Travail de fin d'études et stage[BR]- Travail de fin d'études : Using passive cooling techniques to improve resilience to global warming of nearly zero-energy buildings[BR]- Stage d'insertion professionnelle

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Faculté : Faculté des Sciences appliquées
Diplôme : Master en ingénieur civil électromécanicien, à finalité spécialisée en énergétique
Année académique : 2020-2021
URI/URL : http://hdl.handle.net/2268.2/11569

University of Liege
Faculty of Applied Sciences

Using passive cooling techniques to improve resilience to global warming of nearly zero-energy buildings

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Dissertation presented in fulfilment of the requirements for the master's degree in Electromechanical engineering by Alanis Zeoli

Academic year 2020-2021

AKNOWLEDGEMENT

I would like to thank all the people who helped me make this work a reality.

First, I would like to thank my two supervisors, Pierre Gustin and Vincent Lemort. I thank Pierre Gustin for giving me the opportunity to realise an unforgettable internship at Ecorce, for his wise advice and for the time he devoted me for 80 days. I thank Vincent Lemort for his guidance and time and for the opportunity he gave me to go further in this work with a PhD.

I thank the wonderful team of Ecorce for letting me in for these four months, especially Sophie Haine for her good mood during those uncommon times and the countless cups of tea.

I also thank M. Shady Attia for his advice and support, as well as the other members of the Jury for taking the time to read this work.

I am grateful to Sébastien Doutreloup for taking the time to introduce me to the complexity of climatic simulations and to Essam Elnagar for sharing his information about ventilative cooling and for his enthusiasm. I also thank Johan Haerbele for his precious help with the simulation software.

Finally, I would like to deeply thank my family, my partner and my friends for their unfailing support.

ABSTRACT

With climate change, the energy consumption of buildings for cooling purposes is expected to rise, further enhancing global warming through the increase of greenhouse gas emissions. To break this vicious circle, it is essential to decrease the anthropogenic CO_2 emissions by lessening the energy consumption in all sectors. 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, hence the purchase of an active cooling system.

Passive cooling techniques are investigated through a dynamic simulation of a nearly zero-energy dwelling. Their efficiency is assessed based on their ability to improve thermal comfort while limiting the increase in energy consumption. Thermal comfort is measured based on the theory of adaptative comfort which is the most relevant for a residential building. 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. In Western Europe, day cooling should be combined with night cooling to reduce the overheating risk and improve thermal comfort by 39%. Solar protections and smart glazing also offer an efficient protection against overheating. They improve thermal comfort by respectively 34 and 22%.

The effectiveness of the combined passive cooling techniques is studied over an extreme meteorological event, which is likely to occur by 2100 if nothing is done to prevent global warming. Twenty days of intense heat are studied to evaluate the resilience of a nZEB. It was found that the most efficient combination includes night cooling, thermochromic glazing and adiabatic cooling. Adiabatic cooling is particularly efficient during heat waves. Those techniques allow to decrease the indoor temperature by almost 10°C. However, occupants' behaviour could have a negative impact on the cooling techniques efficiency.

RESUME

Avec le dérèglement climatique, on s'attend à une augmentation de la consommation de froid des bâtiments, et donc de la production de gaz à effet de serre, ce qui aura pour effet d'amplifier le réchauffement climatique. Afin de briser ce cercle vicieux, il est impératif de tout mettre en œuvre pour diminuer les émissions de CO2 et la consommation énergétique en général. Dans l'union européenne, les bâtiments sont responsables de 40% de la consommation énergétique, selon une étude de l'IEA (International Energy Agency). Les bâtiments dits *"quasi zéro énergie"* (qZEN) résultent de ce désir d'accroitre l'efficacité énergétique des bâtiments. Cependant, les spécifications imposées par le label qZEN pourraient ne pas être suffisantes pour empêcher le risque de surchauffe en été, et donc l'achat d'un système de refroidissement actif par les occupants.

Ce document vise à étudier différentes techniques de refroidissement passif via la simulation dynamique d'un appartement qZEN. L'efficacité de ces méthodes est évaluée sur base de leur capacité à accroitre la sensation de confort thermique tout en limitant au maximum leur impact sur la consommation énergétique du bâtiment. Le confort thermique est mesuré via la théorie du confort adaptatif. Cette théorie étant la plus adaptée à un bâtiment résidentiel. Les techniques de refroidissement passif peuvent ensuite être combinées pour garantir la résilience du bâtiment au réchauffement climatique. Les techniques les plus efficaces sont basées sur le refroidissement par la ventilation. En Europe de l'Ouest, la ventilation de jour doit être combinée avec de la ventilation de nuit pour réduire significativement le risque de surchauffe et augmenter le confort thermique de 39%. Les protections solaires et les vitrages dit *"intelligents"* sont aussi des mesures efficaces contre la surchauffe. Ils augmentent le confort thermique de 34 et 22% respectivement.

L'efficacité des combinaisons des méthodes est étudiée lors d'un événement météorologique extrême. Ce type d'événement est susceptible de se produire régulièrement d'ici 2100 si rien n'est mis en place pour lutter contre le dérèglement climatique. La résilience du bâtiment qZEN est étudiée sur vingt jours d'intense chaleur. La combinaison la plus efficace inclut la ventilation de nuit, le vitrage thermochromique et le refroidissement adiabatique, qui est particulièrement efficace durant les vagues de chaleur. Ces techniques permettent de diminuer la température intérieure de presque 10°C. Cependant, le comportement des occupants et la manière dont ils gèrent leur bâtiment peut avoir un impact néfaste sur l'efficacité des techniques de refroidissement.

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1. INTRODUCTION

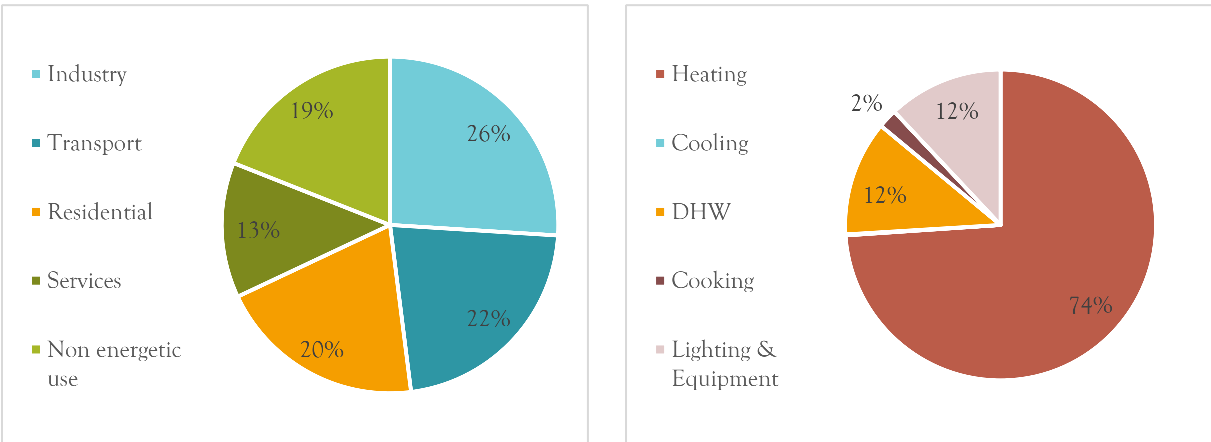
Nowadays, global warming has become a major concern, and we regularly hear about its disastrous consequences, threatening the life quality of current and future generations. Global warming is characterised by a progressive increase of the average atmospheric temperature, strictly related to anthropogenic greenhouse gases emissions in the atmosphere due to the intensive exploitation of fossil fuels in contemporary societies. To slow down or even reverse such upward trend, human beings should strive to drastically decrease their CO_2 emissions, hence limiting the effects of global warming.

The residential building sector is one of the largest energy consumers in most countries of the world. The energy is used mainly for heating and cooling purposes. The fossil energy is used either directly (mostly for heating) or indirectly, through the consumption of electricity, which CO_2 footprint depends on the energetic mix of the country. Climate change impacts the energy performance of buildings by lessening thermal comfort and increasing the energy demand for space cooling. Therefore, 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 [1].

To limit the effects of global warming and decrease the greenhouse gas emissions, the European commission recently published the 2050 long-term strategy, urging all Member States to reduce their CO_2 emissions down to zero. To reach this objective, they should limit CO_2 emissions in all the economic sectors, including the residential sector. In Belgium, the energy consumption of residential buildings accounts for about 20% of the national energy consumption. Of those 20%, 74% of the energy is used for heating (see Figure 1), which almost exclusively uses fossil fuels, such as oil or natural gas. Two solutions have been identified to limit the fossil fuel consumption of residential buildings: decrease the energy consumption through energy efficiency improvements and behaviour changes and direct the energy mix toward greener sources.

Some directives emerged from this desire to reduce the environmental footprint of EU. On the one hand, directives such as Ecodesign or energy labelling guide consumers toward more efficient systems and equipment. On the other hand, the energy performance of building directive (EPBD) resulted in the emergence of nearly zero-energy buildings (nZEBs). Those buildings are better insulated, hence more energy-efficient [2].

Figure 1 – Final energy consumption per sector and Final energy use of households in 2017 in Belgium **[2]**.



Currently, most Belgian residential buildings are not conditioned, as shown by the cooling energy consumption of households. 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, the heat release in nZEBs in more difficult, resulting in a higher overheating risk. Many recent scientific studies focused on this strong link between global warming and building energy performance and some of them are reviewed to position the present work in relation to what has already been done to date.

Rahdi [3] studied the consequences of global warming on the energy performance of air-conditioned residential buildings in the United Arab Emirates. His study has shown that a rise in the ambient air temperature by 5.9°C in Al-Ain city is likely to increase the energy used for residential cooling by 23.5%, resulting in a significant increase in CO_2 emissions. The use of thermal mass and thermal insulation has been demonstrated to be an effective measure against overheating. Emphasis is also made on the window design which can provide energy savings of 6.8-8.1%.

Santamouris *et al.* [4] reviewed the impact of urban heat island (UHI) and global warming on energy and electricity demand of buildings. The urban heat island effect is discussed later in this work. Combined with global warming, it results in an increase of the ambient temperature and an intensification of the energy consumption for cooling purposes of buildings and other structures. At the same time, in heating-dominated climates, a rise of the ambient temperature may offer energy savings. The major impact of ambient temperature rise is related to the possible increase of electricity demand peaks that would compel power management institutions to build additional power plants and probably increase the cost of energy supply. Depending on the characteristics of the building stock, climate zone, urban form, and type of provided energy services, the potential increase of electricity demand per degree of temperature rise varies between 0.5 and 8.5% while the peak electricity demand could increase by 0.45 to 4.6%. To reduce the impact of urban heat island and global warming, building and urban structures must be adapted to the specific climate conditions. The development of low energy or close to zero energy buildings may significantly reduce the energy needs, especially if developed in parallel with the use of advanced urban adaptation and mitigation techniques to limit the rise in ambient temperature.

Closer to the region we are interested in, Hamdy *et al.* [5] studied the impact of climate change on the overheating risk in Dutch dwellings. They concluded there is high risk of overheating in dwellings with higher solar gains and/or lower heat transmission, *i.e.* in new dwellings with high insulation levels and no protection against direct solar irradiation. Ventilative cooling and solar protection seem to be the most effective adaptation measures against global warming. However, the potential of ventilative cooling will decrease as global warming increases. Traditional adaptation opportunities such as natural ventilation, solar shading, or a modification of occupants' behaviour, might not be sufficient to keep the daily average indoor temperature below 25°C in all dwelling types during the whole summer season.

Attia & Gobin [6] contributed to quantifying the impact of climate change on annual overheating hours in newly constructed nZEBs. They concluded that the overheating hours of the 2050 and 2100 scenarios with static and adaptative thermal comfort models exceed the acceptable upper thresholds of discomfort in residential buildings. Failure to address overheating risk during design shall leave active cooling as one of the most convenient choices for tenants and owners: the consequences will be catastrophic, resulting in an increase in carbon emissions and hampering the energy transition.

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. Interest is mainly focused on passive cooling techniques, which, contrary to active cooling techniques, 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. 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 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.

Two more studies have been conducted at the University of Liege by two students in the framework of their master thesis. Ani Hovsepyan [7] studied the energy retrofit of a tertiary building and its resilience to global warming while Camille Gobin [8] analysed the impact of global warming on thermal comfort and energy efficiency of a passive building in Liege. She showed that the requirements of current passive buildings might not be sufficient to guarantee thermal comfort in the future and she ended her work by raising an interesting question:

"How should the nZEB model be improved to avoid overheating risks and ensure resilience to global warming?"

This is the question the present work attempts to answer by combining several passive cooling techniques to guarantee thermal comfort in an nZEB in summer. The present work aims at assessing the energy consumption and thermal comfort of a residential building located in Belgium and their evolution under global warming, assuming that no measure is taken to prevent its evolution. The investigation of the existing passive cooling techniques also allows to propose some guidelines to ensure resilience of nZEBs to global warming. Resilience is a frequently used term as it is closely linked to climate change. It can be defined as the ability of a building to withstand disruptions caused by extreme weather events, man-made disasters, power failure, change in use or atypical conditions and its capacity to adapt, learn and transform after those events occur [9].

Some studies are currently lead at the University of Liege to predict the evolution of the energy demand of the Walloon building stock. The present work could be integrated into that project, to study the impact of global warming on a single building which could then be extrapolated to the nZEB building stock.

This work has been realised in the context of an internship in an engineering consulting company named *Ecorce*. It also aims at connecting theory and practice by applying some techniques that sometimes remain at the laboratory stage to real case studies.

The organisation of the manuscript follows the adopted methodology. Chapter 2 introduces the building chosen as baseline. The case study geometry, envelope, system, and operation are detailed. Since the building behaviour is studied through a dynamic simulation, the assumptions made are also developed. Then the building location and climate are introduced. To simulate the climate evolution in Belgium until 2100, a climatic model, called *MAR*, was used. The scenario considered to predict climate change is a *worst-case* scenario, in which no measure is taken to prevent or lessen climate change and society continues to rely on fossil energies for further development.

The building behaviour is modelled through a dynamic simulation made with IES Virtual Environment software (VE), a building performance simulation (BPS) software. VE has a rather user-friendly interface but must be used as a black box regarding the modelling equations. Since the studied building has not been built yet, there is no available data to calibrate the model and make an empirical validation. To cope with this lack of calibration, another model has been developed with EES. The EES model consists in hand-written equations and is thus rather simplified. It shall allow to make a comparative testing of both models. The results of the comparative testing are presented in Chapter 3 and the major differences between the two models are overviewed. Chapter 4 analyses the results obtained for 2020 in terms of thermal comfort and the latter is extrapolated in 2050 and 2100, if no measures are taken to prevent overheating. Chapter 5 proposes several cooling techniques that could be applied to the building to limit the risk of overheating in summer. Some combinations of techniques are reviewed in Chapter 6 and they are used to assess the building resilience to global warming. Finally, the last chapter concludes this work with a summary of the most relevant results and suggests some guidelines to build resilient buildings.

2. DESCRIPTION OF THE BASELINE SIMULATION MODEL

This chapter deals with all the subjects related to the building simulation model. The BPS model is based on a particular building and the results are thus applicable specifically to that building. However, if the building is chosen wisely, it is possible to extend the conclusions to all the buildings belonging to the same category. The concept of the reference building is introduced in the first section of this chapter. The second section presents the majors characteristics, strengths and limitations of the two software used in this study. In the third section, the form, envelope, system and operation of the studied dwelling are detailed, and the parameters and hypotheses of the base case scenario are described. Based on those characteristics, the reasons for considering the studied dwelling as a reference building are overviewed. Finally, the last section addresses the building location and climate. The accuracy of the climatic model and the associated hypotheses are discussed.

