Passive cooling techniques to improve resilience of nZEBs in Belgium

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Abstract. Nowadays, buildings are responsible for 40% of energy consumption in the European Union, according to the International Energy Agency (IEA). The urge to build more energy-efficient buildings resulted in the emergence of nearly zero-energy buildings (nZEB). However, the specifications the nZEB design should comply with might not be sufficient to prevent the risk of overheating in summer. To limit the energy consumption rise linked to the upcoming cooling demand increase, passive cooling techniques can be used instead of active ones, that are characterised by a high energy consumption. Passive cooling techniques are investigated through a dynamic simulation of a nearly zero-energy dwelling in Belgium. Their efficiency is assessed based on their ability to improve thermal comfort. The passive cooling techniques can be combined to ensure the resilience of the building to global warming. It was found that the most efficient techniques are the ones relying on ventilative cooling. Solar protections and smart glazing also offer an efficient protection against overheating. The effectiveness of the combined passive cooling techniques is studied over an extreme meteorological event, which is likely to occur by 2100 in Belgium if nothing is done to prevent global warming. Twenty days of intense heat are studied to evaluate the resilience of an nZEB. It was found that the most efficient combination includes night cooling, thermochromic glazing and indirect evaporative cooling. Those techniques allow to decrease the indoor temperature by almost 10 K.

Keywords. Passive cooling, climate change, overheating, resilience, thermal comfort.
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1 Introduction

The residential building sector is one of the largest energy consumers in most countries worldwide. Climate change impacts the energy performance of buildings by lessening thermal comfort and increasing the energy demand for space cooling. The energy consumption of buildings affects global warming, which in turn leads to the increment of such consumption, resulting in a vicious circle that needs to be broken to tackle the crucial issues of our generation. From the urge to reduce the environmental footprint of buildings emerged nearly zero-energy buildings (nZEBs). Those buildings are better insulated, hence more energy-efficient [1].

Currently, most Belgian residential buildings are not conditioned. However, together with the emergence of nZEBs and the global warming, the cooling needs of such buildings are expected to rise. Due to their better insulation, extracting heat from nZEBs is more difficult, resulting in a higher overheating risk. Many recent scientific studies focused on this strong link between global warming and building energy performance. All scientists concluded their work by warning the competent authorities about the imminence of the global warming threat and the urge to take actions against the related energy consumption rise. Some of them also investigated the available technologies to reduce or limit the overheating risk in buildings using passive cooling. However, few studies address the combination of passive approaches in residential buildings to improve their energy efficiency. Most studies focus on non-residential buildings. Cooling techniques are gaining attention, especially passive ones, which do not rely on the use of an electricity-driven vapor compression refrigerator. Passive cooling would allow to limit the electricity consumption for residential cooling compared to active cooling. However, the potential of passive cooling capacity is strongly linked to the outdoor climate as colder and drier climates allow for larger capacities. With global warming, the Belgian climate is expected to become hotter and drier [2] and the interest of such techniques in this future climate should be evaluated, as well as their capacity to reduce the imminent risk of thermal discomfort.

The present study aims at assessing the energy consumption and thermal comfort of a residential building in Belgium and their evolution under global warming. The investigation of the existing passive cooling techniques allows to propose guidelines to ensure resilience of nZEBs to global warming.

2 Research Methods

2.1 Description of the case study

This section gives information about the studied dwelling regarding its geometry, envelope and ventilation system operation (see Tab. 1). The building characteristics are based on the plan of the building, the EPBD, and standard ISO 17772 (See previous work of the author [3] for more details). A 3D model of the studied duplex is shown in Fig. 1. The building is South-oriented with a large window-to-wall ratio (0.6). Fig. 2 is the 2D view of the inside of the duplex. This figure also shows the division of the duplex in thermal zones. Eight thermal zones have been defined. The Walloon Region imposes energy performance standards for buildings through the EPBD, which is reviewed each year. All the walls are compliant with the EPBD 2020. The glazing is triple-glazing. The duplex is equipped with a balanced ventilation system with a heat recovery module of 85% efficiency and a by-pass system. The duplex has currently no cooling system.

