Passive Design Strategies for the Improvement of Summer Indoor Comfort Conditions in Lightweight Steel-Framed Buildings

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Abstract

The market for lightweight construction systems is growing rapidly due to their potential in terms of prefabrication, ease of transportation and assembly. However, given their thermophysical properties, these types of structures present a limited thermal capacity that may reduce their performance in terms of comfort and energy consumption during the hot seasons. The present paper, through a series of computational fluid dynamics (CFD) simulations, offers a numerical assessment of the performance of an existing lightweight steel-framed building selected as a case study. The data required to perform the simulations are collected with a deep monitoring campaign and the building is analysed in its current state (actual conditions of use) and after the application of simulated passive cooling strategies. The role of natural ventilation, both day and night, is explored by investigating different opening/closing configurations of external windows and internal doors. Moreover, the positive effects of surface thermal mass and shading systems are numerically validated. The results, although limited to a specific context of analysis, show that, with appropriate adaptation strategies, even in lightweight buildings, occupants can achieve adequate levels of comfort, thus reducing the need for cooling. A combined and weighted use of passive solutions results in a reduction of about 3 °C in the average daily indoor temperature. Ventilation at night and solar shading during the day make a steel-framed building as comfortable as a massive one, both with regard to the internal surface temperature of the building components and to the discomfort indices. Changing the mass of the interior cladding of a wall, ceiling or floor, for example, from plasterboard to cement board, is another effective cooling strategy.

1. Introduction

Reducing costs, increasing speed, and minimizing risks have always been the main objectives of the construction industry. Buildings are therefore increasingly made up of standardized and performance-guaranteed components, both considering the systems and the envelope. The market for lightweight steel-framed building systems (LSF) has thus greatly increased over the last few decades, especially in low-rise residential buildings. Several advantages have driven their spread: ease and speed of on-site installation, low weight combined with high mechanical strength, large potential for recycling and reuse, easy prefabrication, flexibility of use for different architectural retrofit purposes, economy in transportation and handling, resistance to moisture and insect attack (Soares et al., 2017).

However, lightweight structures, particularly steel-framed ones, can contribute towards reducing building energy and indoor comfort performance during hot seasons (Lomas & Porritt, 2016) due to steel's high thermal conductivity and lightness (Santos, 2017). This represents a significant challenge, since with the increase in average annual temperature and the continuous growth of electricity demand, particularly of the residential sector, summer air conditioning has had a very significant influence on the overall energy consumption of buildings (Santamouris, 2016).

However, the use of additional thermal mass and high values of internal areal heat capacity can minimize peak heating and cooling loads in lightweight buildings (Di Perna et al., 2011; Kuczyński & Staszczuk, 2020; Rodrigues et al., 2013), especial-

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ly when coupled with natural or mechanical ventilation (Yang & Li, 2008). CFD simulation is considered the most valuable tool for designing, verifying, and predicting the indoor thermal comfort level in relation to these aspects. Through this type of simulation, Mora-Pérez et al. (2017) explain the benefits of combined use of mechanical and natural ventilation to maximize comfort and reduce energy consumption. Much attention is often paid to the influence of the specific building component. Deng et al. (2017) discuss in depth the impact of window length, aspect ratio, height above the ground, window opening angle and fly screen porosity on the airflow pattern inside residential buildings. Aryal and Leephakpreeda (2015) emphasize how interior partitions significantly change perceived thermal comfort and the resulting energy consumption for heating and cooling, while Hajdukiewicz et al. (2013) focus on highly-glazed façades in meeting rooms. Few articles simultaneously address different cooling passive strategies through CFD simulation, and the study of lightweight structures, such as steel-framed, is still limited in this field.

In this paper we investigate the effectiveness of lightweight steel-framed structures to ensure, through the implementation of passive design and use strategies, high levels of indoor comfort during the hot season. Through CFD simulation, the paper explores the ways in which natural ventilation, wall heat capacity and external shadings can reduce indoor temperatures and improve comfort. Different windows and door opening/closing patterns are compared at (a) different external wind speeds and (b) the ability of windows shadings to mitigate temperature peaks is evaluated. The behavior of (c) different wall surface claddings with changed weight is also investigated and, finally, a comparison (d) is made between the starting lightweight structure (steel-frame with external insulation), the same structure with the implementation of the aforementioned passive strategies, an insulated reinforced concrete massive structure and an insulated brick structure. Simulations are performed on a case study built in 2018 in Barnaul (RU), southwestern Siberia, and monitored for two years. The continental climate of the area has a high seasonal temperature range with lows of -35 °C in winter and highs of +35 °C in the hot season. The summer behavior of the building was examined, taking into account these particular extreme environmental conditions which, however, due to climate change, will also be increasingly common in less severe climates (IPCC, 2021).