2.1. Theory of the reference building

A BPS model can be either specific or generic. A specific model is built when studying a specific dwelling, in the context of an energetic audit for example. BPS models allow to extrapolate the behaviour of a building under different improvements to assess their efficiency. A generic model is built upon a *reference building* and is generally used in the scientific community to draw conclusions that can be generalised to a whole set of buildings.

According to Corgnati *et al.* [10] a reference building can be defined as *"a building characterised by and representative of its functionality and geographic location, including indoor and outdoor climate conditions. It aims to represent typical and average building stock in terms of climatic conditions and functionality".* Reference buildings are used in the scientific community as they allow to compare the results obtained by several researchers without the bias introduced by the building itself. All modelers use the same reference building to begin with the same starting point even though they do not use the same software. Although the building used is the same for all the studies, the results obtained for the base case scenario can vary depending on the modeler inputs or the software itself. This is discussed in the next section.

The data collected to create a reference building can be classified into four categories:

- **Form** regards the type, size and general geometry of the building.
- **Envelope** refers to the construction technologies and materials used in the building, providing a description of the thermophysical properties of the building envelope.
- **System** mainly concerns the HVAC systems.
- **Operation** consists of the operational parameters affecting the usage of the building, expressed through a set of schedules (occupancy, lighting, equipment, heating schedules).

There exist three types of reference buildings which differ by the way data about those four categories are collected.

- An **Example reference building** consists in an ideal building model defined based on experts' inquiries and assumptions. This methodology is used when no statistical data are available. Information come from various sources and are properly combined to provide the most probable building, within a selected location and usage.
- A **Real reference building** is based on a real existing building with average characteristics that represent a specific building category. The advantage is that it allows to validate and calibrate the building model by carrying out a testing campaign.
- A **Theoretical reference building** is an ideal building model defined by processing statistical data. The building is therefore made of the most commonly used materials and systems. It represents the average building of the studied category, but it requires enough data to generate a strong reference building, hence more time for data processing.

The characteristics of the nZEB dwelling used in the present work are presented in section 2.3. Section 2.4 discussed the reasons for considering the chosen dwelling as a reference building.

2.2. Presentation of used software

2.2.1. EES

EES (Engineering Equation Solver, pronounced 'ease') is a general equation-solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations. The program can also be used to solve differential and integral equations, solve optimization problems, provide uncertainty analyses and perform linear and non-linear regression. A major feature of EES is the high accuracy thermodynamic and transport property database provided for hundreds of substances that can be used with the equation solving capability. Moreover, EES automatically identifies and groups equations that must be solved simultaneously. This feature simplifies the process for the user and ensures that the solver always operates at optimum efficiency [11].

Since all the equations should be hand-written, the limitations of the software rapidly appear. The heat transfer models and physical phenomena should remain simple enough to ensure the convergence of the model. In the same way, it is important to limit the number of thermal zones to prevent being overwhelmed by the number of equations to handle. The model created with EES thus gives a more physical approach of the building model and is used to understand the impact of the various variables.

2.2.2. IES VE

Contrary to EES, VE by IES is a software that has been specifically developed for building performance simulation. It includes several modules that handle different features of the building. ModelIT is the tool with which the geometry of the building is created, and the building location and weather file are set. SunCast is a simulation tool used for shadow analysis based on the building geometry and the irradiation from the weather file. From the position of the Sun, it determines the solar irradiation entering the building at every hour of the year. ApacheSim is the core of the model. In this module the building envelope characteristics are defined, as well as the operation schedules, the heating and ventilation systems, etc. It is also the module from which the simulation is launched. Finally, the MacroFlo module is used to model natural ventilation inside the building by defining a window opening schedule and some opening characteristics.

VE has been approved by international standards such as ASHRAE 140, BESTEST, CIBSE, EU EN13791 and ISO, which all set criteria to respect to be recognised as a trustable BPS software.

Unlike EES, VE must be taken as a black box and the underlying equations are not accessible nor modifiable by the user. It is thus more difficult to feel the physics of the model and the errors possibly made when entering the parameters of the model are harder to detect.

2.3. Description of the building characteristics and simulation model parameters

To generate the BPS model, information about the dwelling geometry, envelope, systems, and operation are required. This section details the characteristics of the studied dwelling as well as the hypotheses made when creating the thermal models.

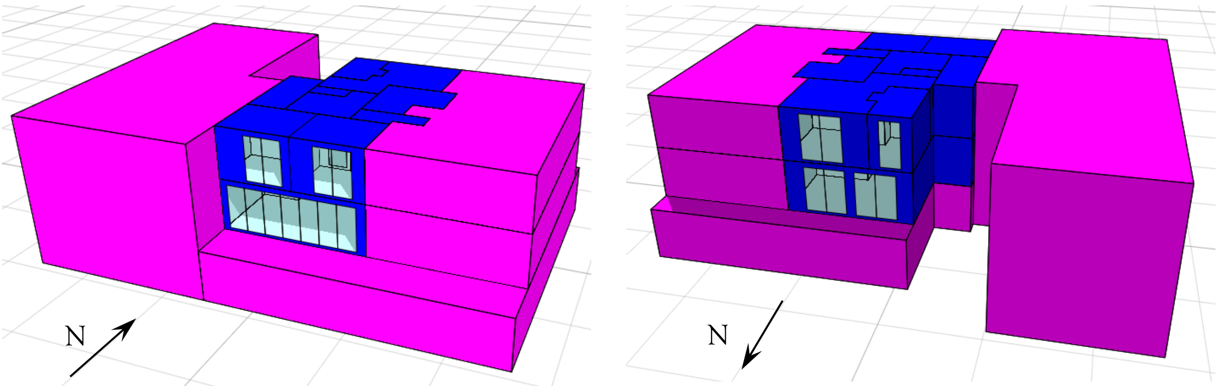
The studied dwelling has not yet been built, but the building's blueprint has already been drawn and the EPB (energy building performance) file has already been encoded. The EPB file is generated by a software based on the EPBD. It consists in a static analysis of the building and contains information about the envelope, ventilation and heating systems, standard values of infiltration rate, and so on.

2.3.1. Building geometry

The studied building will be located in Liege. The current existing dwelling will be demolished to free up the space for the new building. The latter is 10-storey high with a cultural centre on the ground floor, apartments from 1st to 7th floor and two duplexes on the last two floors. This study focuses on one of the two duplexes. The living room of the duplexes is South-oriented, and the South-facing wall is constituted of a bay window. Most recent constructions have a high window-to-wall ratio (WWR), mainly for aesthetic reasons. For this building, the WWR is 0.36.

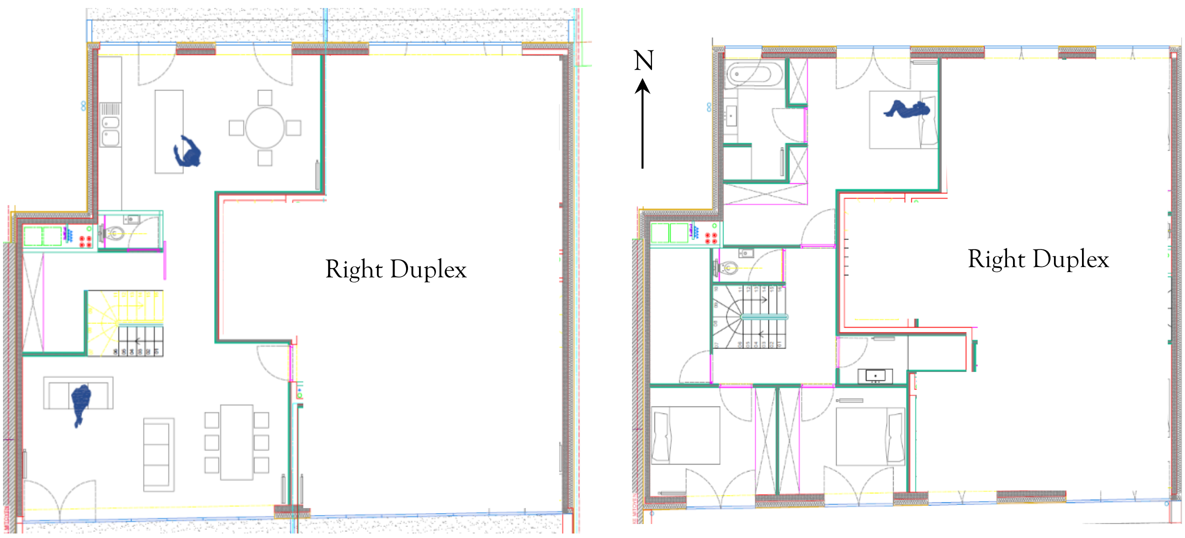
As shown on the 3D model of the duplex (see Figure 2), it is South-oriented and surrounded on the East and West sides by adjacent buildings (shown in pink). It lies above another storey, so it is not in direct contact with the ground. Figure 3 is a 2D view of the inside of the duplex. It has a total surface area of 173 m² and spreads on two floors. On the first floor, there is a living room, communicating with the kitchen, as well as a laundry and toilets. The living room is South oriented, facing the Meuse and the external wall is entirely constituted of a bay window. The second floor is composed of three rooms, two South-facing and one North-facing, two bathrooms, toilets, and a storage room.

Figure 2 – 3D model of the studied building **(a)** South view **(b)** North view.



(a) (b)

Figure 3 – Upper view of the studied duplex (a) first floor (b) second floor



(a) (b)

2.3.2. Building envelope

One of the most important information about a building is its envelope. The wall composition plays a major role in the heat losses to the external environment and in the thermal capacity of the building. The wall materials and thicknesses determine its U-value (W/m²·K). The smaller the U-value the better the building insulation. The Walloon Region imposes energy performance standards for buildings through the EPBD, which is reviewed each year. Table 1 shows a comparison between the U-values of the building walls and the U-value requirements of the EPBD 2020 [12]. All the walls are compliant with the EPBD 2020 and almost all of them also meet the standards of the passive house which impose a maximum U-value of 0.15 W/m²·K for external walls [13]. More information about the building envelope can be found in Appendix A.1.

The glazing has been defined in the EPB file of the building as triple-glazing. The frame of the window, made of wood and aluminium, has a U-value of 0.9 W/m²·K, resulting in a net U-value of 0.6 W/m²·K, in compliance with the EPBD. The U-value is even lower than the standard value of 0.8 W/m²·K for the passive house.

The solar factor of the glazing is a ratio between the solar irradiation that actually enters the building and the solar irradiation that reaches the outer surface of the window. The solar gains thus consist in the irradiation that is directly transmitted through the window and the irradiation that is absorbed by the window and re-emitted inside the room. The solar factor should be at least 50% to ensure that the gains through the glazing are larger than the losses. For a passive house, a South-orientation is recommended to maximise the solar gains. They should compensate for 40% of all the heat losses of the building [13].

Table 1 – U-values of the building envelope.

	U-value encoded in the EPB [W/m²·K]	**Maximum U-value authorised by the EPBD [W/m²·K]**
External walls	0.152	0.24
Wall between two adjacent buildings	0.198	1
Internal wall	0.452	1
Roofing	0.081	0.24
Floor/ceiling	0.132	0.24
Window:		
Net U-value	0.6	1.5
Glass only	0.6	1.1

2.3.3. Furniture model

The room furniture can store energy which is released afterwards and can prevent overheating in summer. Furniture adds inertia to the room and its global inertia is written as

$$C_{room} = (1 + f)\, C_{air}$$

with f the furniture mass factor. Generally, the room thermal capacity is supposed to be 5 or 6 times higher than that of air. This factor is mostly used in simulations that can be compared to measured data to consider the change of density of heated air. When the room is heated, the air expands and its density decreases. Hot air rises and creates a vertical temperature difference. There is a delay before the sensor measures the rise in temperature of the room and this delay is taken into account by artificially increasing the thermal capacity of the room in the simulation.

2.3.4. Systems

2.3.4.1. Ventilation system

There are three contributions to air renewal in a building. Natural ventilation consists in opening windows to guarantee a good indoor air quality. The air is renewed 5 to 40 times more than required. This non-permanent action is desired but cannot be controlled. On the contrary, mechanical ventilation is a desired and controlled action taken permanently to ensure a good indoor air quality. Finally, infiltration is an undesired, uncontrolled and permanent phenomenon due to air flow through cracks.

a. Mechanical ventilation

The duplex is equipped with a type D ventilation system with a heat recovery module. Stale air should be extracted from humid rooms, such as the bathrooms, toilets and kitchen, and fresh air must be supplied in the living room and the bedrooms to ensure a good indoor air quality. The residential ventilation air flow rates are given in norm NBN D50-001 and are specified in Table 2.

Table 2 – Ventilation system: supply and exhaust air flow rates.

1st FLOOR	Supply		Exhaust	2nd FLOOR	Supply		Exhaust
	m^3/h	($m^3/h{\cdot}m^2$)	m^3/h		m^3/h	($m^3/h{\cdot}m^2$)	m^3/h
Living	150	(3.6)		Bedroom	165	(3.6)	
Kitchen			75	Bathroom			50 x 2
Laundry			50	Toilet			25
Toilet			25	Corridor			40
Total	*150*		*150*	*Total*	*165*		*125* +40

If the ventilation flows specified by the norm are used, the equilibrium between supply and exhaust is not reached. It is necessary to add exhaust in some rooms to avoid having an over-pressurized building. For the simulations, it has been decided to add an exhaust air flow rate of 40 m^3/h in the corridor, as marked in red in the table.

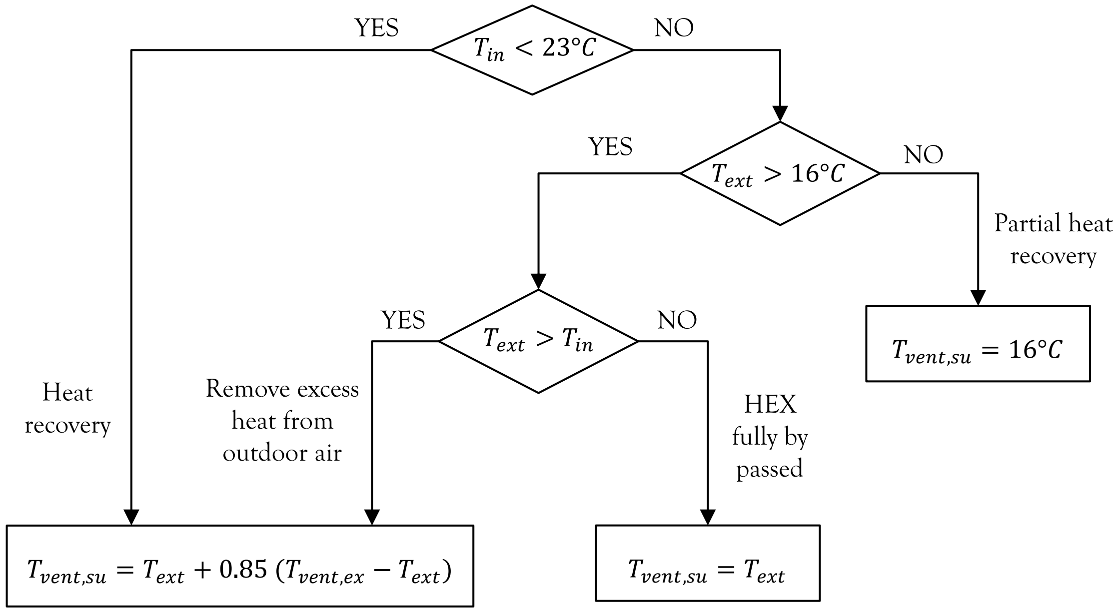
Table 2 also shows that the air flows at each floor are balanced. It is assumed that there is no ventilation coupling through the stairs between both floors. In practice, there could be a coupling through the stairs since the living room is South-oriented, hence has important solar gains, contrary to the corridor. The warmer and lighter air of the living room could rise while the cooler and heavier air of the corridor would tend to go down. However, the air exchange due to buoyancy forces is neglected.