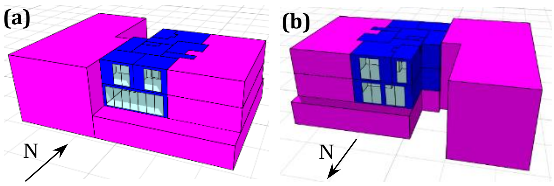

Fig. 1 – 3D model of the building. **(a)** front view **(b)** rear view

2.2 Location and climate

The studied building is in Liege. According to the ASHRAE climate zones, Belgium is part of zone 4A, corresponding to a mixed humid climate. The meteorological files used in this work have been generated at the Laboratory of Climatology of the University of Liege with a regional climatic model called *Modèle Atmosphérique Régional* (MAR) [2]. The MAR being a regional model, it needs to be forced by a general circulation model (GCM) at its boundaries. In this study, two GCMs have been used to better represent the uncertainty spread by 2100 in Western Europe. They are referred to as MPI and BCC. MPI is considered as a colder GCM than BCC. MAR model has been run at 5 km spatial resolution over Belgium. To produce simulations from 2012 to 2100, the GCMs should be coupled with a shared socio-economic pathway that is strongly related to a representative concentration pathway of greenhouse gas. In this paper, the scenario used to account for global warming is SSP5, which describes a society that continues to rely on fossil fuels [4].

Those climate simulation results are used in the BPS program to consider the impact of global warming on the studied building. Fig. 3 shows the evolution of the difference between the simulated average annual temperature and the standard average temperature of Belgium which is 10.9°C. If no measure is taken to lessen global warming, the temperature rise by 2100 is expected to be around 4 K, with a visible global warming effect starting from 2050. It should also be noted that since the circulation models are *global* circulation models, the results obtained with the simulations describe an *average* climate and cannot contain extreme meteorological events.

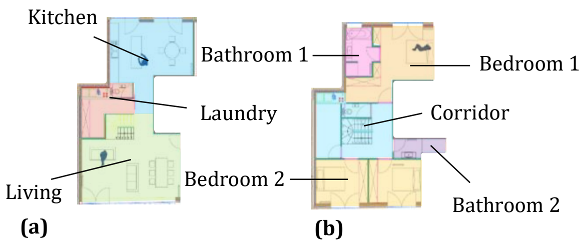

Fig. 2 – Upper view of the duplex **(a)** first floor **(b)** second floor and division in thermal zones.

2.3 Model validation by comparative testing

The building model used in this paper was developed with the IES VE software. The model could not be validated using empirical data. A comparative testing has been performed instead. The building model has

Tab. 1 – General description of the case study.

General information		Envelope		Ventilation system		
Building location	Liege, BE	**Walls**			Supply	Exhaust
Building type	Residential	U-value [W/m²·K]			[m³/h]	[m³/h]
Construction	2020	*External wall*	0.152	Living room	150	-
Nb storeys	9	*Internal wall*	0.452	Kitchen	-	75
Case study	4-person duplex	*Adjacent wall*	0.198	Laundry	-	75
Floor	8-9	*Roofing*	0.081	Bedroom 1	75	-
Orientation	South	*Floor/ceiling*	0.132	Bedroom 2	90	-
Surface	173 m²	**Windows**		Bathroom 1	-	50
WWR	0.6	U-value [W/m²·K]	0.6	Bathroom 2	-	50
Infiltration rate	0.6 ach at 50 Pa	Solar factor [-]	0.5	Corridor	-	65

been developed using two software: IES VE and EES. The outputs of the models (temperature, energy consumption, heating and cooling loads balance) were compared. It appeared that the mean bias error (MBE) and the root mean square error (RMSE) of all the considered variables remain respectively below 5 and 15%. The dynamic behaviour of the building is thus similar in the two simulations and the comparative testing of the model is conclusive [5].

