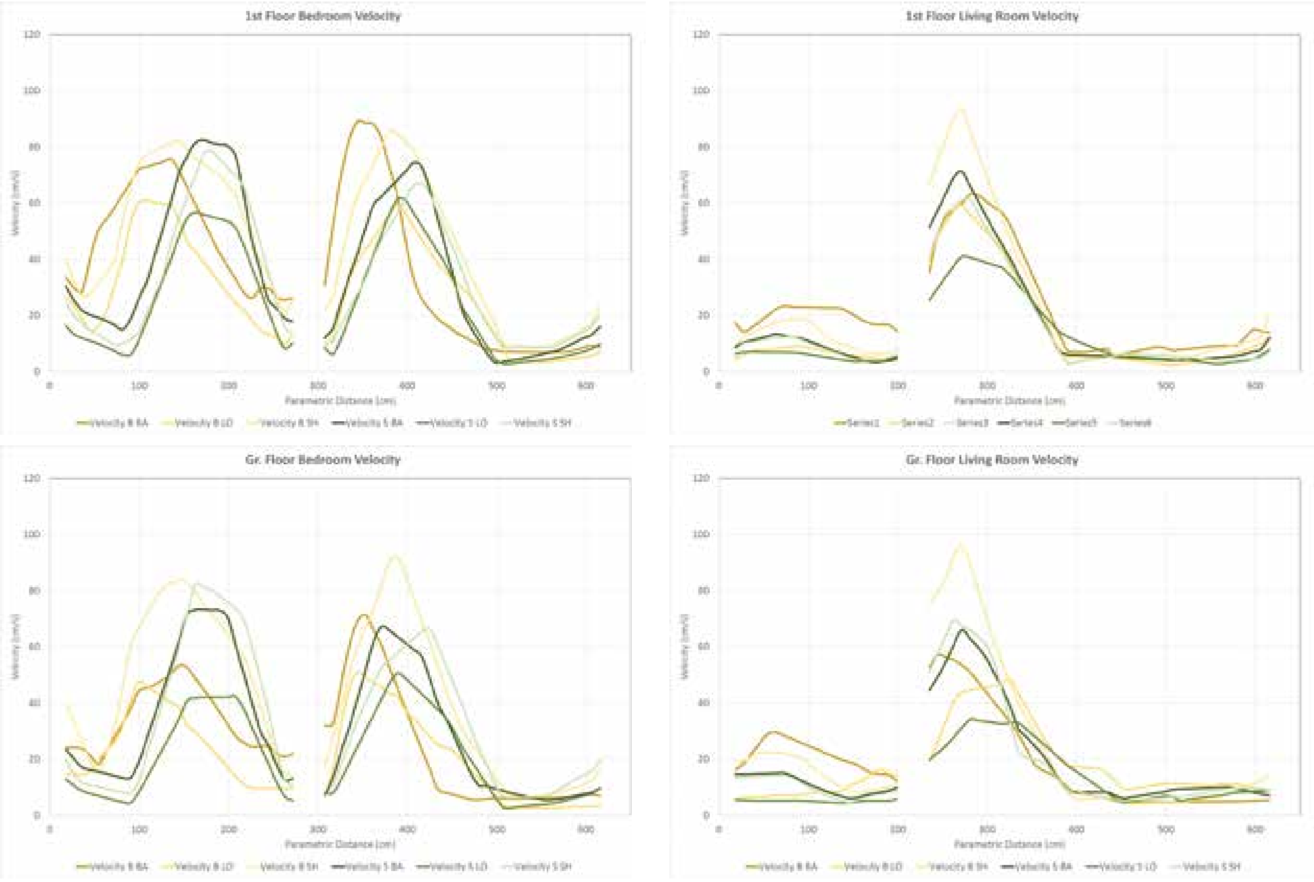


Graph 10–13. Temperature analysis for the rooms (left) and the living room (right)

Wind angel 45:

The analysis of the temperature outputs in the rooms shows that the large window model with overhangs (B-SH) has the best performance with a temperature of about 36ºC. After that, the base model (B-BA) and then large windows with louvers (B-LO) with a temperature between 37ºC and 38ºC are in second place. On the ground floor, the base model had a significant temperature drop of 4ºC. In the living room, the sample with the shading (B-SH) documented the lowest temperature (33–34ºC). After that, there are the large louvered window (max. 36ºC), and the basic model (max. 37ºC).