2. Materials and Methods

In this section, the case study, methodology and simulation tools, as well as the parameters monitored, are presented. In addition, the characteristics and the boundary conditions of the simulation model, the different passive strategies implemented, and the output variables analysed in Section 3 are described in depth.

2.1 The Case Study

The case study is a single-storey residential building realized, as regards the structural design, with panels made of cold-bent steel profiles (Fig. 1a-1b). The building is about 80 square meters and is divided into entrance, living room-kitchen, bathroom, boiler room and two bedrooms (Fig. 2). An insulated ceiling divides the living space from the pitched roof, made of sandwich panels. The heating system is powered by gas condensation boiler, and a controlled mechanical ventilation ensures the indoor-outdoor air exchange.

Fig. 1 – The building during (a) and at the end of the construction phase (b). Picture by Giovanni Manzini, 2019

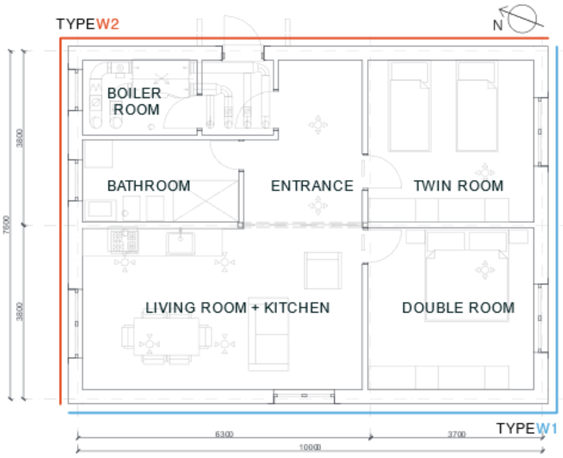

Fig. 2 – Horizontal section of the building

Table 1 – Thermophysical properties of the wall W1

Layers (int. to ext.)	**s [cm]**	**λ [W/(m K)]**	**ρ [kg/m³]**	**c [J/(kg K)]**
Plasterboard	2.5	0.2	800	836.8
Insulated Counter-Wall	7	0.072	101.24	1024.3
Glass wool	8	0.035	35	1030
Plasterboard	1.25	0.2	800	836.8
SteelMAX® Structure + insulation	10	0.067	143.78	1022.6
Cement board	1.25	0.35	1150	836.8

Table 2 – Thermophysical properties of the wall W2

Layers (int. to ext.)	**s [cm]**	**λ [W/(m K)]**	**ρ [kg/m³]**	**c [J/(kg K)]**
Plasterboard	2.5	0.2	800	836.8
Insulated Counter-Wall	5	0.068	101.2	1024.2
Glass wool	5	0.035	35	1030
Plasterboard	1.25	0.2	800	836.8
SteelMAX® Structure + insulation	10	0.067	143.78	1022.6
Cement board	1.25	0.35	1150	836.8
EPS insulation	5	0.038	21	1260

The building has two different external walls (Tables 1-2, Fig. 2) to test in-situ, through monitoring data, the energy performance of two akin solutions. Table 3 describes the thermal properties of the main building components.
The building is equipped with energy and environmental sensors to monitor its behavior 24 hours a day. The monitored parameters are:

- temperature, relative humidity, and CO2 of all indoor environments.
- surface and internal temperatures of walls, ceiling, floor.
- inlet and outlet temperature of the controlled mechanical ventilation machine.
- energy consumption.
- external environmental conditions (temperature, humidity, wind speed and direction, solar radiation).

The data monitored provided the necessary information to set the boundary conditions for the simulation model.

2.2 The Simulation Model

Computational fluid dynamics (CFD) is a branch of fluid mechanics that analyses and solves problems involving fluid flows using numerical analysis and data structures (Lomax et al., 2013). CFD analysis involves the simultaneous calculation of temperature and velocity domains, flows and pressures, considering the interaction between these variables. The great advantage of this type of simulation, compared to simplified empirical formulae, is the three-dimensional representation of the results. Properly setting the calculation grid and cell size, which have a significant impact on the calculation time and memory demands, as well as on the accuracy of the results, is a key prerequisite for the robustness of the CFD simulation. The minimum size of the cells is determined according to the specific problem to be analysed: for this case study, the volume of a single calculation cell is 8 cm^3 (2x2x2 cm). The number of cells also depends on the calculation domain. In order to include the effect of wind, which is essential for assessing the benefits of natural ventilation, a larger calculation domain than the building envelope is required, which may lead to a higher calculation effort.