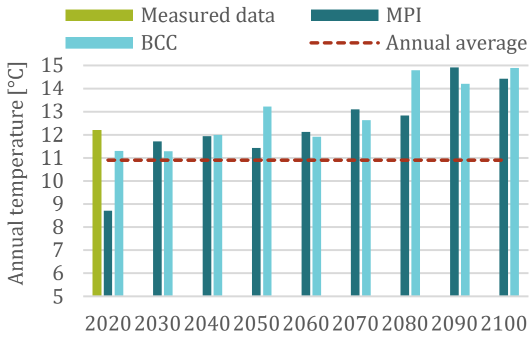

Fig. 3 – Evolution of the annual average temperature with global warming.

3 Thermal comfort analysis

This section focuses on the analysis of thermal comfort in the dwelling and its evolution with global warming. Thermal comfort is evaluated based on the adaptive comfort theory. Studies have shown that in naturally ventilated buildings without any conditioning system, the occupants of the building feel more connected to the outdoor environment and can bear higher temperatures in summer. The maximum adaptive comfort temperature can be expressed by a relationship depending on the mean outdoor temperature:

$$T_{comf,max} = 0.33\, T_{rm} + 21.8 \quad [°C] \qquad (1)$$

where T_{rm} is the running mean outdoor temperature and is calculated as specified by standard NBN EN 15251. This theory can be used if there is no mechanical cooling system and that the occupants can modify their behaviour depending on the climatic conditions, i.e. by adapting their clothing or opening the windows.

Thermal comfort is evaluated in the living room, which is the room with the highest risk of thermal discomfort. It has been decided to study the living room only because it is a South-oriented room, *i.e.* with higher solar gains. Moreover, the living room has a high window-to-wall ratio to account for the fact that new buildings generally tend to have some south-oriented bay windows to increase the illuminance inside the building. It is also a room with more constant and standard internal gains than a kitchen, in which occupants' behaviour can be more difficult to model.

Fig. 4 shows the evolution of the risk of overheating with global warming. This risk is defined according to the percentage of occupation time during which the maximum adaptive comfort temperature is exceeded. If this temperature is exceeded for less than 5% of the occupation time, it is assumed that the overheating risk is negligible and above 10%, an active cooling system becomes mandatory to ensure thermal comfort. Even in 2020, the overheating risk is not negligible and, as expected, it only worsens with global warming, irrespectively of the climate simulation. It is strongly recommended to take some precautions during the conception phase of a building to limit the risk of overheating in the future but also nowadays, as heat waves are becoming more frequent. Passive cooling techniques should be chosen carefully depending on some inherent features of the building, such as orientation or occupancy schedule. Different passive cooling techniques are introduced in the next section.

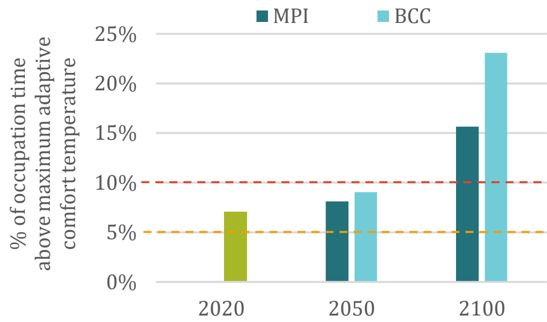

Fig. 4 – Evolution of thermal comfort with global warming.

4 Passive cooling techniques

Maintaining a comfortable environment within a building in a hot climate using passive cooling relies on reducing heat gains into the building and/or fostering the removal of excess heat [6]. The goal of this paper is to show that it is possible to reduce the overheating risk but not completely limit it. The passive cooling techniques principles and models are overviewed all along this section.

4.1 Reducing solar gains

The solar radiation can be blocked either before it enters the building by solar protections or by the glazing itself. The solar protections can be movable or fixed. Generally, movable solar protections cover the entire surface of the window and the orientation of the slats can be adjusted depending on exterior conditions. The impact of shutters is not discussed within this article as it can hamper the passage of wind, reducing the benefits of natural ventilation. Only the fixed solar protection is considered. The principle is illustrated in Fig. 5. There exists an optimum overhang depth which blocks solar beam irradiation from the high summer sun but still allows the low winter sun to shine in to avoid increasing the heating load [7].