The heat recovery module has an efficiency of 85% and is equipped with a by-pass system, as required by the EPBD. In winter, the heat from the exhaust air is recovered to heat up the fresh supply air directly coming from the outside and to avoid creating a local thermal discomfort due to cold air draught.

During transition seasons, the heat recovery module can be by-passed to perform free cooling. When the indoor temperature becomes too high due to high internal or solar gains, the heat from the exhaust air is not recovered and fresh air is supplied directly into the rooms. It allows to increase the heat losses through ventilation, hence decrease the indoor temperature and improve thermal comfort. However, if the indoor temperature becomes too high while the outdoor temperature is low, for example during a particularly sunny winter day, the heat recovery module can be partially by-passed.

In summer, when the outdoor temperature is higher than the indoor temperature, it can be useful to stop by-passing the heat recovery module to remove the excess heat from outdoor air and slow down the heating process by preventing heat from entering the building for as long as possible. Figure 4 shows the flow chart diagram used to compute the supply ventilation temperature, $T_{vent,su}$, based on the indoor and outdoor temperatures, respectively T_{in} and T_{ext}. $T_{vent,ex}$ is the exhaust air temperature.

Figure 4 – Flow chart diagram of the supply ventilation temperature.



b. Natural ventilation

Several methods can be used to take advantage of natural ventilation in a building and their efficiencies can be compared. The considered methods are described in more details in Chapter 5.

To model the natural ventilation in VE, the MacroFlo module shall be used. The required characteristics to compute the air flow entering through the opening are the openable area, the exposure to the outside environment and the opening category. Those parameters are presented in Table 3. In the case of the studied building, the Southern facade is facing the Meuse and is exposed to wind while the North facade, facing a building block, is considered as semi-exposed. Since the duplex is at the 8th floor of the building, the building type is high-rise, and the wind speed is adapted accordingly.

The parameters that determine the opening schedule of the window are discussed in section 5.4.

Table 3 – Definition of the opening types in MacroFlo.

	Living	Kitchen	Bedroom 1	Bedroom 2
Exposure type	High-rise exposed wall	High-rise semi-exposed wall	High-rise semi-exposed wall	High-rise exposed wall
Opening category	Sliding window	Sliding window	Bottom-hung window	Bottom-hung window
Openable area	50%	50%	95%	95%
Max angle open	-	-	10°	10°

c. Infiltration

The infiltration rate inside the building cannot be known in advance. It can be obtained by performing a blower door test. The building is pressurised to 50 Pa and the necessary air flow rate to maintain the pressure difference is measured. This value is called the leakage rate at 50 Pa and is noted q_{50} (m³/h). Commonly, the leakage rate is rather expressed in ach (air change per hour) and is noted n_{50}. For a new residential construction, the EPBD requires a value of n_{50} in the range of 0.6 to 1 ach [12], [13].

MacroFlo also offers the possibility to model the infiltration by defining a crack flow coefficient and a crack length for each opening. However, since those values cannot be measured and the infiltration losses are negligible, the infiltration rate is chosen to the theoretical value of 0.6 ach at 50 Pa.

2.3.4.2. Heating system

The duplex is heated through a traditional heating system composed of water radiators fed by a gas boiler. The gas boiler feeds the whole building, but in the context of this study it will be assumed that it is unique to the duplex. The radiators have not been dimensioned yet; their nominal power is deduced from the simulations. The radiators are made of aluminium and their temperature regime is 70/50 °C.

a. Temperature set point

The temperature set point is the temperature at which a room should be maintained during occupancy period. Depending on the room purpose and on occupants' clothing, the temperature set point can vary. They are specified in norm EN 12831 [14] (see Table 4). Since those temperatures should only be reached when the room is occupied, two heating strategies can be applied. The first strategy consists in keeping the set point temperature all the time, even when the room is unoccupied. The second strategy is to turn off the heating system during the night and to rely on the building inertia to keep the room temperature near the set point. However, it is important to prevent temperature from dropping under 18°C, otherwise it would take a larger heating power to bring the room back to the set point temperature. In this case, since the building is properly insulated, meeting such a requirement does not cause major problems.

Table 4 – Definition of the temperature set points for heating.

Type of activity/clothing	Room	Temperature set point [°C]
Room with normally dressed people doing sedentary activity	Kitchen Living	20
Sleeping	Bedroom	18
Room with under dressed people doing sedentary activity	Bathroom	23
Room with normally dressed people doing a short activity or simply passing through	Laundry Corridor	16

b. Heat load of the radiators

The rooms are heated up with aluminium radiators, but their heat load has not yet been sized. Several methods can be used to size the radiators. Generally, some norms impose guidelines at a regional level that should be carefully followed. For example, in Belgium, a software based on norm EN 12831 has been developed. It realises a steady-state analysis of the heat losses when the outside temperature is -8 °C. The radiators should be sized to compensate those losses. This design ignores the internal gains brought by people, equipment, and lighting, as well as the solar gains. It thus consists in a *worst-case scenario* that ensures that the building can always be heated at the desired set point temperature.

The heat load can also be computed through the dynamic simulation. The software adds the internal gains, subtracts the heat losses, and deduces the heat load that must be applied to maintain the temperature set point.

c. Annual energy consumption

As far as the annual energy consumption of the building is concerned, there are binding limitations to be respected for a building to be considered as an nZEB. On the one hand, according to the EPBD 2020, the annual energy consumption of a new residential building should not exceed 115 kWh/m^2·year. On the other hand, the passive house standard requires an annual energy consumption for domestic heating of 15 kWh/m^2·year, or 10 W/m^2 peak demand, and the overall energy needs should not exceed 42 kWh/m^2·year [15], [12], [13].

2.3.5. Operation

The building operation is characterised through a set of schedules describing occupancy, electric appliances, lighting, heating, and consumption of domestic hot water. Since the building has no characteristic operation, the operation schedules and consumptions should be defined based on representative norms, *i.e.*, norms ISO 17772, NBN EN 15193 and NBN EN 15251 [16]. More information about norm ISO 17772 can be found in Appendix A.2.

2.3.5.1. Internal gains

Some internal gains can be added in the model to consider the heat produced by the occupants or the energy gain of equipment such as television, fridge, oven, washing machine, dishwasher and other domestic appliances that consume electricity and can release energy in the surrounding atmosphere. The internal gains are divided into three categories: occupancy heat gain, lighting gain and equipment gain. The heat production from lighting and equipment is strictly related to their power consumption. For each type of internal gain, a schedule is specified as well as a power consumption/production.

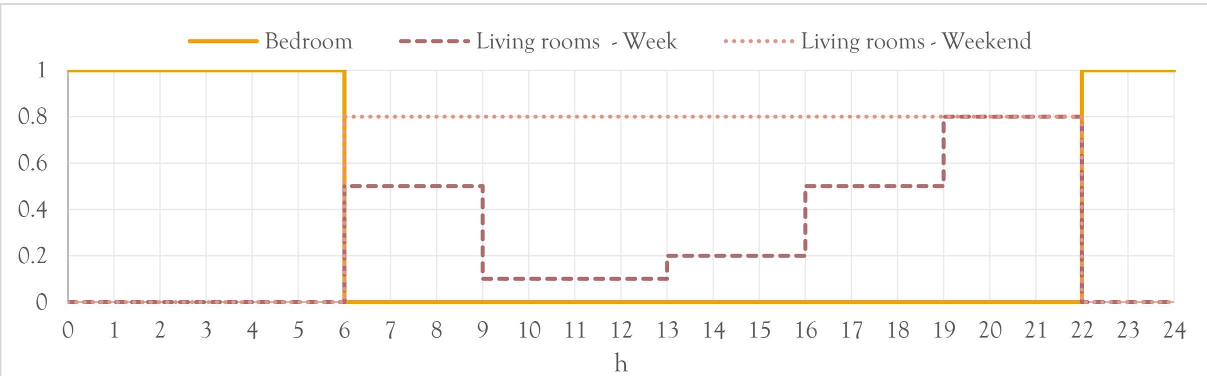
a. Occupancy heat gain

The occupancy heat gain corresponds to the heat produced by the occupants. Each occupant is supposed to produce a certain amount of heat which depends on its metabolic rate. To describe the occupancy heat gain, a heat rate production as well as an occupancy schedule are required.

The occupants' metabolic rate is influenced by their activity, age and sex. For example, young children are assumed to have a metabolic rate of 60 W while 100 W are generally considered for teenagers or adults doing a sedentary activity [17]. According to norm ISO 17772, an average person is supposed to produce 70 W while sleeping and 100 W while doing a sedentary activity such as reading, watching TV, or eating. One third of the energy emitted by an average person is released as latent energy.

The number of people occupying the building can be deduced based on the number of bedrooms. In this case, the apartment is designed for four people. And they are all supposed to have an adult metabolic rate. Contrary to a tertiary building such as an office or a school, the occupancy profile of a residential building strongly varies depending on the occupants' behaviour and occupation. ISO 17772 specifies the occupancy schedule that should be used by default (see Figure 5). It is expressed as a modulating profile, meaning that when the value of the occupancy profile at hour *h* is 1, all the occupants are present in the apartment. The shape of the occupancy schedule suggests that the occupants are an active couple with two children attending school. During daytime (from 6am to 10pm), the occupants are supposed to be evenly distributed in the living areas, *i.e.*, the kitchen and the living room.

Figure 5 – Occupancy schedule.



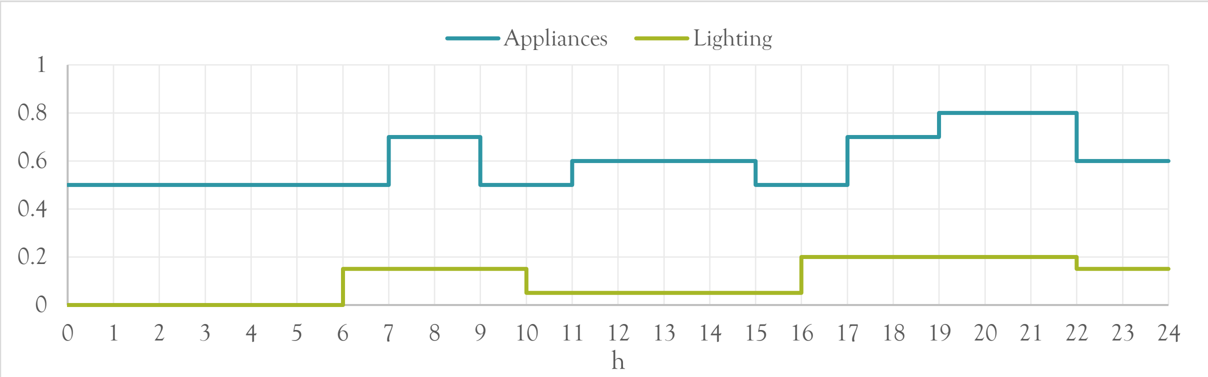
b. Lighting gain

The second source of internal gain is lighting. The energy consumption related to luminaires can be found in the norm NBN EN 15193, specifically dedicated to lighting [18]. A good approximation of the average energy consumption of the building for lighting is to consider 6 W/m² in each room. Then the modulating profile of Figure 6 can be applied. The lighting profile, found in norm ISO 17772, is supposed to be the same during week and weekend.

c. Equipment gain

The last internal gain to be considered is equipment gain. Just as in the case of occupancy profile, there can be as many equipment profiles as equipment users. Norm ISO 17772 gives a default equipment schedule for residential buildings, which is also shown in Figure 6. The energy consumption related to equipment is supposed to be 3 W/m² in the living room, the kitchen, and the laundry, which are the room where most of the electricity is consumed. The bedrooms and bathrooms are supposed to have an energy consumption of 2 W/m². Those values are consistent with the annual consumption of electricity of a 4-person residential building in Belgium, which has been estimated at 3 200 kWh/year in 2018 [19]. The total energy consumption of this dwelling is 2 850 kWh/year, or 16 kWh/m²·year.

Figure 6 – Equipment and lighting schedules.



2.3.5.2. Domestic hot water consumption

Still according to norm ISO 17772, the global hot water (DHW) consumption of a residential apartment is supposed to be 100 L/m²·year, for a total of 17.3 m³/year. 80% of the water is used in the bathrooms and 20% in the kitchen.

2.3.6. Thermal zoning

Sometimes, modelling all the physical zones of a building is too difficult and time-consuming. Zones that are thermally similar can be gathered in one single thermal zone, reducing calculation time. To be gathered in a thermal zone, rooms must have the same behaviour when it comes to:

- **Usage:** all the rooms should have similar internal loads and usage schedules.
- **Temperature control:** all rooms should have the same temperature set point.
- **Solar gains:** all rooms should have the same orientation, solar shading, and glazing characteristics.
- **Ventilation:** all rooms should be either humid (air exhaust) or dry (air supply).

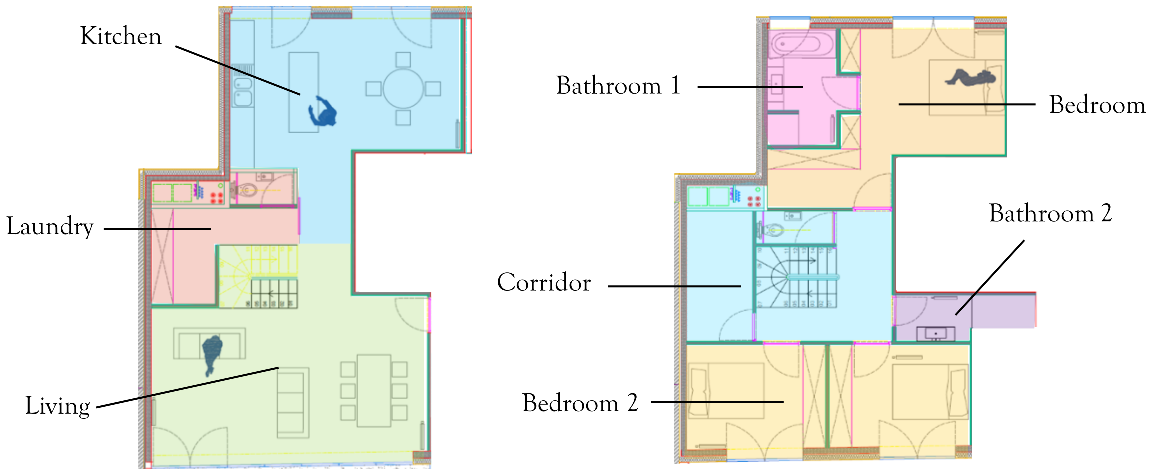
The thermal zoning of the studied building and the attributed names are shown in Figure 7.

2.4. Assessment of the representativeness of the building

The building studied in the present work belongs to the Belgian nZEB stock. It has been demonstrated that its envelope is compliant with all the EPBD requirements, and the operation of the building has been standardised following the specifications of norm ISO 17772. The only reason for which this dwelling could not be considered as representative of other nZEBs is because of its geometry. The dwelling is a four-person duplex located on the last floor of a 10-storey building. This case study is interesting since it gathers all the conditions that could lead to overheating. First, the duplex is designed to be a family duplex, which increases the internal gains. Then, as most passive houses, it is South-oriented to maximise the solar gains. Because of its South-orientation, the high window-to-wall ratio and the fact that it is on the last floor of the building, this duplex is prone to overheating. The results might not be generalised to the whole building stock, even though nowadays new constructions tend to have a high South window-to-wall ratio. But most of the conclusions of this work could be extended to other nZEBs to prevent overheating during the design phase.