Table 3 – Thermal properties of the building components

	W1 Walls	W2 Walls	Ceiling	Ground floor
Thickness [cm]	30	30	43	45
Thermal transmittance [W/m²K]	0.194	0.186	0.27	0.31
Decrement factor [-]	0.59	0.32	0.07	-
Time lag [h]	6.68	8.8	14.2	-
Internal areal heat capacity [kJ/m²K]	22.4	20.9	38.2	-
Periodic thermal transmittance [W/m²K]	0.114	0.06	0.019	-

The domain must be large enough not to bias the result and is typically expressed as a function of the building size. In accordance with Etheridge (2011), the following domains have been evaluated:

- Domain A: this coincides with the internal surface of the envelope. Boundary conditions at the inlets and outlets must be specified to run the simulation
- Domain B: external domain. The supply flow rate is determined as part of the simulation for this type of domain, which has dimensions that are normally twice those of the envelope. This means that the boundary conditions are different, and problems of convergence can arise.
- Domain C: the external flow to the inlet is included in the calculation. This requires extending the domain by an order of magnitude larger than the envelope.
- Domain D (used in the calculation): CFD boundary conditions for internal flows are generated using CFD data for the external flow.

Domain type D used in the case study simulation is a volume of 260 m³ (10.3x7.8x3.25 m) with boundaries that coincide with the internal walls. Based on a calculation previously carried out with an enlarged domain (type C: size of the domain is five times the size of the building), CFD allows wind velocity and air pressure along the building surface to be calculated. This choice reduces computational effort and, at the same time, enables the wind effects to be adequately considered. As regards the turbulence model for the calculation, the k-epsilon model was applied. The simulation model is built in Flovent®, proprietary software from Mentor Graphics®. For any other specifications regarding the methodology or the theory underlying the calculation, please refer to (Mentor Graphics Corporation, 2018).

2.3 Cooling Passive Strategies

2.3.1 Daytime natural ventilation

The transient simulation investigated the daily behavior of the building to the variation of the external climatic conditions, by focusing the analysis on the 48 hottest hours of the summer (3rd-4th of July). The set time step is 1 hour. Several monitor points were defined at different heights and in different rooms. The initial boundary conditions were set according to the data measured on site (Tab. 4). At first, an average wind velocity of 1.3 m/s in a north-westerly to south-easterly direction was considered, equal to the average wind speed measured in situ on that day. Then, extreme conditions of no wind and strong wind (0 and 5 m/s) were set to verify the reliability of the results and the magnitude of the wind.

Table 4 – Simulation boundary conditions

	Min	Max	Mean
Hourly outdoor temperature [°C] (see also Fig. 7c)	13.6	32.2	23.1
Solar radiation [W/m²]		873 (at 12.30 PM)	
Starting indoor temperature [°C]		25	

Several combinations are simulated (Tab. 5) with different window opening/closing schemes (Fig. 3). The daytime period is considered to start at 4 AM and end at 9 AM. In this case, it was considered that night ventilation was not feasible for other reasons (e.g., safety, noise, security).

Table 5 – Daytime natural ventilation: simulation cases

Sim.	Int. doors	Awning Windows	Hopper Windows	Wind
0	Closed	-	-	-
D10	Closed	-	F1, F2, F4, F5, F6	1.3 m/s
D11	Closed	-	F1, F2, F4, F5, F6	0 m/s
D12	Closed	-	F1, F2, F4, F5, F6	5 m/s
D13	Opened	-	F1, F2, F4, F5, F6	1.3 m/s
D14	Opened	-	F1, F2, F4, F5, F6	0 m/s
D15	Opened	-	F1, F2, F4, F5, F6	5 m/s
D20	Closed	F1, F2, F4	F5, F6	1.3 m/s
D21	Closed	F1, F2, F4	F5, F6	0 m/s
D22	Closed	F1, F2, F4	F5, F6	5 m/s
D23	Opened	F1, F2, F4	F5, F6	1.3 m/s
D24	Opened	F1, F2, F4	F5, F6	0 m/s
D25	Opened	F1, F2, F4	F5, F6	5 m/s