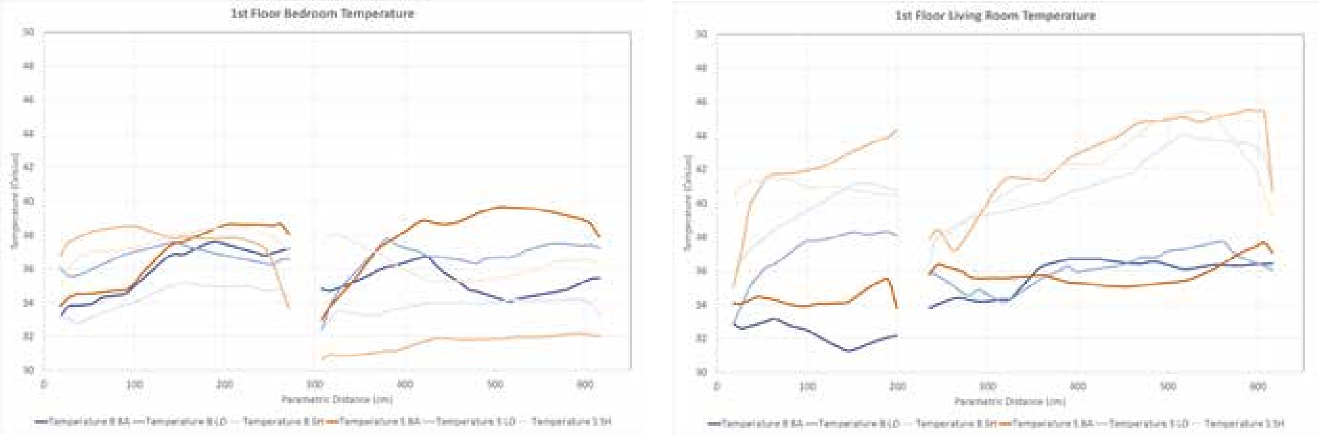
As airflow, overhanging big window model (B-SH) performs better. The airspeed in these models in the room reaches about 0,9 m/s; And in the living room, it arrives at a maximum of around 1 m/s. In addition, the distribution of airflow in this model is much better, and more space in the room is affected by natural ventilation. Sometimes, following the shaded model, the big window base model (B-BA) also shows as good performance as the B-SH model. In these analyses, both louvered models always provide the lowest airflow speed (max. 0,5 m/s).



Graph 14–17. Velocity analysis for the rooms (left) and the living room (right)

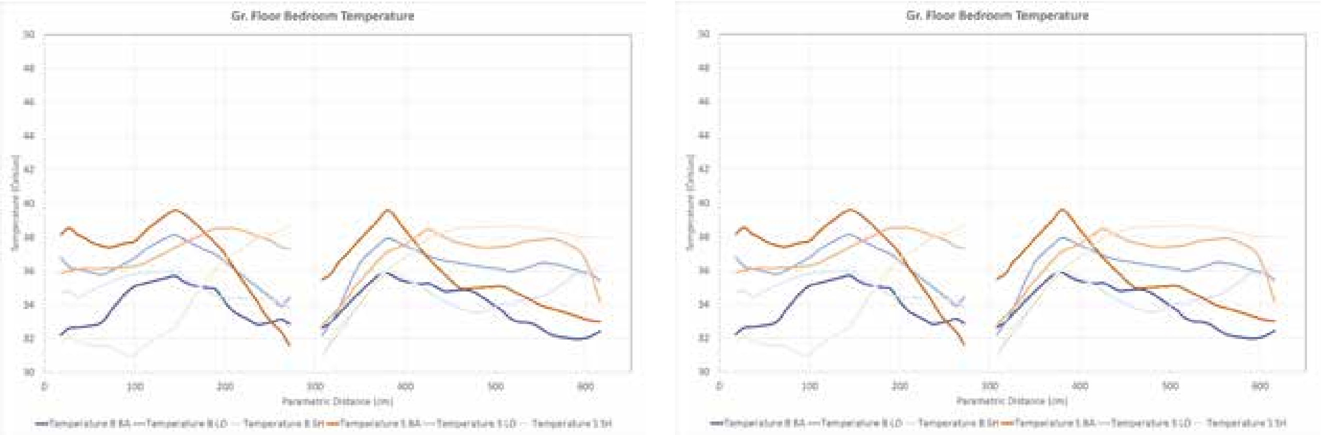
Wind angel 90:

In models where the wind blows with an angle of 90 degrees, a lower temperature of 34–36 is made in rooms with large shaded windows. In this situation, the base model also works well. Due to the location of the entrance windows in the wake region, rooms experience highly inefficient and unpredictable functions when using louvers. In the living room, the basic model, which provides more ventilation volume, has better efficiency, and in this model, the temperature is reduced to at least 32ºC. This number reaches a maximum of 34ºC with the addition of the canopy on the ground floor.

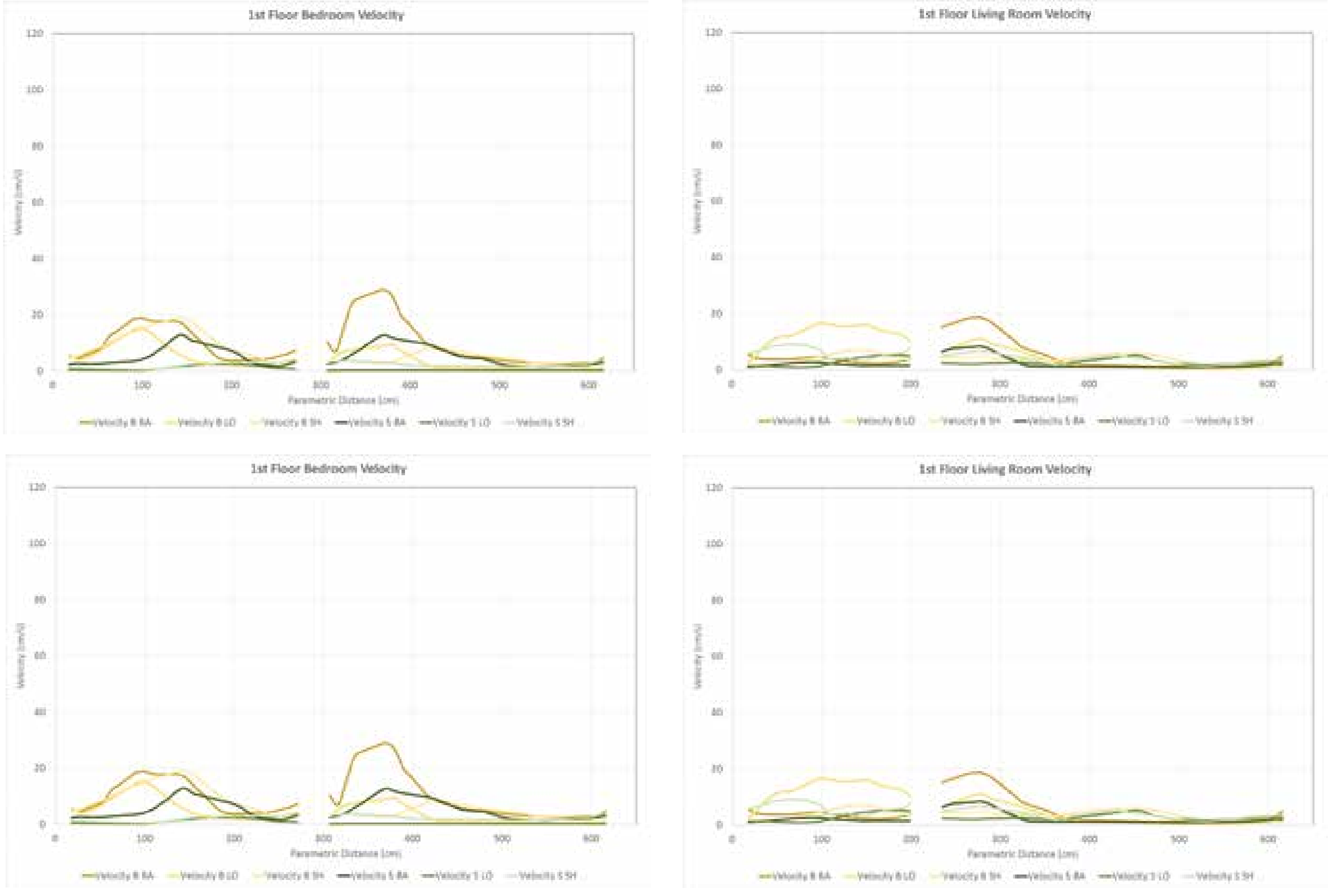


Graph 18–19. Temperature analysis for the bedrooms (left) and the living room (right)

Regarding air flow, in all cases, the basic models with large windows had better efficiency, but it should be noted that in this scenario the maximum air flow is 0,3 m/s, which is completely insignificant. In this situation, the models with overhangs can work close to the basic model in some cases.



Graph 20–21. temperature analysis for the bedrooms (left) and the living room (right)