The reference building proposed in this study is thus a mix between a real and an example reference building. The form and envelope of the building are based on a real existing building while systems and operation are based on norms.

Figure 7 – Division in thermal zones.



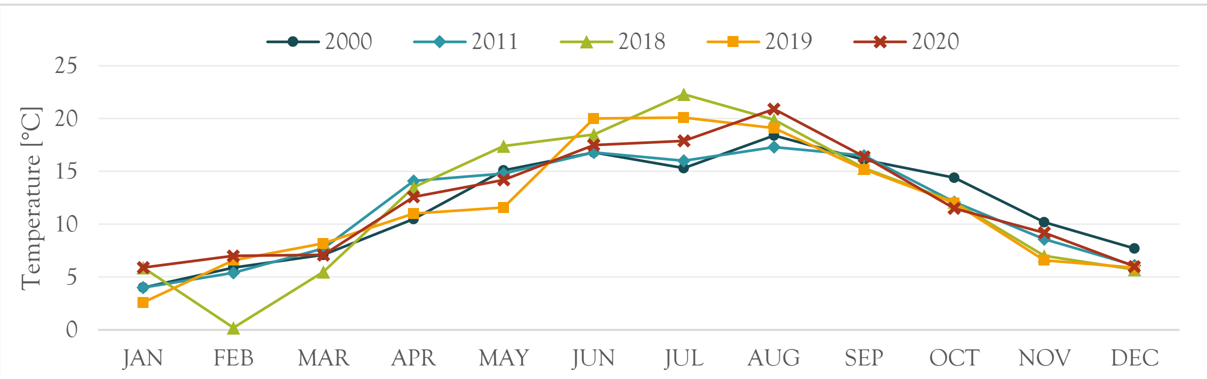
2.5. Location and climate

Climate plays a key role in the energy consumption of any building, so it is important to use the appropriate location settings for any analysis. The studied building is in Liege. According to the ASHRAE climate zones, Belgium is part of zone 4A, meaning that the climate is considered as mixed humid.

2.5.1. Description of 2020 climate

The Royal Institute of Meteorology (IRM) describes the year 2020 as exceptionally warm and sunny but with precipitation close to normal in frequency and quantity [20]. The spring months and September were particularly sunny compared to the average of 1991 to 2020. Globally, each month experienced higher temperatures than average, making 2020 the warmest recorded year since measurements began in Uccle in 1833, with an annual average temperature of 12.2°C. The previous record was 2018 with 11.9°C while the average is 10.9°C.

Figure 8 – Evolution of the temperature along the year in Belgium.



Since 2010, the annual temperature tends to increase. The average annual temperature has increased from 10.5°C between 1981 and 2010 to 10.9°C between 1991 and 2020. Moreover, 2020 is the 6th consecutive year experiencing a heat wave. Figure 8 shows the evolution of the monthly temperature since 2000. The monthly temperatures in 2000 and 2011 are similar and close to the normal temperatures. 2018, 2019 and 2020, as a consequence of the global warming, have been warmer in summer than the beginning of the century. The winter period on the other hand seems to remain stable.

Those observations from the IRM in Belgium have also been reported at a bigger scale in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2001 [21].

2.5.2. Obtaining weather conditions with the MAR model

When performing a dynamic simulation, information about the weather is required. VE gives access to some Energy Plus weather files containing data for variables such as dry bulb and wet bulb temperatures, wind speed and direction, direct and diffuse solar irradiation, or cloud cover for each hour of the year at various locations. The nearest location for which VE has a weather file is St-Hubert, about 70 km South of Liege. The available weather files are often TMY files. A Typical Meteorological Year is not a real year but an average of the measured data over a 10-to-20-year period to smoothen the weather anomalies. However, those files are generally old and with global warming, they can be obsolete. The files used in this work have been generated at the Laboratory of Climatology and Topoclimatology of the University of Liege with a regional climatic model called *Modèle Atmosphérique Régional* (MAR) that is used to make projections of climate change in the greatest cities of Belgium.

Projections of climate change due to anthropogenic forcing, *i.e.* the increasing greenhouse gas (GHG) concentration, are generated with modelling tools called coupled Atmosphere-Ocean General Circulation Model (AOGCM). An AOGCM is a climatic model based on the Navier-Stokes equations applied to a rotating sphere and on thermodynamics balance equations to include the energy sources. This model allows to predict the atmosphere circulation as well as the ocean circulation. However, to give a good representation of the ocean circulation, timescales of the magnitude of 0.01 to 0.001 seconds are required. To avoid too long computation times while respecting the convergence condition of Courant-Friedrichs-Lewy [22], the horizontal spatial resolution of AOGCMs is relatively coarse (150 to 600 km). AOGCMs provide a good representation of the *global* average climate. However, regional climate is often influenced by forcing and circulations that occur at the sub-AOGCM horizontal grid scale. Consequently, some "regionalisation" techniques have been developed to create regional climate models (RCM), which are AOGCMs nested in a limited area [21]. Compared to global circulation models, RCMs are calibrated for a specific region, with a detailed physics developed for it. RCMs thus increase spatial resolution for an identical computation time [23].

The AOGCM has been downscaled to an RCM by the University of Liege using the MAR. The MAR was created in the end of the 20th century and was initially designed for polar regions. Since then, it has been further developed at the University of Liege and adapted specifically for Belgium [24]. It allows to perform high-resolution (5 km) simulations over Belgium [25] and it was used to create global warming simulations for the largest Belgian cities from 2012 to 2100.

The RCM MAR characterises the current and future evolution of hydroclimatic conditions and global irradiation [26]. However, even though the model was perfect, it could not make accurate predictions if the initial conditions were not correct. Errors in the initial conditions would eventually be amplified, pulling the prediction away from reality. To limit the risk of such errors, the climatic model is reanalysed, meaning that it is adjusted to provide results as close as possible to the observations. Hersbach *et al.* define a reanalysis model as an optimal combination of models and observations that provides consistent climate variables and strives to ensure integrity and coherence in the representation of the main Earth system cycles [27]. Historical simulations were performed with the MAR over the period 1980-2014.

Once the initial conditions have been determined, the climatic model also requires boundary conditions and a plausible scenario for climate change predictions. As already stated, the regional circulation model is nested in a limited area and the boundary conditions are provided by a larger scale climatic model, called a global circulation model (GCM). There exist over thirty GCMs which better describe some regions of the world. The MAR was forced at its boundaries with the three GCMs that best represent the current atmospheric circulation over Western Europe.

Climate projections are driven by anthropogenic GHG emissions, which themselves depend on societal development. Several hypotheses can be made to define future pathways of societal development, called the Shared Socioeconomic Pathways (SSPs). The scenario considered in this work is called SSP5 and corresponds to the scenario in which the society continues to rely on fossil fuels for further development and no measure is taken to avoid or limit global warming. It is thus a *worst-case* scenario. This SSP can be linked to an evolution of the concentration of GHG in the atmosphere, called a representative concentration pathway (RPC). Some RPCs have been calculated by the IPCC and the only one plausible with the SSP5 scenario is RPC-8.5 [28]. This means that by 2100, the GHG emissions will increase in such a way that radiative forcing would grow by 8.5 W/m^2. Radiative forcing is the infrared irradiation that the Earth should emit in order to balance the irradiation entering and leaving the atmosphere. The direct consequence of radiative forcing is the rise in temperature.

Future projections, from 2012 to 2100, were then achieved with the MAR under the SSP5-8.5 scenario with the three chosen GCMs at its boundaries. They are then classified according to the temperature they indicate at the end of the 21st century, giving a cold, a medium and a warm model (called simulations in the following). This ranking allows to obtain an uncertainty spread for the future, in the case no action is taken to prevent global warming or at least to lessen its consequences.

Currently, the urban heat island (UHI) effect is considered in the MAR with a simplified model. UHI is the most documented phenomenon of climate change. The phenomenon is known for almost a century and is related to higher urban temperatures compared to the adjacent suburban and rural areas. Higher urban temperatures are due to the positive thermal balance of urban areas caused by the important release of anthropogenic heat, the excess storage of solar radiation by the city structures, the lack of green spaces and cool sinks, the non-circulation of air in urban canyons and the reduced ability of the emitted infrared radiation to escape in the atmosphere [29]. In the current version of the MAR, the UHI effect is simply accounted for by assuming that an urban pixel is warmer than a suburb pixel. A more complete characterisation of the UHI effect will be made in a further study and is likely to introduce changes in the global warming simulations. However, this more detailed model is not expected before 2022 and it should be kept in mind that it could influence the conclusions of the present work.

The results of the cold and medium simulations are used in the BPS programs to consider the impact of global warming on the studied building. For the year 2020, instead of using actual data files, it has also been decided to use the results of the simulations for 2020. The reasons of this choice are explained below.

2.5.3. Choice of weather data for the baseline

At the time of the present work, only two out of the three simulations had already been performed. Only the results of the cold and medium simulations were available. The monthly average temperatures of the two simulations are compared with the actual temperatures observed in 2020 in Figure 9. Globally the cold simulation underestimates the temperature observed in 2020. The normalised mean absolute error on the temperature is 3.5°C for the cold simulation against 1.5°C for the medium one. In both cases, the simulation data underestimate the real data. But in the case of the medium one, the simulated data remain under the 2°C threshold imposed by [21]. Therefore, the year 2020 of the medium simulation has been chosen to represent the 2020 scenario.

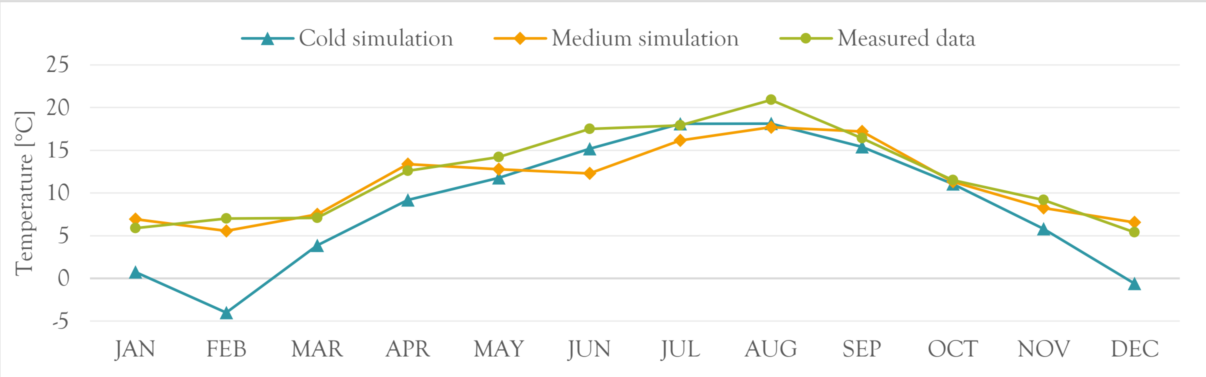
Great care must be taken when comparing the results of the MAR simulations with real measured data. The simulated temperatures were obtained by forcing the MAR with a GCM. By definition, a GCM represents an *average* climate with an *average* variability among the simulated variables. A specific year of the global warming simulation does not contain the weather anomalies that can be observed during the real corresponding year. Extreme meteorological events are not supposed to occur in the simulations.

Another source of uncertainty is the measured data itself. On the one hand there can always be measurement errors due to sensors and on the other hand, the data come from the meteorological station located in Uccle, about 100 km East of Liege [20].

For the sake of consistency regarding the building location and the nature of the weather files, it has thus been decided to use the meteorological file built based on the results of 2020 of the medium simulation.

Even though the cold simulation is not used in the 2020 model, it is considered when studying the impact of climate change on the building behaviour in 2050 and 2100 to account for the uncertainty spread.

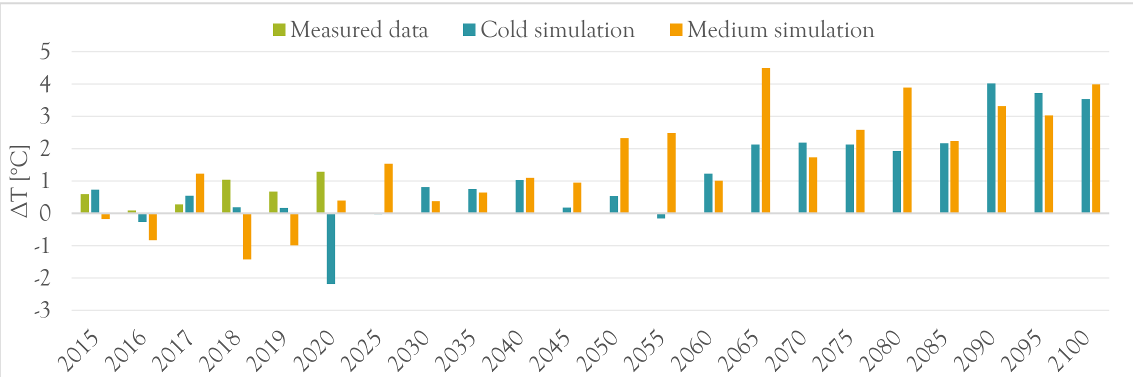
Figure 9 – Comparison of the monthly average temperature in 2020 for the two global warming simulations of the MAR and the measured temperatures.



2.5.4. Analysis of global warming simulations

As already mentioned in the previous section, two simulations are studied to understand how the energy consumption of the building evolves with global warming. Figure 10 shows the evolution of the difference between the average annual temperature of the measured and simulated data and the standard average temperature of Belgium which is 10.9°C. Globally the medium simulation is warmer than the cold one but in 2100, the annual temperature is almost similar for both simulations. If no measure is taken to lessen or even reverse global warming, the temperature rise by 2100 is expected to be around 4°C.

Figure 10 – Evolution of the anomalies in annual average temperature with global warming.



This study mainly focuses on three years to study the impact of global warming. 2020 is taken as the baseline and 2050 and 2100 are used to quantify the impact of global warming on energy consumption and thermal comfort. Figure 11 shows the monthly temperatures obtained for the three studied years with the two global warming simulations. The cold simulation, shown on Figure 11a, results in an overall warming which is even more dramatic in winter than in summer. On the contrary, in the medium simulation, the temperature in winter is almost constant through the century, while summers are becoming hotter.

There are no extreme events in the meteorological files, and there should be no heat waves. The World Meteorological Organisation defines a heat wave as five or more consecutive days of prolonged heat, i.e. with a daily maximum temperature at least 5°C higher than the average maximum temperature. Currently, the average maximum temperature in Belgium is 25°C but with global warming it is expected to increase. Phenomena that are today called "heat waves" might become an ordinary situation in the future, hence there could be today's heat waves in the future simulations.

Global warming does not only impact the environmental temperature. The global warming simulations have been obtained by forcing the global circulation model with an increasing GHG concentration. Temperature increase is the direct consequence of the emphasised greenhouse effect, but all the variables considered in the model interact together and they can be influenced either by a negative feedback or by a positive one. For example, on the one hand, a rise in temperature can enhance evaporation, hence increase specific humidity and formation of clouds that block some of the sun irradiation. On the other hand, if the temperature increases, it tends to increase the partial pressure of saturated water, resulting in a decrease in relative humidity, hence less condensation and less clouds to obstruct the sun irradiation.

For the considered simulations, there is a positive feedback between temperature and solar irradiation. Figure 12 shows the increase in temperature, cloudiness and irradiation compared to the climate of 2020 for each simulation. The temperature affecting positively the solar irradiation further enhances the risk of overheating in summer.

Figure 11 – Impact of global warming on the monthly temperature in the (a) coldest, (b) medium simulations.