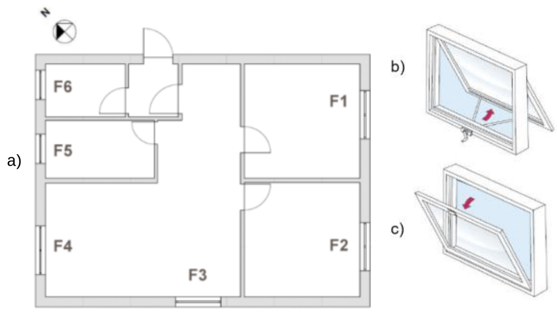

Fig. 3 – Windows nomenclature (a). Awning window example (b); hopper window example (c). https://blog.jonnew.com/assets/windows/types.jpg

For this and all simulations described in the next subsections, the output control variables are:
- Indoor temperature
- Internal wall surface temperature
- Predicted mean vote (PMV) (UNI, 2006)
- Predicted Percentage of Dissatisfied (PPD) (UNI, 2006)

Regarding PMV and PPD, to facilitate the calculation, some conditions were assumed to be constants:
- standing activity (1.2 met).
- summer clothing (0.5 clo).
- a relative humidity of 50 %.

The focus of the research was the thermal performance of the building. No acoustic and/or lighting comfort requirements were considered.

2.3.2 Nighttime cooling ventilation

The reduction of surface temperature of the walls, floor, and roof as a result of opening windows at night was explored by running a dynamic simulation. The role of various external window and internal door closing/opening techniques was examined. The night period is considered to start at 9 PM and end at 4 AM. The boundary conditions for temperature and solar radiation are the same as those shown in Table 4. The different combinations are listed in Table 6.

Table 6 – Nighttime cooling ventilation: simulation cases

Sim.	Int. doors	Awning Windows	Hopper Windows	Wind
0	Closed	-	-	-
N10	Closed	-	F1, F2, F4, F5, F6	0.5 m/s
N11	Closed	-	F1, F2, F4, F5, F6	0 m/s
N12	Closed	-	F1, F2, F4, F5, F6	5 m/s
N13	Opened	-	F1, F2, F4, F5, F6	0.5 m/s
N14	Opened	-	F1, F2, F4, F5, F6	0 m/s
N15	Opened	-	F1, F2, F4, F5, F6	5 m/s
N20	Closed	F1, F2, F4	F5, F6	0.5 m/s
N21	Closed	F1, F2, F4	F5, F6	0 m/s
N22	Closed	F1, F2, F4	F5, F6	5 m/s
N23	Opened	F1, F2, F4	F5, F6	0.5 m/s
N24	Opened	F1, F2, F4	F5, F6	0 m/s
N25	Opened	F1, F2, F4	F5, F6	5 m/s

2.3.3 Influence of thermal mass

To evaluate the effect of the surface thermal mass (UNI, 2017), three different simulations were carried out by varying the internal finishing layer, from plasterboard to cement board to plaster (Table 7).
- Sim n° 0: original case study.
- Sim n° M1: the internal plasterboard is replaced by 2 panels of cement board.

- Sim n° M2: the internal plasterboard is replaced by 3 panels of cement board.
- Sim n° M3: the internal plasterboard is replaced by 2cm of plaster (the air layer in the ceiling is thus eliminated).

The reduction of the surface temperature of the walls, floor, and roof due to the material replacement was studied, as well as the comfort (PMV/ PPD) and the reduction of the internal temperature peaks during the day. The dynamic analysis was carried out on two days with conditions similar to those shown in Table 4. The effects were evaluated on the second day of the analysis.

Table 7 – Thermal mass influence: simulation cases

	Internal areal heat capacity [kJ/(m²K)]		
Sim.	**North Walls**	**South Walls**	**Ceiling**
0	20.9	22.4	38.2
M1	33	34.6	43.9
M2	42.2	43.6	49.8
M3	33.3	34.3	52.2

2.3.4 Final comparison

The best cases from the previous 3 analyses were combined to obtain a best practice (case a). This was compared with the original building (case b) and with the same building modifying the load-bearing structure from insulated steel-frame (λ=0.58 W/(m K), ρ=100 kg/m³) to reinforced concrete (λ=1.4 W/(m K), ρ=2300 kg/m³ - case c) to brick (λ=0.35 W/(m K), ρ=700 kg/m³ - case d). A further comparison was made by optimizing "case i" by adding windows external shading (case e). This was simulated by reducing the solar heat gain coefficient of window glass by 85 % when the windows are closed.