Advanced solar glazing is a glazing with a low-emissivity coating that reduces heat gains. Panes absorb solar radiation selectively, more in the near infrared and less in the visible spectrum. With the absorbing pane facing the environment, a large portion of the absorbed radiation is rejected back to

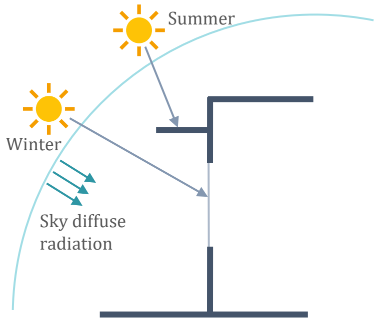

Fig. 5 – Fixed solar protection.

the outdoor environment resulting in a low solar factor [8]. Compared to fixed shading, advanced solar glazing has the advantage to control both direct and diffuse radiation.

Thermochromic glazing is a switchable glazing which can dynamically vary its optical properties. This adaptiveness is allowed by the integration of smart functional materials/layers within glass panes, enabling modulation of the amount of solar radiation transmitted through them. Across a transition temperature, the thermochromic glazing undergoes a structural transformation from "light" to "dark" state. Both states having a different transparency to infrared radiation [9]. Thermochromism being a passive system, it offers no possibility of being manually controlled by the user.

4.2 Removing excess heat

Ventilative cooling uses the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads, while guaranteeing a comfortable thermal environment. The outdoor air driving force can be either natural, mechanical or a combination of both. Ventilative cooling performances vary between countries due to climate variations, energy prices and other factors [10]. The two ventilation strategies considered are day and night cooling through natural ventilation.

The aim of natural ventilation is to take advantage of the cooler outside air to evacuate the excess heat lingering inside the building. To perform an efficient ventilation, the room should be ventilated if the indoor temperature gets close to 25°C and the outdoor temperature is lower than the indoor temperature. The window opening in the simulation is commanded by a control signal *s*. A value of 1 means that the window is open.

$$s = \begin{cases} 1, \; if \; T_a > 24°C \; and \; T_o > 18°C \\ 0, \; otherwise \end{cases} \qquad (2)$$

This method is deterministic and not a really good representation of the reality. The building occupants' behaviour can have a negative impact on indoor thermal comfort, as shown by Naspi et al. [11] and Haldi & Robinson [12]. Guaranteeing a good indoor thermal comfort while remaining in the adaptive comfort theory might require occupants' training. Some limitations or constraints on the use of the natural ventilation may be necessary to avoid overheating or overcooling.

The night cooling strategy is typically implemented in temperate climates where night-time temperature is significantly lower than during the day. The basic concept involves cooling the building structure overnight to provide a heat sink that is available during the occupancy period. Night cooling is highly dependent on climatic conditions, as a sufficiently high temperature difference between ambient air and building structure is required to achieve efficient convective cooling of the building mass. The night cooling efficiency has essentially been demonstrated in Europe. However, due to the inherent stochastic properties of weather patterns, a series of warmer nights can occur and passive cooling by night-time ventilation alone might not be sufficient to guarantee thermal comfort at all times [13].

The value of the control signal *s* that handles window opening is set with a control formula. The formula used in the present work is based on the model developed by Iddon & ParasuRaman [14].

$$s = \begin{cases} 1, \; if \; T_a > T_o \; and \; T_a > 20°C \\ 0, \; otherwise \end{cases} \qquad (3)$$

This formula is only valid between 10 p.m. and 6 a.m. during the cooling season when there is a high risk of overheating. Night cooling is generally used during heat waves when day cooling cannot be relied on as the outdoor temperature is higher than the indoor temperature.

Handling night cooling with natural ventilation has several drawbacks. The opening of a window being a manual action, it is unlikely that the occupants will wake up to close it if the temperature drop is too abrupt or if it rains. In some situations, it could result in overcooling. Night cooling might be associated with automatically controlled windows or used only in extreme cases during heat waves. To cope with those disadvantages, it is also possible to perform night cooling through mechanical ventilation. The advantage of using mechanical ventilation is that it ensures a constant air flow all night long and avoids draughts. One major drawback of overventilation is that the fan power consumption increases as the cubed air flow rate, resulting in a significant increase in electricity consumption.