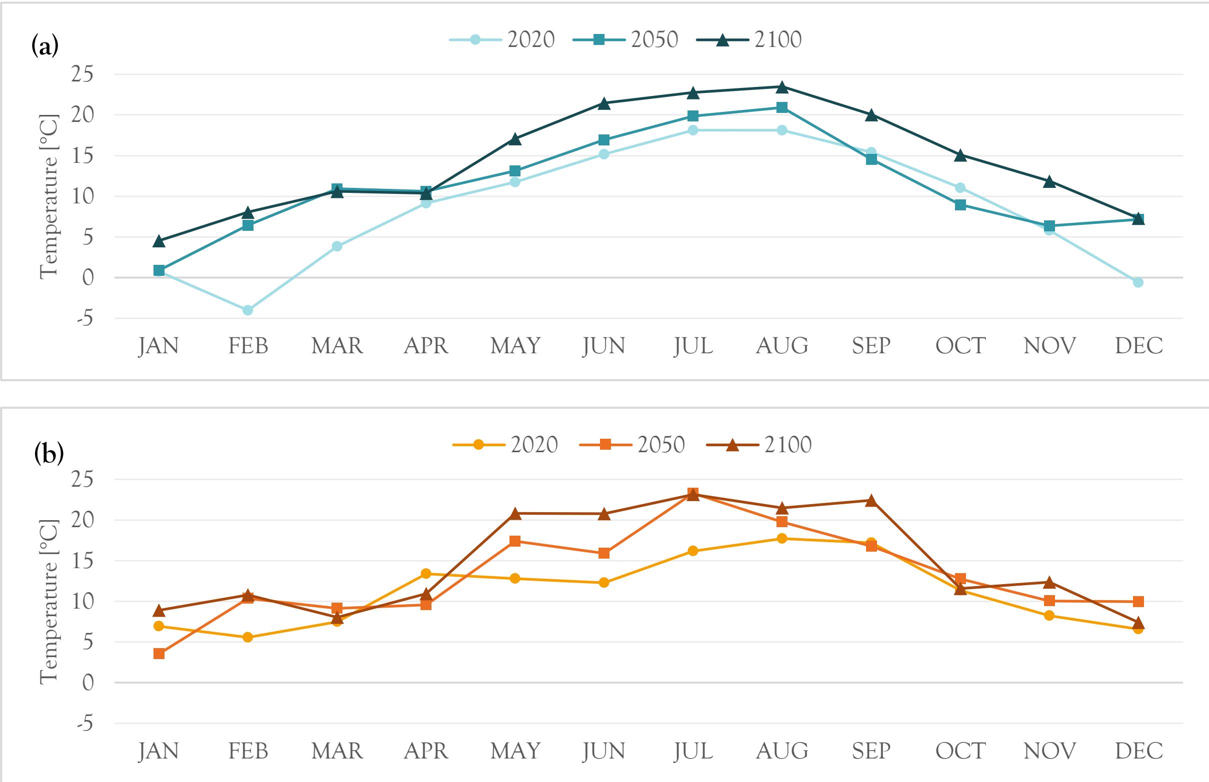
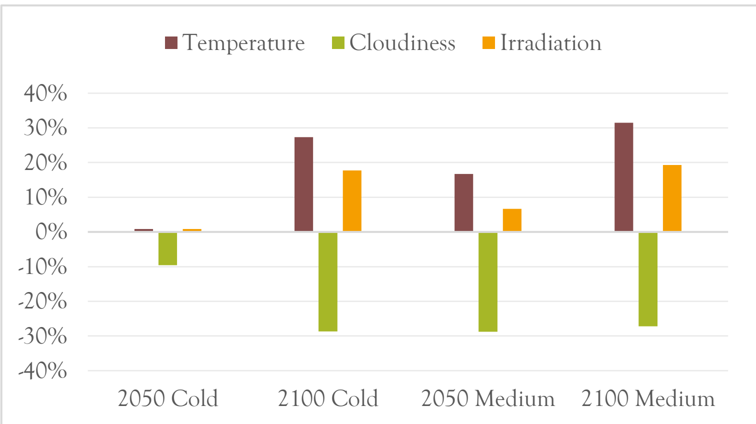


Figure 12 – Evolution of the mean temperature, cloudiness and irradiation with respect to the climate of 2020 depending on the global warming simulation.



2.5.5. Extreme meteorological event

Pidcock & MacSweeney [30] created an interactive map gathering more than 350 peer-reviewed studies looking at weather extremes around the world. Their analysis revealed that 70% of the 405 extreme weather events and trends included in the map were found to be made more likely or more severe by human-caused climate change. Combining the evidence over the past 20 years, the literature is heavily dominated by studies of extreme heat (33%), rainfall or flooding (20%) and drought (17%).

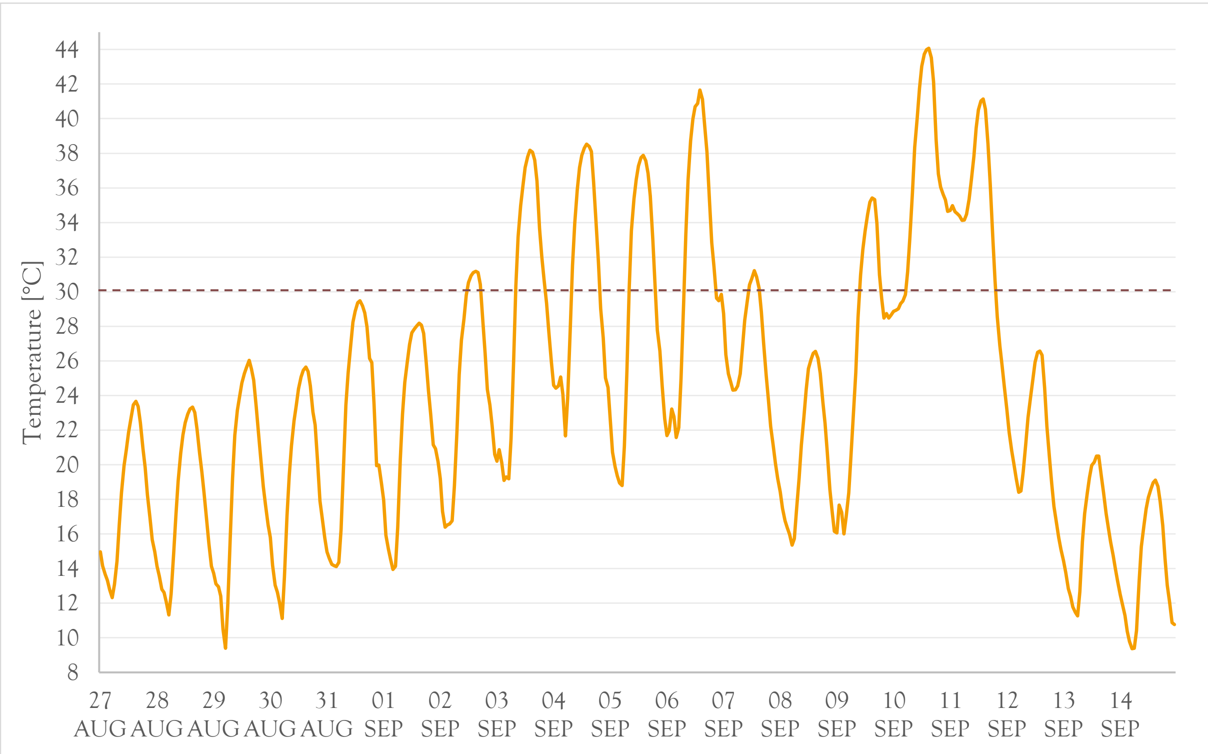
In Belgium, it was found that climate change made the intensity and frequency of extreme heat at least twice as likely [31]. One of the purposes of the present work being to assess the resilience of nZEBs to global warming, it has been decided to study the dwelling behaviour during a period of intense heat.

The period of intense heat has been retrieved from the meteorological file built upon the 2100 medium simulation. As mentioned previously, the results of the simulations consist in average meteorological data and there should contain no extreme weather event. However, the frequency of heat waves is expected to increase, and their definition is likely to change. The meteorological event studied in this section is thus a heat wave according to nowadays definition of the heat wave, but it is expected to become an "ordinary" event in by 2100 and is referred to as a period of intense heat.

The period of intense heat extends from 30th August to 12th September 2100. The hourly temperature predicted by the medium simulation is shown in Figure 13. The average maximum temperature of 25°C is exceeded during 15 consecutive days and 9 of them have a temperature above 30°C, as shown by the dotted line. This period of intense heat is rather extreme, especially from 10th to 12th September but since it is an event that is likely to occur with global warming, this period has been chosen to study the resilience of the building.

The indoor temperature of the dwelling during this period will be studied with and without improvements. The proposed improvements consist in combinations of passive cooling techniques that should allow to maintain the indoor temperature below the 26°C threshold. The resilience of the building to the period of intense heat is discussed in section 6.3.

Figure 13 – Hourly temperature during the period of intense heat of 30th August to 12th September 2100.



2.6. Conclusion

This chapter lays the foundation of the methodology used in the present work. A VE model is built based upon the nearly zero-energy dwelling described in this chapter. The model can then be calibrated to fit with reality and a sensitivity analysis is performed to ensure that the hypotheses uncertainties cannot significantly alter the results. The comparative testing and the sensitivity analysis are described in the next chapter. Chapter 4 analyses the results obtained for the baseline scenario. Then the behaviour of the building is extrapolated using the global warming simulations. Based on a global heat balance realised for all the rooms, the passive cooling techniques that would be the most efficient are determined. Those passive cooling techniques are implemented in Chapter 5.

3. MODEL CALIBRATION AND SENSITIVITY ANALYSIS

In the previous chapter, the building used in the BPS simulations has been described in details and some hypotheses were made on the building operation. When using a black box model such as VE, errors can only come from the inputs provided by the user due to a misunderstanding of the role of the parameters. The input data should be calibrated to obtain a model fitting with reality. Once the baseline model gives realistic results, it is possible to introduce changes and quantify their impact on the building. In this case, the building model should be calibrated so that it is possible to extrapolate the behaviour of the building with global warming. Generally, calibration is done based on an empirical validation. But as the building has not yet been built, comparative testing has been selected instead. In the first section of this chapter, building model validation and calibration is explained in further details and the comparative testing of the models is developed.

The second section of this chapter is a quality assurance of the VE model. Since the building operation mainly relies on hypotheses, it is important to confirm that they do not have a strong influence on the behaviour of the building. A sensitivity analysis has thus been performed to ensure that small variations of the inputs do not significantly alter the results.

3.1. Building model validation and calibration

3.1.1. Theoretical background

The next step after creating a thermal model is the calibration and validation of this model to verify that it is a good representation of the reality. When using a BPS software, a distinction must be made between the validation of the software itself and the validation of the model built by the user.

The validation of the software consists in evaluating the strength of the algorithms used by the software to produce results as close as possible to the reality. The BESTEST method [32] was developed to systematically test whole-building energy simulation models and diagnose the sources of predictive disagreements. It provides a very cost-effective way to evaluate building energy simulation programs. It consists of a series of carefully specified test case buildings that progress systematically from extremely simple to relatively realistic. Output values for the cases, such as annual loads, annual maximum and minimum temperatures, annual peak loads, and some hourly data are compared, and used in conjunction with diagnostic logic to determine the algorithm responsible for predictive differences. The more realistic cases, although geometrically simple, test the ability of the programs to model effects such as thermal mass, direct solar gain windows, window shading devices, internally generated heat, infiltration, and so on.

The validation methodology of a building energy simulation software requires three testing steps. The advantages and disadvantages of each technique are summarised in Table 5.

- **Analytical verification** – The output of a program, subroutine or algorithm is compared to the result of a known analytical solution for isolated heat transfer mechanisms, under very simple boundary conditions.
- **Empirical validation** – Calculated results from a program, subroutine or algorithm are compared to monitored data from a real structure, test cell or laboratory experiment.
- **Comparative testing** – A program is compared to itself or to other programs. The comparative testing approach includes *sensitivity testing* and *inter-model comparison*.

Even though a software can be considered as trustworthy regarding the provided results, it does not guarantee that the model built by the user is correct. Empirical validation and comparative testing can also be used to assess the validity of a building model. Generally, an empirical validation is used to calibrate the model so that it gives representative results, and the model can further be used to extrapolate the behaviour of the building under possible improvements [33].

In this case however, the energy building model is based on a building that has not yet been built. The reliability of the VE model is evaluated by comparative testing with a second model built with EES.

Comparative testing has a lack of truth standard, meaning that both models could give the same results but be a false reflection of the reality.

Table 5 – Validation techniques: advantages and disadvantages.

Technique	Advantages	Disadvantages
Analytical Test of numerical solution	• No input uncertainty • Exact truth standard given the simplicity of the model • Inexpensive	• No test of model • Limited to cases for which analytical solutions can be derived
Empirical Test of model and solution process	• Truth standard within experimental accuracy • Any level of complexity	• Measurements involve some degree of input uncertainty • Detailed measurements of high quality are expensive and time-consuming • A limited number of data sites are economically practical
Comparative Relative test of model and solution process	• No input uncertainty • Any level of complexity • Inexpensive • Quick, many comparisons possible	• No truth standard

3.1.2. Comparative testing of EES and VE

Comparative testing is done between two models generated with two software, EES and VE. In the EES model, all the equations have been manually entered and the model is thus rather simplified regarding the physics of the building. The VE model, on the contrary, shall be used as a "black box". The equations are not accessible to the user, and it is impossible to modify them. The user only interacts with the model through the encoding of the input parameters and the accessible outputs provided by the result interface.

The equations implemented in the EES model describe a rather simplified physics, but they already give a good representativeness of the building behaviour. More importantly, they allow to understand the physics underlying the VE model. The equations are not detailed in the core of the report since it is out of the scope of this work. They are fully described in Appendix B.1.

The results of the EES and VE models have been confronted to understand the origin of the divergences between the two models. When comparing the results of the two models, it is important to consider the same inputs and hypotheses. They are fully described in the previous chapter (section 2.3). To avoid the multiplication of potential sources of differences between the models, the comparative testing should be performed in a rather simplified situation. There are two phenomena that are highly likely to introduce divergences between the results of both simulations: solar shading and natural ventilation. Solar shading requires a shadow analysis to calculate the fraction of direct solar radiation stopped by the shading device. Natural ventilation is not modelled similarly in all software and strongly depends on wind speed and direction, as well as on the air temperature. The comparative testing of EES and VE is thus performed without considering natural ventilation nor any shading device to avoid introducing new sources of uncertainties.

In this section, only the results of the analysis are presented, as well as the benefits drawn from this analysis. The detailed explanation of the hypotheses on the origin of the divergences is given in Appendix B.2.

So far, statistical indices are the most used criteria to assess the accuracy of calibration and establish whether a model should be considered calibrated. These criteria are generally used to determine how well simulated data match the measured utility data at the selected time interval. They do not constitute a methodology for calibrating building models, but rather a measure of the goodness-of-fit of the building energy model.

Statistical indices have become the international reference criteria for the validation of calibrated models. The ASHRAE guideline 14 [32] , [34] uses two indices to evaluate the goodness-of-fit of the building energy model: the mean bias error, MBE and the coefficient of variation of the root mean square error, CV(RMSE). Those indices are generally used to compare simulated and measured data. In this case however, those indices are applied to the results obtained with the two models.