3. Results and Discussion

As regards natural daytime ventilation, with reference to the simulations from D10 to D15 shown in Table 5, the most cooled surfaces are the floor (massive element), followed by the leeward external walls, the internal partitions and, finally, the windward walls and the roof (Fig. 4). The cooling rate is similar for the different configurations. In simulation D15 (strong wind and open internal doors), the greatest benefits are found in terms of reduction of indoor temperature and surface temperature (about 3 °C), but the indoor air velocities lead to unacceptable levels of discomfort. The considerations are similar for simulations D20 to D25 (awning windows). It is worth noting that the results are very dependent on the boundary conditions and are mainly useful for comparison. Simulations D10 and D20, which are, in Fig. 4, compared with the base case, reveal that a proper window opening strategy during the daytime, with appropriate outdoor environmental conditions, can reduce the daily average surface temperature of the building components by approximately 2 °C during a typical summer day.

In the case of nighttime natural ventilation combined with an accurate opening strategy for windows and internal doors, it is possible to reduce the temperature of the internal surfaces of the building by up to 7 °C (Fig. 5). Different natural ventilation strategies lead to different results. The analysis shows that cross ventilation, enabled by the opening of the inner doors, produces a 1 °C reduction in the internal temperature compared with single side ventilation. The combination of curtains and hopper windows (SimN23) is most effective in cooling the air volume near the floor area (Fig. 5), which could positively affect comfort conditions of a person lying at rest.

As regards the analysis performed by modifying the wall and roof cladding surfaces (Fig. 6), it can be stated that:

- in the M1 case study, with the replacement of plasterboard by cement board, the reduction of the average internal temperature is about 1°C during the daytime
- the 3 fibrocement panels(M2), which are, in any case, not easy to install from a technical point of view, so were considered only as a theoretical comparison, would guarantee a temperature reduction of 3 °C, with excellent benefits also in terms of PMV and PPD

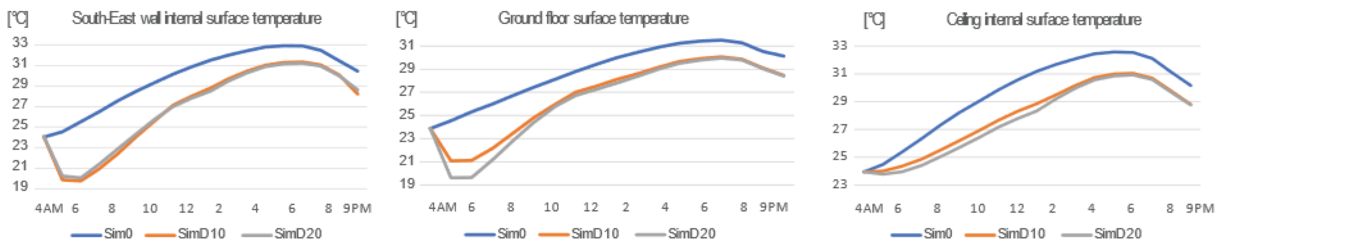

Fig. 4 – Daytime natural ventilation simulations results: internal surface temperatures of different building components (4th of July)

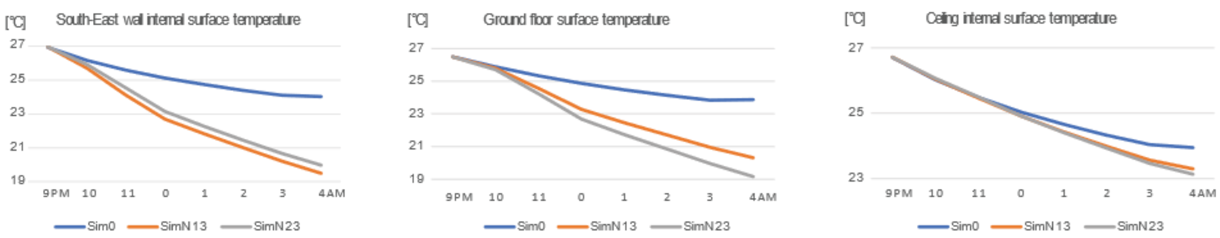

Fig. 5 – Nighttime natural ventilation simulations results: internal surface temperatures of different building components (4th of July)