The last technique that has been studied is indirect evaporative cooling (IEC). It consists in cooling the extracted air by humidification and then, via a heat exchanger, it cools down the incoming outdoor air. The process is illustrated in Fig. 6. The advantage of indirect evaporative cooling over direct humidification of the incoming air is the avoidance of a possible contamination. In summer, this technology provides gentle air conditioning and consumes a minimum energy as it can be coupled with the mechanical ventilation system. The water consumption of this type of systems is also very modest [15]. IEC has been modelled by changing the

Fig. 6 – Schematic of an Indirect Evaporative Cooler.

supply ventilation air temperature. IEC is used when the outdoor air temperature either exceeds 25°C or is higher than the indoor temperature. It is assumed that the extracted air is cooled down to the wet bulb temperature and that the efficiency of the heat exchanger remains unchanged. The temperature of the incoming air can be calculated as:

$$T_{vent,su} = T_o + 0.85 \cdot (T_{wb} - T_o) \quad (4)$$

The advantage of IEC is that it remains efficient even during heat waves, contrary to natural ventilative cooling. A more complete IEC model is currently under investigation to cope with the hypotheses done in this work and evaluate the performance of IEC systems in different climates.

4.3 Comparison of passive cooling techniques

In the previous section, various passive techniques were introduced, and their strengths and limitations were overviewed. Fig. 7 shows how the indoor thermal comfort is impacted by the addition of those passive cooling techniques to the case study. Some passive cooling techniques are efficient but none of them is sufficient to guarantee thermal comfort in 30 or 80 years from now. They can be combined to considerably reduce the overheating risk. To be efficient, a combination of passive cooling techniques should involve at least a solution to decrease the solar gains and one to increase the ventilation losses.

The impact of the combined passive cooling techniques is shown during a period of intense heat when an active cooling system might be the most useful method to prevent the overheating risk. If thermal comfort can be guaranteed during a heat

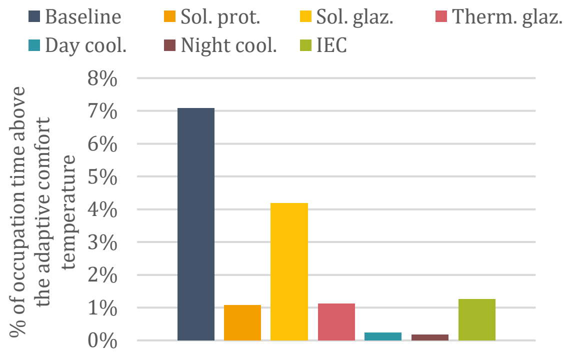

Fig. 7 – Impact of passive cooling techniques on overheating risk.

wave, it can be assumed that the overheating risk has been sufficiently reduced. It also allows to study the resilience of the building. Resilience is defined as the ability of a system to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions [16]. The hazardous event that has been studied is the heat wave as it is the extreme weather event that is the most likely to occur with climate change in Western Europe.

Fig. 8 shows the evolution of the temperature in the living room during a period of intense heat. The improvements have been added one by one to visualise the improvement generated by each passive cooling technique and determine when the building is sufficiently cooled down to withstand the period of intense heat. The studied passive cooling techniques are presented below in the order they have been added. The legend of the graph shows only the last added technique. The only techniques that have been studied separately are the solar protections as three of them have been investigated.

The first improvement is day cooling as it is the easiest technique to implement in reality. The