MBE is a non-dimensional measure of the overall bias error between the simulated data in a known time resolution, and is usually expressed as a percentage [33]:

$$MBE = \frac{\sum_{i=1}^{N_p} \left(s_{VE,i} - s_{EES,i}\right)}{\sum_{i=1}^{N_p} s_{VE,i}}$$

where $s_{x,i}$ are the simulated data at time interval i with software x and N_p is the total number of data values. Due to a compensation effect (positive and negative values contribute to reduce MBE final value), MBE is usually assessed together with the CV(RMSE). This index represents the variability of outputs between both software and specifies the overall uncertainty in the prediction of the building behaviour, reflecting the errors size and the amount of scatter. It is defined as:

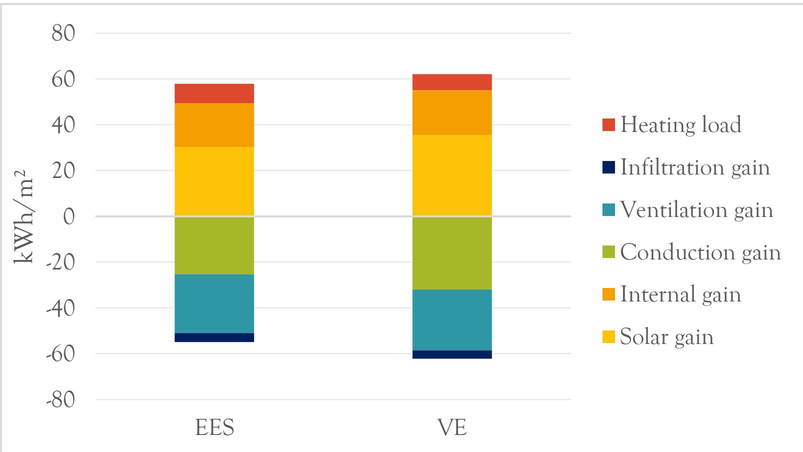
$$CV(RMSE) = \frac{1}{s_{VE}} \sqrt{\frac{\sum_{i=1}^{N_p} \left(s_{VE,i} - s_{EES,i}\right)^2}{N_p}}$$

where, besides the quantities already introduced in the previous equation, s_{VE} is the average of the simulated VE data. The MBE and CV(RMSE) are computed on an hourly basis.

The MBE and CV(RMSE) are computed with the temperatures provided by EES and VE for all the rooms. The MBE never exceeds 4% while the CV(RMSE) remains below 6% for all the rooms. And for the hour at which the absolute error is maximum, this value does not exceed 15%. It can thus be concluded that both models are describing the same building behaviour. No modelling aberration, nor any modelling input error are reported.

The global balance of the duplex for the whole year can be compared for both software (see Figure 14). The main differences between the software come from the conduction gain, the solar gain and the heating load. Waddell & Kaserekar established that generally, when comparing the results of two simulation software, the main source of differences comes from the calculation of solar gains [35]. The distribution of the solar irradiation transferred through or re-emitted by glazing is not handled similarly by all software. As far as the conduction gain is concerned, there also exist several wall models. For example, in EES, a wall is modelled as an electrical circuit with resistors and capacitors.

Figure 14 – Global balance of the duplex for the whole year computed with the two software.



The MBE and CV(RMSE) are computed for the gains and losses listed in Figure 14. All the MBE values remain below 5%, while the CV(RMSE) is limited to 15%, except in the case of the heating load. The hourly heating loads of EES are extremely scattered compared to VE. This is due to the heating system controller. In VE, the heating load is calculated by an iterative process so that the desired indoor air temperature is reached at any moment. In EES however, the heating load is proportional to the temperature difference between the set point temperature and the room air temperature. This control strategy leads to abrupt variations in heating load, hence room temperature. To have a finer regulation of the room temperature and remain at the desired temperature instead of having some oscillations around the set point temperature, using a PID controller would be better practice. More information about the heating strategy can also be found in Appendix B.2.

The two models were primarily built to combine the strengths of both software. By comparing the results obtained with both models, the inputs of each model could be calibrated to get closer to each other. By comparing a more physical model with a black box model, some modelling mistakes could be detected and corrected. Developing all the equations in EES, even though they are simple, allows a deeper understanding of the underlying physics of the model, which could then be extrapolated to understand the physics behind the VE model as well.

This analysis also shows that even though the EES model is rather simplified, it can acceptably predict the behaviour of a building with complex interactions between the thermal zones. The models can be used together to mitigate each other's weaknesses. From now on, only the VE model is used as a finer model of shading and air displacement is required to propose some improvements to cope with overheating.

3.2. Sensitivity analysis

The sensitivity analysis consists in a quality assurance of the model. The sensitivity analysis is performed only with the VE software, as it is the model used in the rest of this work. It aims at confirming that the hypotheses made in Chapter 2 have no significant influence on the simulation results. Most of the parameters concerning the operation of the building were set based on standard values fixed by norms. However, it does not guarantee that those parameters will reflect the real operation of the building. Therefore, the impact of those parameters on the results of the simulation is studied through a one-at-a-time (OAT) analysis. The influence of the parameter on an output can be obtained by launching a new simulation in which the value of the studied parameter has been slightly varied to account for the uncertainty spread.

The OAT analysis is also a useful tool to determine whether the building operation has a strong influence on its energy consumption. The parameters studied in the sensitivity analysis are shown in Table 6. Several simulations have been performed, and each time, the input value of a parameter has been changed. The impact on the chosen output is quantified by computing the sensitivity index (SI) of each parameter. It corresponds to the output difference, in %, for the extreme values of the considered parameter. The sensitivity index is computed as follows [36]:

$$SI = \frac{E_{max} - E_{min}}{E_{max}}$$

When the parameter SI changes considerably, it can be considered sensitive, thus influent. The output parameters studied in through the sensitivity analysis are the gas consumption, the overall energy consumption, and the design heating load of the radiators. The gas consumption corresponds to the energy used for heating purposes only while the overall energy consumption also accounts for the electricity consumption of electric appliances and lighting. The design heating load of the radiators corresponds to the maximum power required to maintain the desired temperature set point.

The results of the OAT analysis are shown in Figure 15. The key that links the reference numbers in the plot to the factor description is included in Table 6. The parameters with the largest impact on the heating system consumption are the heating system itself and the equipment.

The furniture mass factor has been changed from 4 to 5 to account for the factor uncertainty and study the impact of a modification in the thermal capacity of the room. It can be concluded that the room thermal inertia does not impact the heat load nor the energy consumption of the building.

The electricity consumption of lighting and equipment is estimated at 6 W/m^2 and 3 W/m^2 respectively, according to norm ISO 17772. The sensitivity index has been calculated by increasing this consumption by 30%. Electric appliances and lighting have an opposite impact on the gas and electricity consumptions.

If the electricity consumption of the appliances is increased, the gas consumption decreases as the energy released by those appliances covers a part of the room heating.

In the baseline, a family of four adults was considered. To study the impact of occupant gains, a family with two children and a mono-parental family have been simulated. In both cases, it results in an increase of the heating system consumption. The variations remain below 10% and are considered as irrelevant.

The domestic hot water consumption is found to have an insignificant impact on the gas consumption, meaning that it cannot alter the indoor conditions.

The operation of the heating system is characterised by two main parameters that can be modified: the temperature set point and the heating schedule. When the temperature set point is adjusted, it changes the gas consumption and the design heating load of the radiators accordingly. On the contrary, heating schedule has a more mitigated impact. On the one hand, if intermittent heating is implemented by switching the heating system off for the night, a higher power is needed to launch the radiator in the morning to reach the set point temperature, hence increasing the design heating load. On the other hand, the gas consumption of the installation can be significantly reduced.

The infiltration rate has been increased to reach a n_{50} value of 0.7. The sensitivity index remaining below 10%, infiltration rate is considered to have poor influence on the energy consumption of the building.

The conclusion of the sensitivity analysis is that most of the hypotheses have little influence on the simulation results and are thus not likely to alter the conclusions of the present work. Only the HVAC system strongly influences the energy consumption. A more detailed analysis of the heating system operation is carried out in Appendix C.1.

Figure 15 – One-at-a-time results for gas consumption, heating load design and global energy consumption of the building.

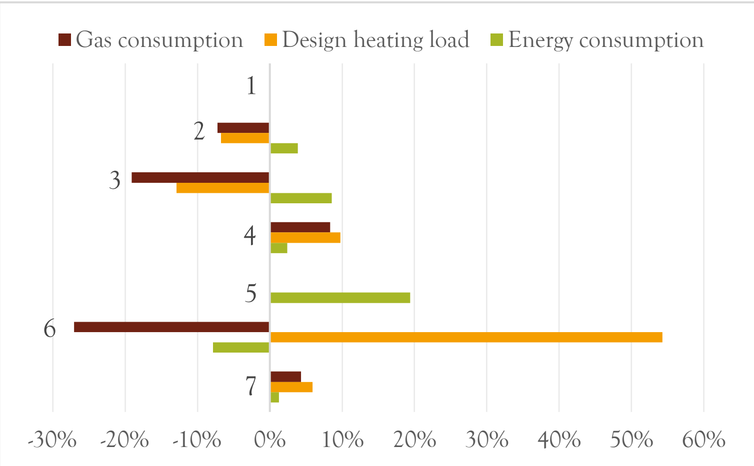


Table 6 – One-at-a-time factor with corresponding reference numbers.

Ref. number	Factor
1	Furniture mass factor
2	Lighting
3	Equipment
4	People
5	DHW
6	HVAC system
7	Infiltration

3.3. Conclusion

The comparative testing and the sensitivity analysis allowed to guarantee, to some extent, that the VE model of the baseline is correct and provides coherent results that cannot be altered significantly by the hypotheses made on the parameters.

Since we now know that VE model has consistent physics, it will be the one used to extrapolate the behaviour of the building to different input conditions. The behaviour of the building is first studied by changing the weather conditions of the simulation to account for global warming. Then some improvements can be proposed to reduce the overheating risk in the building. The VE model has been chosen to continue this study rather than the EES model since VE has been approved by international standards and recognised as a trustable BPS software. Some phenomena such as solar shading or natural ventilation have dedicated modules and the VE model is globally more complete than the EES model. Moreover, VE is more user-friendly, easier to manipulate and requires less computation time than EES.

4. THERMAL COMFORT ANALYSIS

This chapter focuses on the analysis of thermal comfort in the dwelling and its evolution with global warming. Thermal comfort is analysed based exclusively on the results obtained with the VE model. As already mentioned, the sole purpose of the EES model was to better understand the physics of the VE model and identify potential mistakes in the inputs. The first section introduces existing criteria to evaluate thermal comfort in a dwelling. Those criteria are then used to measure thermal comfort for the baseline scenario. The behaviour of the building is extrapolated for 2050 and 2100 in order to study the evolution of thermal comfort with global warming. The two global warming simulations are used to represent the uncertainty spread by 2100. Finally, the sources of thermal discomfort in the most relevant rooms of the apartment, *i.e.* the living room, the kitchen and the bedrooms, are analysed in further details through a heat balance. The heat balance allows to outline the improvements that should be further investigated to reduce the risk of overheating.

4.1. Theory of thermal comfort

Once the building model has been created, thermal comfort can be evaluated based on the results of the simulations. In this case, since the building is heated, the cold winter temperatures should not be a problem. The analysis mainly focuses on the risk of overheating in summer. Several criteria can be used to evaluate the risk of thermal discomfort. They are described below and then their strengths and weaknesses are compared to choose the most relevant criterion in the context of the present work.

I. At design stage, a nZEB can be modelled with a software called PHPP (Passive House Planning Package). After entering the characteristics of the building, PHPP ascertains if the construction respects the passive house standards based on a static building model. According to the passive house standards, if the room temperature exceeds 25°C for 10% of utilisation time, there is a high risk of overheating and summer thermal discomfort [15].

II. To evaluate the risk of overheating in a new construction, the EPBD has established a benchmark called the *degree hour criterion*. It is based on the weighing factor, which is a representation of the non-usable or storable heat inside the inertia of the building. As soon as the building stops storing or evacuating heat through its walls, the additional heat accumulates in the rooms, and it can cause overheating. The weighing factor considers each hour of the year and is computed as follows:

$$wf = \sum_{i=1}^{N_h} (\max(T_i - T_{max} ; 0) \cdot f_{occ,i} \cdot (1 - f_{h,i}))$$

where $f_{occ,i}$ is the occupation factor (1 when the room is occupied, 0 otherwise) and $f_{h,i}$ is the heating factor (1 during the heating period, *i.e.* from 1st October to 30th April, 0 otherwise). The temperature T_{max} is the temperature above which heat starts to accumulate and is assumed to be 23°C. N_h is the number of hours in a year, i.e. 8760h. The EPBD strongly recommends staying below 1000 K·h. Above that threshold, there is a risk of overheating and the probability of installing an active cooling system increases continuously with the weighing factor. This probability reaches 100% at 6500 K·h and, according to the EPBD, the building does not meet the overheating criterion and must be modified to avoid fines [12], [37].

III. The two first criteria are based on temperature only. In practice, there are other parameters that can influence thermal comfort, such as relative humidity, air displacement rate and occupants' clothing and metabolic rate. Fanger [38] has developed a theory of static comfort that takes into account those parameters. They can be used to compute the predictive mean vote (PMV). The PMV is an expression of how comfortable people feel in a room. It scales from –3 (very cold) to 3 (very hot). To ensure thermal comfort all year round, the PMV should always be between -0.5 and 0.5.

IV. The last criterion refers to the theory of adaptative thermal comfort. 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 adaptative comfort temperature can be expressed by a relationship depending on the mean outdoor temperature:

$$T_{comfort} = a\,T_{rm} + b$$

with T_{rm} the running mean outdoor temperature over a period of seven days before the considered day, meaning that the comfort temperature also depends on the past. According to the norm NBN EN 15251 [39], the running mean outdoor temperature is calculated as follows:

$$T_{rm} = \frac{T_{ed-1} + 0.8\,T_{ed-2} + 0.6\,T_{ed-3} + 0.5\,T_{ed-4} + 0.4\,T_{ed-5} + 0.3\,T_{ed-6} + 0.2\,T_{ed-7}}{3.8}$$

And the adaptative comfort temperature is given by:

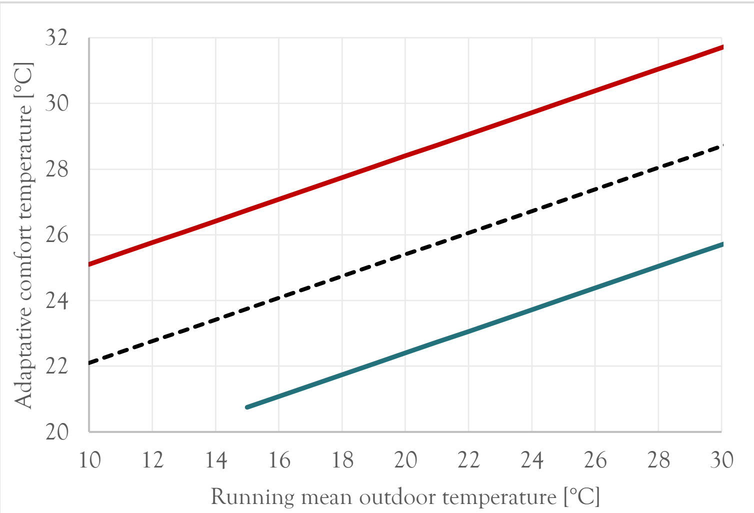
$$\begin{cases} T_{min} = 0.33\,T_{rm} + 15.8 & if\ 15 < T_{rm} < 30°C \\ T_{max} = 0.33\,T_{rm} + 21.8 & if\ 10 < T_{rm} < 30°C \end{cases}$$

Since occupants can modify their behaviour depending on the climatic conditions, the range of temperature considered as pleasant is larger than in the static comfort theory. But if T_{rm} exceeds 30°C, the adaptative comfort theory is no longer applicable and the static comfort theory prevails. For a building of category II, *i.e.* a new or renovated building with normal level of expectations, the maximum acceptable temperature is 26°C [38].