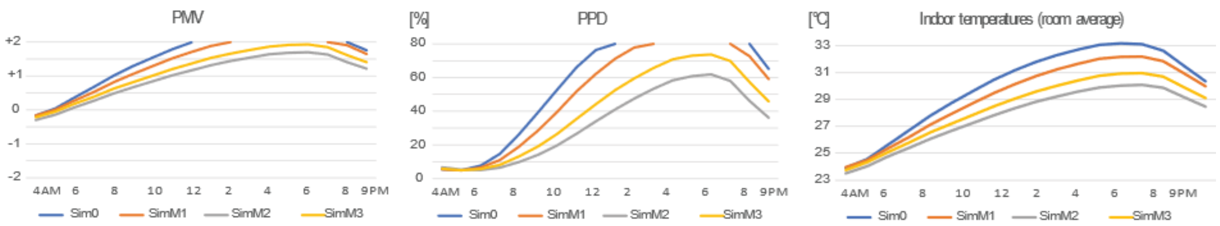

Fig. 6 – Thermal mass simulations results: PMV (a), PPD (b) and indoor temperature (c) trends (4th of July)

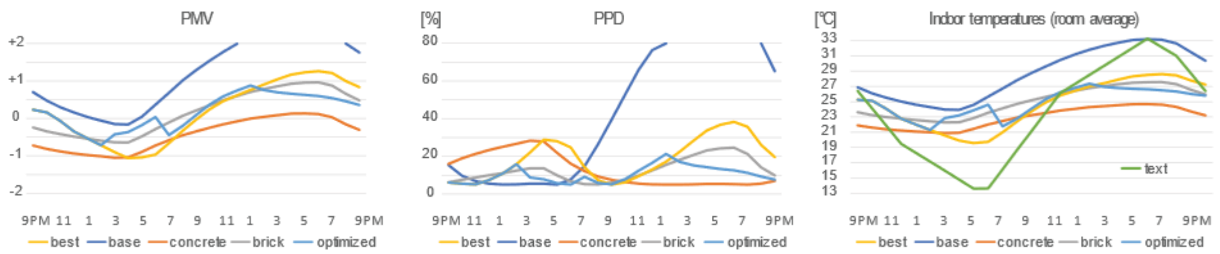

Fig. 7 – Final comparison results: PMV (a), PPD (b) and temperature (c) trends (3rd-4th of July)

- plaster would certainly be more efficient than plasterboard (M3), with a reduction of about 2.2 °C in the average internal temperature.

This positive effect also affects internal surface temperatures for all building components, thus increasing the indoor mean radiant temperature. Therefore, in the M2 case, the percentage reduction of PPD is over 20 %.

Fig. 7 compares data from the on-site monitoring system (base) with simulations described in Section 2.3.4. Massive/Solid constructions (concrete and brick) prove to be effective in softening outdoor temperature peaks, as noted in the literature. However, the combination of multiple passive cooling strategies (best), including a well-planned window opening strategy and heavier interior surface cladding materials, can positively reduce the risk of overheating even in steel-framed constructions.

The "optimized" case, which simulates the presence of a shading system through the reduction of the window solar heat gain coefficient, demonstrates how it is possible to achieve a more-than-acceptable level of comfort in light structures even in summer. Please note that the plots in Fig. 7 represent a 24-hour zoom on a simulation conducted over multiple days. For this reason, the initial indoor temperature conditions do not reflect those described in Table 4.

2. Conclusion

This work, starting from the monitoring of a real case study, provides a numerical evaluation of the indoor thermal comfort achieved in residential buildings during summer by applying passive cooling strategies. The focus is on lightweight steel-framed buildings, where, as the literature has frequently highlighted, overheating is still a big issue. Different strategies were tested through CFD simulations: from natural day and night ventilation to the implementation of different interior surface finishing materials, from different window opening configurations to external shading systems.

Based on the achieved results the paper confirms that:

- it is possible to adjust the nighttime discomfort level (too cold or too hot temperatures) by natural ventilation. It is necessary to find a compromise between the need to cool the envelope components and the internal ambient temperature, which strongly depend on the strategy adopted and, more generally, on the external temperature, wind speed and direction. Acoustic and lighting comfort issues should also be considered.
- the most effective strategy to regulate the daytime discomfort level is to shade window surfaces.
- daytime ventilation, in the analyzed conditions, produce limited effects. It is highly influenced by outdoor environmental condition trends, solar radiation, and sun exposure.
- by simply replacing the internal surface layer, without modifying the load-bearing structure, the internal areal heat capacity of the walls can be increased with positive effects on thermal comfort.

In this paper, monitoring data were exclusively used to set the boundary conditions for the simulation model. In the future, the implemented monitoring system will make it feasible to compare simulation findings with on-site measurements, calibrate the model, and put the recommended strategies into practice, involving building users. Further analysis will be required to evaluate the achieved results at different times of the year and with other building types.

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