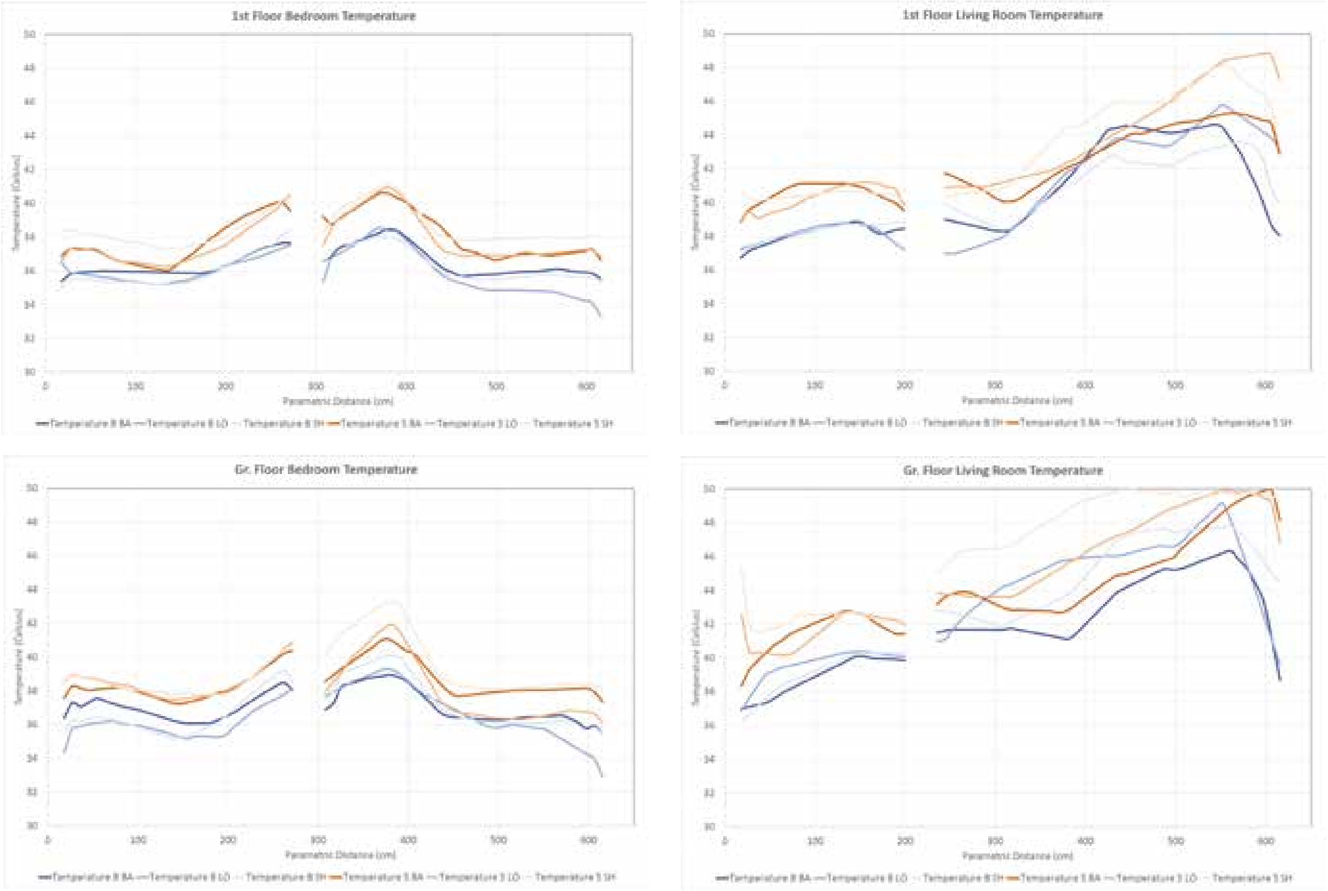


Graph 22–25. velocity analysis for the rooms (left) and the living room (right)

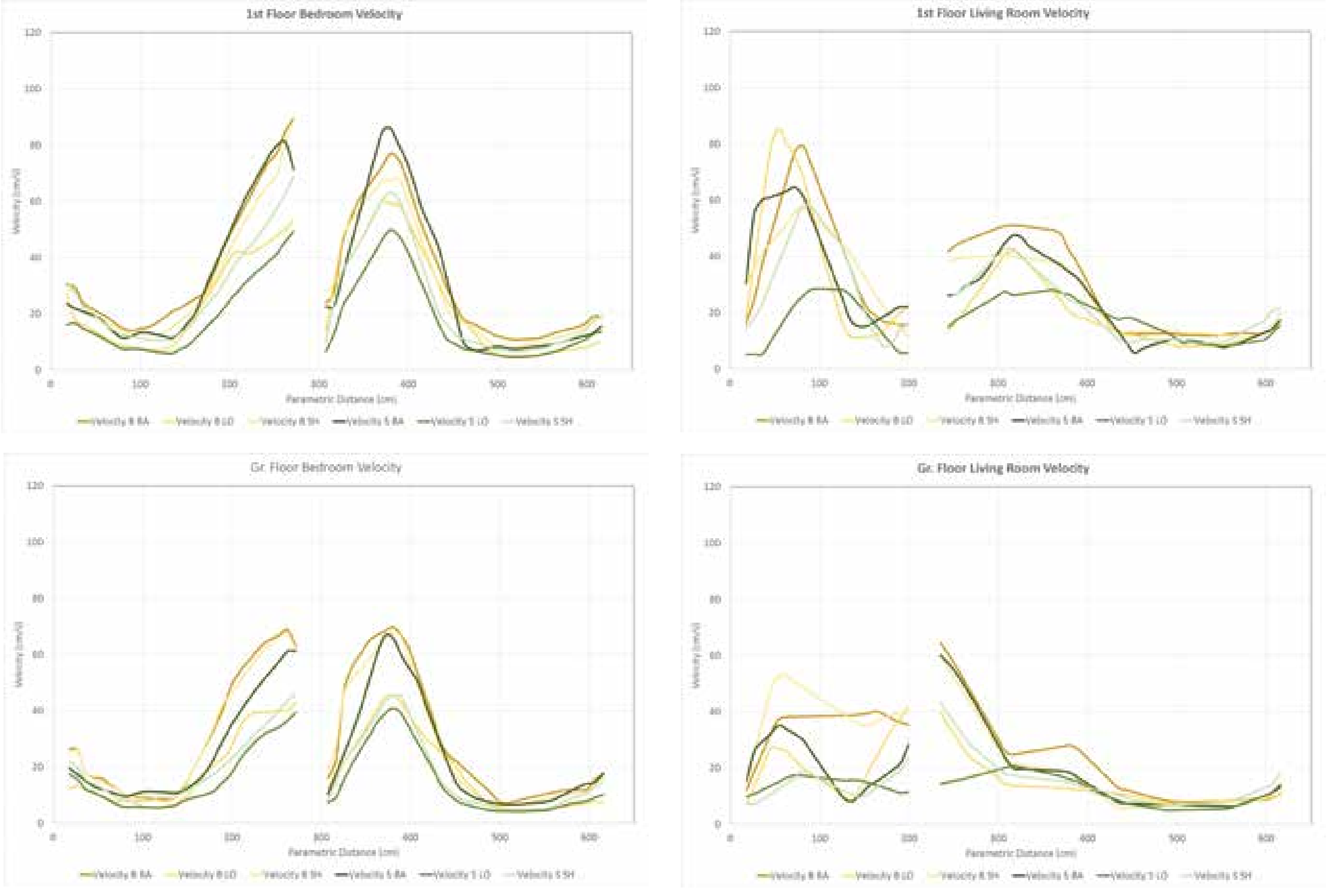
Wind angel 135:

In this scenario, large windows have better performance and keep the room temperature in a lower range. The performance of different cases is not very different and only slightly better conditions in sun-protected rooms. In the living room, large windows behave similarly, but here the base model shows a slightly better performance. In this scenario and also later scenarios, the air enters the building from the side where the walls and other components of the building such as windows and solar protectors are exposed to the sun and this heat enters the house. Therefore, the importance of using shading devices is better understandable.

Airflow speed is also higher in models with large windows. The performance of all three models is close to each other, but since there is no obstacle against the wind in the base model, the speed is a bit higher. But the difference is not really significant. The speed of airflow in the rooms on the ground floor is about 0,7 m/s and 0,9 m/s on the first floor. In the living room, the large window model works best.



Graph 26–29. temperature analysis for the bedrooms (left) and the living room (right)



Graph 30–33. velocity analysis for the bedrooms (left) and the living room (right)

Wind angel 180:

In the scenario of 180 degrees, the temperature of large windows is still significantly lower than that of small windows. In these cases, in some situations, the performance of large windows with louvres (B-LO) is the best. The temperature of the living room in this simulation with big windows is between 36-38°C and in the rooms it reaches 34-36°C.

The speed of the air flow is higher for the models with big windows of the base and shaded models (B-BA and B-SH) and shows a better air distribution. This variable was measured between 1 and 1.1m/s in the room and 1.2m/s for the living room.

Wind angel 225, 270 and 315:

Due to the fact that the outputs and results of the analyzes at angles higher than 180 degrees were very similar to their counterparts, we will not describe them separately. It should be noted that the results at the angle of 225degrees were similar to the results at 135degrees. Also, the conditions in 270degrees were very close to 90degrees. Finally, the results of the case outputs at 315degree were similar to the 45degree case. Below are the pictures of each of these studies (225, 270 and 315). All the research process, data and graphs are presented in the link [22].

Conclusion

Design strategies must be reconsidered to address the effects of climate change. This study explored small-scale solutions to improve thermal comfort. Results base on evaluation showed that larger windows had a positive impact on air temperature and flow in most of the 48 samples tested. Adding sun protection with overhangs further enhanced this effect. Generally, temperature in living rooms is lower when the inlets are bedroom's windows, in these cases usually large windows perform better both in temperature and velocity. Also, other general conclusion to make is that ground floor temperature is lower because of the protection against solar radiation; and airflow is relatively less than the first floor. But the airflow pattern and temperature distribution is almost the same in both floors. This shows the importance of the effect of the windows and their features to the variables.

Two places are vulnerable to the high temperature, areas in front of the inlet windows (also hallway in this case because of the venturi effect), and areas far from the inlet or outlet windows or better to explain the areas hard to ventilate. In both cases the larger windows help a lot to reduce these areas with high temperature. The focus in this study is more on these areas as the temperature fluctuation is not comfortable so the aim in analysis was to optimize it.

Finally, two more point to mention; First, the shoe box models (models with just a box as a room of a house, with fixed dimensions that even are not common in architecture, and also the unrealistic size and location of the windows) are not useful for making decisions in the field of architecture. This research method, which is very common in the field of mechanics, cannot be used in architecture. This research shows that there are many other important variables in architecture like solar radiation, indoor walls, air inlet direction, and the floor (here ground and 1st floor studied) that effect on the temperature and air velocity. Secondly, louvers and sometimes overhangs are not suitable because of solar radiation and should be used carefully.