Figure 16 shows the evolution of the comfort temperature depending on the mean outdoor temperature. The theory of adaptative comfort can only be used if the following criteria are met:

- There is no mechanical cooling system and the heating system is not in operation.
- Occupants have metabolic rates corresponding to sedentary activities and they are free to adapt their clothing to the indoor and outdoor conditions.
- Opening and closing windows should be of primary importance as a mean of regulating thermal conditions in the space. Occupants can also have additional options for personal control over the indoor environment such as solar shading or ventilation.

Figure 16 – Evolution of adaptative comfort temperature depending on the running mean outdoor temperature. The indoor temperature should be between $\boldsymbol{T_{min}}$ (in blue) and $\boldsymbol{T_{max}}$ (in red). The dotted line shows the average of the two temperatures.



All the criteria use the operative temperature to assess thermal comfort. The operative temperature is an average between the air temperature of the room and the temperature of the walls as the human body exchanges heat by both convection with ambient air and radiation with the surrounding walls. VE provides the operative temperature of the rooms, and it is thus used to analyse the results.

In this work the theory of adaptative comfort is used to assess thermal comfort. The two first criteria are based on a static analysis of the building made with the PHPP and EPB software, respectively. The index of thermal discomfort is thus only valid with the assumptions made in the software and they should not be applied in a dynamic simulation. The criteria have been defined based on the calculation method of the software and the related hypotheses. Compared to the PHPP and EPB, a dynamic simulation allows to evaluate thermal comfort in more details by using hourly results.

In an office building, the PMV criterion is generally used since occupants have a rather constant clothing and metabolic activity. Those values can be entered as parameters in VE to evaluate the PMV. In a residential dwelling, however, the adaptative comfort theory clearly prevails. People are free to change their clothing very easily to adapt to the ambient temperature and they can open or close windows as they please. The parameters that are considered as constant in the PMV calculation are thus indirectly accounted for in the adaptative comfort theory.

The theory used in this work to evaluate thermal comfort is the theory of adaptative comfort since it truly reflects thermal comfort in a residential building. The next section evaluates thermal comfort in the building in the base case scenario.

4.2. Thermal comfort analysis for the baseline

In the previous chapter, the EES and VE models were compared. The EES model was kept as simple as possible to avoid introducing more possible sources of divergences between the two software. It was thus considered that the windows could not be opened and there was no shading device. However, in the continuation of this work, only the VE model is used to extrapolate the behaviour of the building with the global warming simulations and the investigated improvements.

If the situation studied in the previous chapter is not improved, it does not allow to use the theory of adaptative comfort as all the requirements are not met. However, such a situation is highly unlikely in a residential building where occupants are free to open the windows as they please. Windows are generally equipped with shading devices, at least to ensure the occupants' intimacy. To cope with this unrealistic assumption, a MacroFlo module has been developed to deal with window opening and a controllable shading device has been added. The chosen shading devices are venetian blinds as they are common in residential buildings. The natural ventilation method that has been considered is a stochastic method to account for the unpredictable occupants' behaviour. More information about the modellisation of natural ventilation can be found in the next chapter. This scenario allows to use the theory of adaptative comfort and to have a representative overview of current nZEBs where no meaningful measure against overheating is taken. It is thus considered as the baseline scenario, and it shall be used as a basis for further comparisons.

Thermal comfort is evaluated in the living room, the kitchen and the bedrooms (see Figure 17) as they are the most often occupied rooms in the apartment. However, it should be noted that the thermal comfort is difficult to assess in the kitchen since it is a room where the internal gains can increase suddenly but for a short period of time. When people are cooking, they also tend to feel warmer because of a higher metabolic rate, and they could be more tempted to open a window even in winter. Those phenomena are ignored in the dynamic simulation, but they can have a significant impact in reality.

Figure 17 – Orientation of the studied rooms in the apartment.

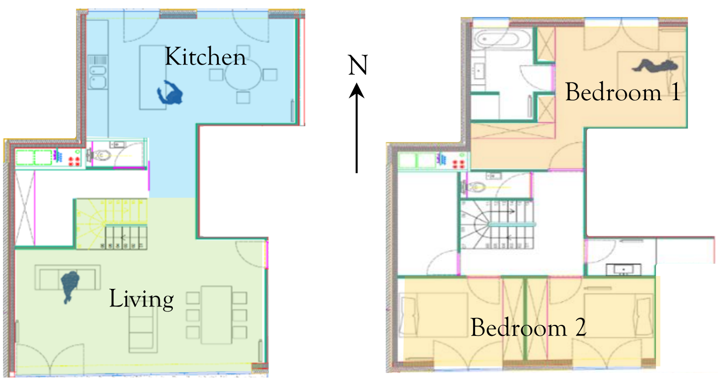
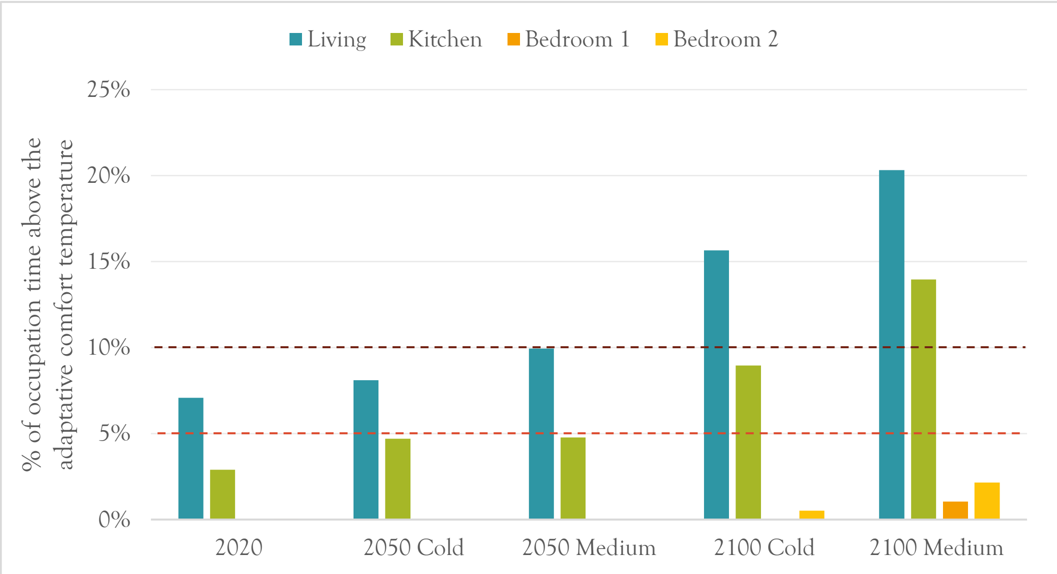


Figure 18 shows the thermal comfort in 2020 for the four rooms of interest according to the adaptative comfort theory. The graph shows the percentage of occupation time during which the adaptative comfort temperature is exceeded. If the upper level of adaptative temperature is exceeded for less than 5% of the occupation time, it is assumed that the overheating risk is negligible. If the temperature exceeds the maximum temperature for more than 10% of the occupation time, the probability to purchase an active cooling system is 100%. Between those thresholds, the probability to invest in an active cooling system is supposed to increase continuously.

In 2020, thermal comfort is reached in the bedrooms and in the kitchen. In the living room, the probability to invest in a cooling system does not yet reach 100%. The living conditions are acceptable, and the building should not be subject to fine. However, it is strongly recommended to take passive measures to improve thermal comfort, especially in the living room. In the next section, thermal comfort is evaluated using the global warming simulations.

Figure 18 – Evolution of thermal comfort with global warming.



4.3. Evolution of thermal comfort with global warming

As already discussed in section 2.5, global warming is driven by an increase in greenhouse gas concentration, which leads to an increase in exterior temperature through enhancement of radiative forcing and to an increase in solar radiation due to a lower cloud coverage. Thermal comfort is expected to deteriorate with global warming.

4.3.1. Evolution of adaptative thermal comfort

Figure 18 shows the evolution of adaptative thermal comfort with global warming in all the rooms of interest, *i.e.*, the living room, the kitchen and the bedrooms. The dotted lines correspond to the thresholds of 5 and 10% that have been defined in the previous section. If the indoor temperature does not exceed the maximum temperature for more than 5% of the occupation time, the overheating risk is negligible. Between 5 and 10% of the occupation time, the probability to purchase an active cooling system increases continuously until 100%.

As expected, thermal comfort worsens independently of the considered simulation. It is highly likely that the occupants invest in an active cooling system by 2100, especially for the living room and the kitchen. The risk of overheating is lower in the kitchen than in the living room because of the room North orientation and the associated lower solar gains.

The bedrooms are less likely to be subject to overheating, mainly because they are occupied during night-time when the outdoor temperature is lower. The interest of using the adaptative comfort theory is to widen the range of thermal comfort by taking into account the dynamic behaviour of the occupants. However, in the bedrooms, the use of the adaptative comfort theory could be questioned. During the night, it is very unlikely that occupants will wake up to open windows or change clothes. A static comfort theory should be used instead. The two theories are compared in the next section.

4.3.2. Comparison of the thermal comfort criteria

Figure 19 is a comparison of the four comfort criteria considered in section 4.1. The values shown in the graph are the percentage of occupation time during which the thermal comfort criterion is not respected.

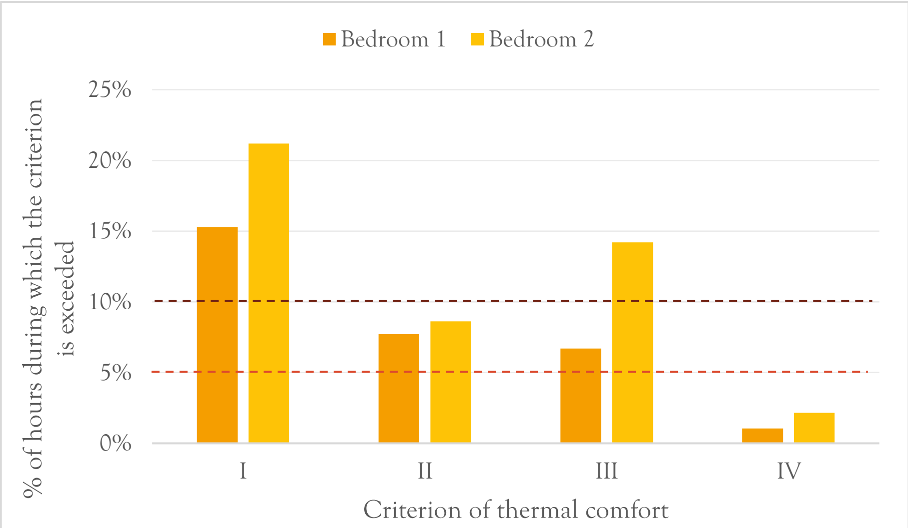
For criterion I, it is assumed that there is a risk of overheating if the percentage of occupation time during which the temperature is higher than 25°C exceeds 10%. The value showed on the graph is thus the percentage of hours during which the temperature exceeds 25°C. The criterion is respected in none of the bedrooms, so according to the PHPP, there is a significant risk of overheating.

Criterion II uses the weighing factor, which is calculated for the whole year. It is not possible to directly deduce the percentage of hours during which the criterion is not respected. It was said in section 4.1 that the EPB considers that the overheating risk increases continuously between a weighing factor of 1000 K·h and 6500 K·h. In the other criteria, a high overheating risk is implied when the percentage of hours during which the thermal comfort criterion is not met is 10% and 5% is the threshold above which worries can begin. It is assumed that it is also the case for that criterion so that it can more easily be compared to the others. When the weighing factor is 6500 K·h, it corresponds to an exceedance of 10% of the overheating criterion and some measures should be taken to improve thermal comfort. A weighing factor of 1000 K·h corresponds to the threshold of the 5%. For 2100, the weighing factors of the North and South bedrooms have been estimated to 3983 and 4992 K·h respectively, corresponding to a moderate thermal discomfort.

In criterion III, it was said that the PMV should remain between -0.5 and 0.5. The graph shows the percentage of hours during which the value of 0.5 is exceeded, corresponding to the risk of overheating. The PMV is calculated via VE considering a sleeping metabolism (*i.e.* 0.7 met) and summer clothing (*i.e.* 0.3 clo). The nominal air speed is supposed to be 0.15 m/s, *i.e.* the default value proposed by VE. According to this criterion, there is a risk of overheating in the bedrooms, especially in the South-oriented one.

The criterion IV relates to the theory of adaptive comfort and the graph simply shows the percentage of occupation time during which the maximum tolerable temperature is exceeded.

Figure 19 – Comparison of the four thermal comfort criteria in the bedrooms for the year 2100 of the medium simulation.



It can directly be seen that not all the criteria give the same results concerning the risk of overheating. The adaptative comfort theory predicts a lower risk of overheating in the future. It is assumed that when the occupants are aware of the external climate conditions, the range of temperatures considered as pleasant by the occupants is wider.

In the bedrooms, the thermal comfort criteria are generally reinforced [40]. For example, in their study on the overheating risk in Dutch dwellings, Hamdy *et al.* considered that in the bedrooms, the temperature of 26°C could not be exceeded for more than 1% of the occupation time while this temperature was set to 28°C in the living areas [5]. In conclusion, when using the theory of static comfort, there is a risk of overheating in the global warming simulation, especially in the south-oriented bedroom.

4.3.3. Limitations of the theory of thermal comfort

There are several limitations to the theory of thermal comfort in general. Some of them were already mentioned above but they are all gathered in this section for the sake of completeness.

First, the criteria of static comfort developed by the PHPP and the EPBD are meant to be general methods linked to the use of the related software. They are intended to be easily calculated and are not supposed to be used in the context of a dynamic simulation. However, they can be considered as standards, and they can already give a good idea of global thermal comfort in the building.

The theory of comfort based on the PMV is also a static theory, meaning that it does not take into account the existing relation between the occupants and the outdoor environment. However, it is more appropriate than the adaptative comfort theory to measure thermal comfort in the bedrooms. The theory of adaptative comfort is particularly suitable for the living room, where the occupants have a sedentary metabolic rate and are free to open windows.

The theory of adaptative comfort also does not apply for a running mean outdoor temperature above 30°C. Generally, it is recommended to avoid exceeding a temperature of 28°C in a living area [13]. However, it is not unlikely that human beings will eventually adapt to global warming and be able to withstand higher temperatures, leading to an adjustment of the limitations of the adaptative comfort theory.

Nevertheless, it is 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. Some measures should be taken in the living areas as well as in the bedrooms to avoid disturbing the occupants' sleep. In the next section, the causes of overheating are determined by analysing the thermal balance of the rooms. It allows to draw some guidelines about the passive cooling techniques that should be used to improve thermal comfort depending on the orientation and thermal behaviour of the room.

4.4. Causes of thermal discomfort

To identify the causes of thermal discomfort in the studied rooms, a balance between the heat gains and losses has been made (see Figure 20). It can be used to understand the behaviour of the rooms. The balance has been made only for the months during which there is a risk of overheating, *i.e.*, from April to September included.

4.4.1. North-oriented rooms

In the previous section, it was shown that there is a risk of overheating in the kitchen. However, since the room is North-oriented, the solar gains are lower than in the South-oriented ones. The sum of internal and solar gains is globally lower than in the living room and the bedroom 2 so they cannot be the only source for thermal discomfort.

It can be noted that, contrary to the other rooms, the kitchen experiences little losses through ventilation as it is a room where air is extracted. The air supplied to the kitchen comes from the living room and is thus at a warmer temperature. All the heat must be evacuated through conduction towards other rooms or to the external environment. However, since the building is well insulated to comply with the EPBD, the evacuation of that heat is hampered, resulting in higher temperatures in the kitchen. *A priori*, the improvements that would have the most significant impact on overheating risk in the kitchen are the implementation of natural ventilation and/or the installation of a vent to supply fresh air to the room.