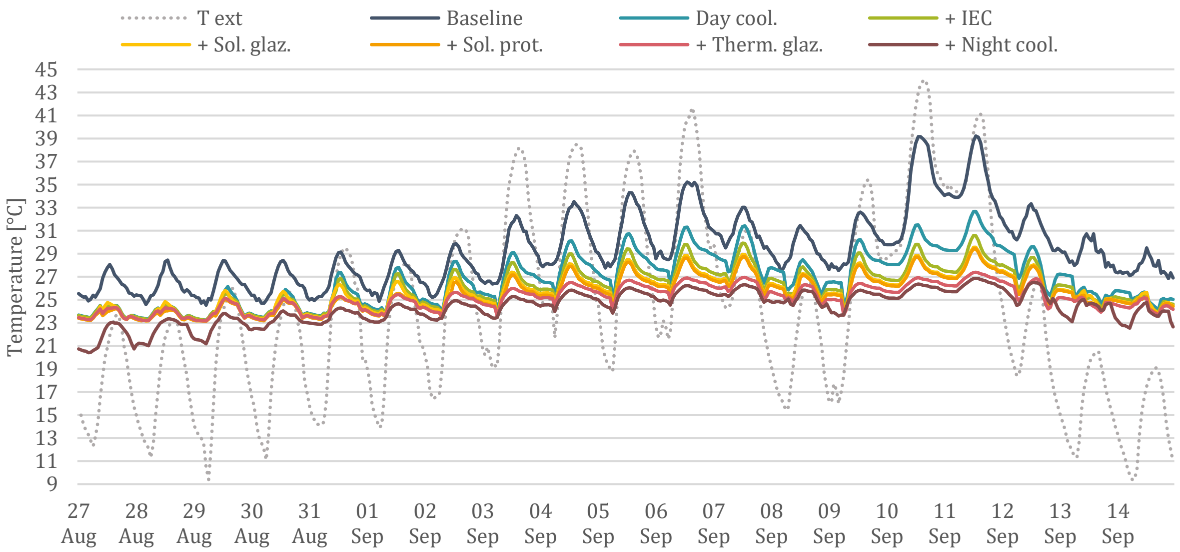

Fig. 8 – Evolution of the indoor temperature during a heat wave considering passive cooling techniques.

efficiency of day cooling appears even before the heat wave. Contrary to the case without improvement, the building has not stored heat within its walls all summer. The thermal inertia of the building is thus available to slow down the temperature increase. But during the heat wave per se, day cooling is helpful only a few hours a day in the morning when the temperature has not yet reached 25°C. Day cooling alone already allows to decrease the temperature by 2.6 K on average.

The second improvement is IEC because it is a promising and easy to implement technique as all new constructions should be equipped with a mechanical ventilation system on which the IEC module can be added. When combined with day cooling, it leads to a further temperature decrease of 0.95 K on average. IEC is expected to become more efficient in the future as the outdoor air will become drier. If the outdoor air and, a fortiori, the indoor air become drier, the temperature decrease due to humidification would be more significant, resulting in a more efficient cooling.

Day cooling and IEC have then been combined with the three solar protections that were considered as the most relevant. Solar glazing and fixed solar protection have almost the same impact on the indoor air temperature. On average, they further decrease the indoor temperature by 0.43 and 0.6 K respectively. Thermochromic glazing allows a temperature reduction of 1.1 K and is the most efficient to decrease solar gains. The characteristics of the glazing are changed continuously depending on the indoor environment conditions and the glazing gets darker as the irradiation becomes more important, smoothing out the temperature peak observed with the other configurations. None of those combinations allows to remain below the threshold of 25°C during the whole heat wave. However, with the use of thermochromic glazing, the maximum indoor temperature is 27°C even when the outdoor temperature reaches 43°C.

A further reduction of the temperature is possible by adding night cooling to the previous passive techniques. Night cooling has been added last although it is a very efficient technique because it can sometimes result in overcooling of the building. Night cooling is particularly efficient because of the outdoor temperature drop during the night. It can also be noted that night cooling impacts the building thermal inertia for several days. During the last days of the heat wave, the outdoor temperature does not fall below 25°C during the night, making night cooling useless. Since the building has been correctly cooled down during the previous days, it allows getting through those days of intense heat. The outdoor temperature is too high to prevent the indoor temperature from exceeding 25°C. However, 25°C is the comfort temperature nowadays and it is not unlikely that in the future, if the temperature rises, people will adapt and be able to withstand higher temperatures.

After the heat wave, it takes less than one day to the building to get back to the same behaviour it had before the heat wave. The resilience of the building is ensured, especially due to natural ventilative cooling.