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PRAWIDŁOWY SPOSÓB CYTOWANIA
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Abstract: In countries with cold winters such as Poland, there is growing evidence for proliferating overheating in summer times due to climate change. Hence, buildings become more uncomfortable for their occupants during hot summers. To tackle this challenge, we use the passive strategies potential to adapt buildings in line with their experimental and engineering analysis of the indoor environment. This paper demonstrates the results of both thermal and airflow simulation of existing naturally ventilated in double-bedroom homes in Poland. Thermal and airflow simulation is used to improve the natural ventilation system and to address summer thermal comfort problems due to excessive hot airflow caused by climate change. In the first step of the research, over 300 multi-family home plans all over Poland were categorized by size, ventilation type, facade organization, and fenestration type. In the second part, computational fluid dynamics (CFD) analysis is used on 3D models to predict indoor airflow velocities for different levels of the building envelope airflow permeability. Then, a coupled thermal and airflow simulation with 2 different window size, fully open, and with 3 integrated shadings options (base model or no shadings, 30 cm overhang with side-fin, and 10 cm depth horizontal louvers) are done to investigate whether the more opened envelope reduces a summer overheating problem. The results for the optimized natural ventilation through fenestrations successfully address houses' summer discomfort problem by reducing the indoor temperature between 2–3°C and in some cases up to 4°C cooler than similar model with small windows.

Keywords: Passive strategies, Natural ventilation, CFD simulation, polish multi-family home

Streszczenie: WPŁYW WIELKOŚCI PROJEKTOWANYCH OKIEN NA PRZEPŁYW POWIETRZA I TEMPERATURĘ W NATURALNEJ WENTYLACJI KRZYŻOWEJ. STUDIUM PRZYPADKU: MIESZKANIE DWUPOKOJOWE W ZABUDOWIE WIELORODZINNEJ W POLSCE. Z powodu zmian klimatu w krajach o mroźnych zimach, takich jak Polska, pojawia się coraz więcej dowodów na coraz częstsze przegrzewanie się pomieszczeń w okresie letnim. Dlatego budynki stają się bardziej niewygodne dla ich mieszkańców podczas upalnego lata. Aby sprostać temu wyzwaniu, wykorzystano potencjał strategii pasywnych do adaptacji budynków zgodnie z ich eksperymentalną i inżynierską analizą środowiska wewnętrznego. W artykule przedstawiono wyniki symulacji termicznej i przepływu powietrza w istniejących polskich mieszkaniach dwupokojowych z naturalną wentylacją. Symulacja termiczna i przepływu powietrza służy do poprawy systemu naturalnej wentylacji i rozwiązania problemów związanych z komfortem cieplnym w lecie, spowodowanych nadmiernym przepływem gorącego powietrza związanym ze zmianami klimatycznymi. Na pierwszym etapie badań ponad 300 projektów domów wielorodzinnych z całej Polski zostało skategoryzowanych pod względem wielkości, rodzaju wentylacji, organizacji elewacji i rodzaju okien. W drugiej części analiza obliczeniowej dynamiki płynów (CFD) była wykorzystywana na modelach 3D do przewidywania prędkości przepływu powietrza w pomieszczeniach dla różnych poziomów przepuszczalności powietrza przez powłoki zewnętrzne budynku. Następnie przeprowadzano połączoną symulację termiczną i przepływu powietrza z dwoma różnymi rozmiarami okien, całkowicie otwartymi, i trzema zintegrowanymi opcjami zacienienia, aby zbadać, czy bardziej otwarta powłoka budynku zmniejsza problem przegrzania mieszkania w okresie letnim. Wyniki pokazują, że zoptymalizowana naturalna wentylacja przez okna skutecznie rozwiązuje problem dyskomfortu w domach latem, obniżając temperaturę wewnętrzną o 2–3°C, a w niektórych przypadkach nawet o 4°C w porównaniu do podobnych modeli ze standardowymi oknami.

Słowa kluczowe: architektura wielorodzinna w Polsce, wentylacja naturalna, strategie pasywne, symulacja CFD