4.4 Limitations of passive cooling techniques

Theoretically, the building can be defined as resilient and the techniques that are the most efficient to reduce overheating are proper use of ventilative cooling (during the day and especially during the night), thermochromic glazing and, to a lesser extent, IEC. With those techniques, the temperature peaks are smoothed out and remain close to 25°C even though the outdoor temperature significantly increases.

However, in this analysis, one of the most important factors, closely linked to residential building usage, could not be accounted for: the occupants' behaviour. In the simulations, the windows are open and closed exactly when necessary, to avoid overheating during the day and overcooling during the night. Brown & Cole [17] studied the influence of occupants' knowledge on comfort expectations and behaviour. They identified some potential factors that can impact the "performance gap" between simulations and reality. The systems usability or accessibility for the users can strongly impact the building control. The users can lack immediate responsiveness or the sufficient knowledge to manage the building correctly. They also tend to be responsive to an imminent discomfort crisis while it would be more appropriate to continuously optimise the building operation. Building operation should however not entirely lean on the occupants. The human-building interaction should be ongoing and bidirectional by offering immediate and relevant feedback to the occupants for them to know the risks of thermal discomfort. Tam et al. [18] also studied the energy-related occupant behaviour and its implication in energy use. They concluded that the best way to account for and minimise occupant energy-related behaviour is to act instantaneously and make them aware of the implications of their actions in a real-time performance of a building. Moreover, occupants should be well informed of the best practices when dealing with building systems, such as lighting, HVAC, equipment, DHW, etc. Each building should be provided with a user guide towards a better building performance.

The present work tries to remain as general as possible as it aims to the transposition of its conclusions to similar buildings. However, Elnagar & Kohler [19] showed that the building orientation can significantly impact its energy demand. South orientation leads to the smallest heating energy demand while the cooling demand can be decreased with a North orientation. In both cases, a West or East orientation increases the energy demand. They are also the orientations for which external fixed shading devices are the most difficult to design as the Sun has almost the same position in the sky all year round. The passive cooling techniques should also be adapted depending on the orientation.

5 Conclusion

The thermal model of a nearly zero-energy dwelling has been built with a BPS software called VE. The thermal comfort was studied in the dwelling for 2020, 2050 and 2100 using global warming simulation weather file. The years 2050 and 2100 were simulated assuming a "business as usual" scenario. As expected, it was found that thermal comfort deteriorates with global warming. By 2100, the need for an active cooling system will be bound to happen. Another conclusion of this analysis is that, in South-oriented rooms with high window-to-wall ratio, thermal comfort is not even reached nowadays, meaning that the design of nZEBs has not been conceived to be resilient. The resilience of the buildings should be engineered at design stage by including some passive cooling techniques.

Passive cooling techniques present the advantage to considerably limit the energy consumption increase of the building while significantly improving thermal comfort. The studied passive techniques mainly aim at decreasing the solar heat gains and enhance ventilation losses to remove excess heat from the building. Ventilative cooling was found to be the most relevant cooling technique. It is followed by solar protections and solar glazing. Finally, indirect evaporative cooling has been proven to be useful especially during heat waves. It should be combined with ventilative cooling to guarantee a good thermal comfort.

The resilience of the building has been assessed by analysing its behaviour during a period of intense heat while applying various passive cooling combinations. It was shown that combining night ventilation, indirect adiabatic cooling and thermochromic glazing can reduce the indoor temperature by 10 K.

The purpose of the present work was to study some passive cooling techniques combinations and to apply them to a nearly zero-energy building to reduce the risk of overheating in summer due to the airtightness of new constructions. Some guidelines have been proposed to build more resilient buildings. In any case, it is really important to keep in mind that even though the building has been perfectly designed, the operation strongly relies on the occupants' behaviour. To get rid of that unpredictable variable, buildings should be automated as much as possible. However, a too high level of automation would fail the requirements of the theory of adaptive comfort, narrowing the temperature range considered as pleasant. A balance has to be found between automation and thermal comfort widening by favouring an ongoing and bidirectional human-building interaction. The building should offer immediate and relevant feedback to the occupants so that they know about risks of thermal discomfort.

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The datasets generated and analysed during the current study are not available because they have been generated during an internship in a private company and are therefore confidential, but the authors will make every reasonable effort to publish them in near future.