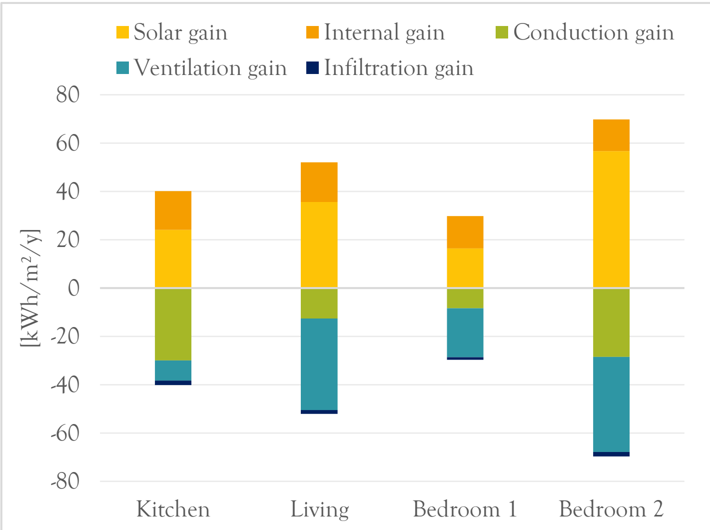
As the bedroom 1 is correctly ventilated and has poor solar gains, it is not likely to be subject to overheating, hence no specific measure should be taken to prevent thermal discomfort.

4.4.2. South-oriented rooms

The living room and the bedroom 2 have almost the same behaviour. They are both characterised by solar gains that are more than three times the internal gains due to occupants and equipment. They are thus the main source of overheating in summer, and they should be limited if thermal discomfort is to be avoided. As the rooms are South-oriented, a solar protection blocking direct solar irradiation should be implemented. The shading device should ideally block the solar beams in summer but let them inside in winter to avoid increasing the heating energy consumption.

Losses mainly occur through ventilation as the supplied air is cooler than the indoor air. A ventilation strategy should also be efficient to decrease the overheating risk.

Figure 20 – Summer heat balance of the rooms of interest for thermal comfort.



4.5. Conclusion

If the model of the passive house is not adapted, thermal comfort is not guaranteed, even nowadays. With global warming, it can only worsen. From this section, it can be concluded that nZEBs are not designed to prevent overheating and the model of passive houses should be improved. In the next chapter, some cooling techniques are implemented to study their impact on thermal comfort.

5. PASSIVE COOLING TECHNIQUES

Cooling can be achieved through many ways. There are two major categories of cooling techniques: active and passive cooling. Active cooling techniques comprise a refrigeration cycle and are thus characterised by the direct injection of cold into the room, either through supply air ventilation or cold water running in radiant panels. Passive cooling can pursue three objectives: prevention of heat gains, modulation of heat gains and heat dissipation. Important research has been conducted on passive cooling in buildings. Existing experience has shown that passive cooling provides excellent thermal comfort and indoor air quality, together with very low energy consumption [41].

Some hurdles remain however in the application of passive cooling concepts. Firstly, the robustness of passive cooling techniques can be negatively influenced by user behaviour. Specifically, the manual control of windows is simplified in most studies to deterministic temperature thresholds at which windows are assumed to be opened, although it has been shown that user influence can be substantial [42], [43]. Secondly, the performance of passive cooling cannot be guaranteed to the same extent as for active cooling, for example air flow rates through open windows are uncertain and depend on many factors. Simply oversizing by using a safety factor, as is normal practice for active cooling, is often not possible [44].

In the present work, only passive cooling techniques are considered. The goal is to show that it is possible to reduce the overheating risk but not completely limit it. The passive cooling techniques principles and modellisation are overviewed all along this chapter.

5.1. Definition of a passive cooling technique

Passive cooling involves the use of natural processes to achieve balanced indoor conditions. The flow of energy should happen by natural means, radiation, conduction, or convection without using an electrical device. Maintaining a comfortable environment within a building in a hot climate relies on reducing heat gains into the building and fostering the removal of excess heat. The underlying principle of passive cooling concepts is to prevent heat from entering the building or evacuate it afterwards. Two conditions must be met: the availability of a heat sink which is at a lower temperature than indoor air, and the promotion of heat transfer towards the sink. Standard heat sinks are outdoor air (heat transfer mainly by convection through openings), water (heat transfer by evaporation inside and/or outside the building envelope), night sky (heat transfer by long wave radiation through the roof and/or other surface adjacent to a building) or the ground [45].

The heat gains consist in the internal and solar gains. In the internal gains, only the share of electric appliances and lighting can be reduced, by improving their energy efficiency. However, decreasing the household electricity consumption requires either environment-consciousness or governmental restrictions, which are unpredictable factors. On the contrary, solar gains can easily be reduced with proper shading device.

It is possible to act on ventilation to increase the thermal losses and evacuate the heat from the building. Some improvements can be proposed on natural and mechanical ventilation. For example, in summer, night ventilation can be implemented to cool the building with fresh air and restore its thermal inertia.

Another passive cooling technique that can be thought of is related to the building envelope itself. Since the building has not been built yet, it could be proposed to add some improvements directly in the building envelope to prevent overheating.

5.2. Hypothesis on equipment consumption

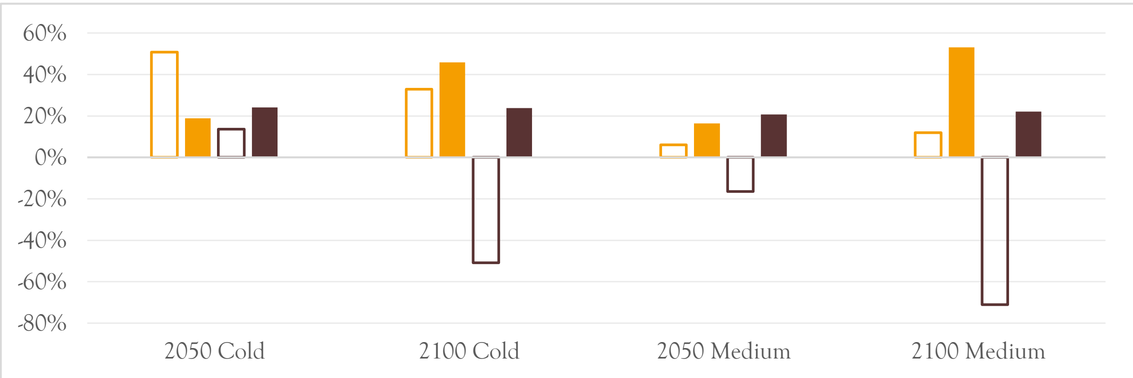
As already mentioned, in a nearly zero-energy building, internal gains account for a large share of building heating. The first and easiest way to reduce the overheating risk is thus to use more performant equipment. It was shown in section 3.2 that the equipment consumption could impact up to 20% of the gas consumption of the building. Similarly, it could significantly decrease the overheating risk in summer.

With the undergoing energy transition, electric equipment tends to be less energy consuming and the use of energy label gives consumers a more energy-efficient approach when choosing household appliances. The statistic office of Enerdata reported an annual 1% decrease of the energy consumption of households in the EU between 2008 and 2017. Belgium is one of the countries where this decrease has been the most important [46]. To study the impact of this significant energy consumption reduction, a conservative hypothesis is made. In 2050 and 2100, the consumption of electric appliances will be respectively 75% and 45% of their present consumption. A decrease in internal gains should have a positive impact on thermal comfort, even though it cannot counterbalance the temperature rise due to global warming.

The decrease in internal gains has indeed a positive impact on thermal comfort by limiting the risk of overheating. Equipment consumes electricity which is, after transformation, released as heat by convection and radiation. By decreasing the energy consumption of electric appliances, it is possible to slightly decrease the risk of overheating. The impact of the decrease in internal gains on the thermal comfort and the heating load is shown in Figure 21. The percentage of increase is shown compared to the same simulation weather file but with unchanged internal gains to demonstrate the positive impact of such a decrease on thermal comfort. They are also compared to the baseline to show that limiting the energy consumption of household appliances is not a sufficient measure to reduce the overheating risk.

This section shows that guidelines such as energy labelling have a positive impact on the energy consumption of the building and on thermal comfort. All possible efforts should be undertaken to pursue that trend. However, since the mentality of the future occupants of the building is impossible to predict, passive cooling techniques should be investigated.

Figure 21 – Impact of the annual decrease in internal gains due to energy-efficiency improvement. □ Increase of heating energy consumption compared to the baseline. ■ Increase of heating energy consumption due to the internal gains decrease. □ Improvement of thermal comfort compared to the baseline. ■ Improvement of thermal comfort due to the internal gains decrease.



5.3. Improvements aiming at decreasing solar gains

Research has been carried out to study the impact of solar shading on building energy consumption and indoor thermal comfort. Most of the studies have been conducted on buildings equipped with active cooling systems and are mainly focused on how solar shading devices can decrease the cooling energy consumption. In this case however, the solar shading aims at sufficiently decreasing solar gains to prevent the installation of an active cooling system.

In the scenario studied in section 4.2, the building was equipped with venetian blinds. A requirement of the theory of adaptative comfort being to equip the building with a controllable shading device. Venetian light blinds are not an effective measure to reduce solar gains. Since they are placed on the inner face of the window, they do not prevent solar beams to enter the room and the solar gains are very similar to the solar gains without any protection. The decrease of solar gains in summer can be improved either by placing some external shading devices on the building or by using glazing with a lower solar factor. Four solutions are explored: external shutters, fixed external shading, solar glazing and thermochromic glazing.

5.3.1. External movable solar shades

The external movable solar shades, also called shutters, can be adjusted to changing outdoor conditions. They are more efficient at reducing heat gain than internal window coverings. Regardless of their high performance, external movable solar devices are rarely used in hot summer and cold winter zones due to relatively high initial costs [47].

Shutters can be controlled either manually or automatically. Generally, occupants shut down the blinds when they experience visual discomfort due to a too high illuminance that prevents them from performing their task correctly. They can also be bothered by the direct solar irradiation that creates a local thermal discomfort. The automated control can be designed to guarantee thermal comfort within the room, based on indoor and outdoor environments. Since they are subject to the external climate conditions, they cannot be shut down if there is a risk of damaging the device. A condition on the maximum wind speed should be defined.

In VE, shading devices may be attached to glazed constructions. This is a quick way to specify shading features to all instances of a glazing construction. The results of the shading calculations performed for these shading devices are combined with those carried out by SunCast. The glazing should be assigned an external shading device and some conditions are defined to raise or lower the device.

$\text{condition to lower device: } T_a > 25.5°C$
$\text{condition to raise device: } T_a < 24.5°C \text{ or } w_s > 10\,\mathrm{m/s}$

with w_s the wind speed and T_a the room temperature. The maximum wind speed is taken from a datasheet for external shading devices of Helioscreen [48]. Even though it is usual to use the incident irradiance as a parameter to raise or lower the device, in this case, it has been chosen to use the room temperature as the control variable. As already mentioned, the operation of the shutters is generally linked to visual discomfort from glare. However, in this case, the building has a North-South orientation. In summer, the sun is high in the sky, considerably reducing the risk of glare due to direct irradiation as it penetrates less far in the room. Moreover, the present work aims at studying the risk of overheating and implementing passive cooling techniques to lessen it. The shutters are used as a mean to reduce the overheating risk by limiting the temperature rise due to solar irradiation. The variable used to control the shutters is thus the room temperature. The temperatures to raise or lower the shading device have been chosen so as to create a hysteresis around 25°C, the temperature at which thermal discomfort begins. The device is lowered if the condition to lower it evaluates to true and the condition to raise it evaluates to false.

In the shading device model, the shading coefficient of the device for various orientations should also be specified. The shading coefficient determines the fraction of the solar irradiation that is transmitted through the shading device. The evolution of the shading coefficient has been defined according to the recommendations of the IES VE user guide (see Table 7). The major problem linked to VE is that the conditions were defined to raise or lower the device but there is no condition related to the orientation of the shading device and there is also no information on how those shading devices are handled by VE during the simulation. VE does not give information on the state of the shading device in the result viewer.

Table 7 – Transmission factor of the shutters at 15-degree increments of tilt angle.

0°	15°	30°	45°	60°	75°	90°
0.8	0.65	0.4	0.15	0	0	0

The main advantage of the external solar protection is that they can be shut down only when necessary, which allows to keep the winter solar gains at their original value, limiting the rise of heating energy demand. However, winter is the period during which the sun is at the lowest and the solar beams can penetrate further in the room, creating a high risk of local thermal and visual discomfort. Occupants could be tempted to shut down the shutters for visual comfort, hence increasing the heating energy demand. In addition, in summer, even though shutters allow to significantly decrease the solar gains, they also spoil the view towards the outside and decrease solar illuminance, creating a visual discomfort that could bother the occupants and prompt them to raise the solar shading [49].

As another drawback, shutters can have a negative impact on natural ventilation in transition seasons by adding a resistance to the passage of wind. It might thus not be advantageous to combine shutters and ventilative cooling.

5.3.2. Fixed solar shading

Fixed shading devices are generally used in the building envelope to block solar radiation in summer. However, they also block a significant amount of solar radiation in winter, resulting in an increase in heating energy demand. Although, many studies suggested that there exists an optimal overhang depth which blocks solar beam irradiation from the high summer sun but still allows the low winter sun to shine in (see Figure 22) [47].

Yao & Zheng [50] studied the optimal overhang depth for South-facing windows with window-to-wall ratios between 0.15 and 0.57. They did not study the optimal overhang depth for larger ratios because it generally corresponds to window curtain wall cases which usually either do not install overhang for aesthetic purpose or are hard to install due to no external wall. In this case, the window-to-wall ratio is higher than 0.57 for the Southern facade but the benefit of an overhang is studied anyway. Yao & Zheng showed that the larger the window-to wall ratio, the larger the optimal overhang depth. The overhang depth is chosen at the largest length they studied, which is 1m, also for aesthetic reasons.

Fixed shading devices have been implemented only on the southern facade. They are modelled by adding a local shade via ModelIt in the 3D model of the apartment. The new solar irradiation reaching the window is recalculated by SunCast considering the fixed shading device. Figure 23 shows the evolution of the shading over the year. In winter, the solar gains are globally lower than in summer and they remain unchanged even though the solar protection is present. In the spring, sun rises in the sky and shading covers an ever-increasing part of the window, until it reaches its maximum in June when almost all the window is shaded. The tendency reverses in autumn, bringing to light the most important drawback of fixed solar protections. Autumn and spring have the same solar gains but with different needs. In September, the average temperature is 18°C, which can be a source of overheating. In March, the average temperature is 8°C and solar gains could be useful [51].

Another drawback of the fixed solar shading is that, unlike shutters, it cannot effectively control sky diffuse irradiation, as also shown in Figure 22. But contrary to shutters, fixed solar shading does not significantly decrease the illuminance inside the room.

Figure 22 – Optimal overhang depth [47].

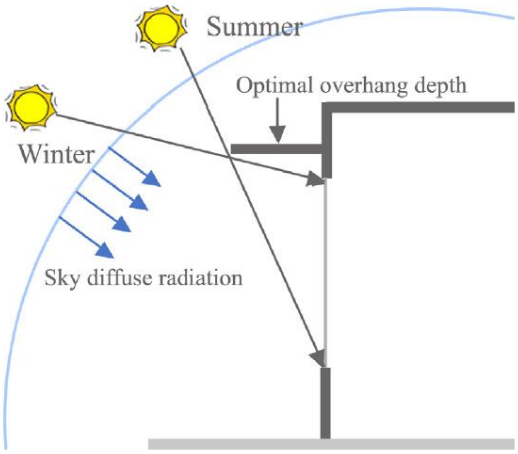
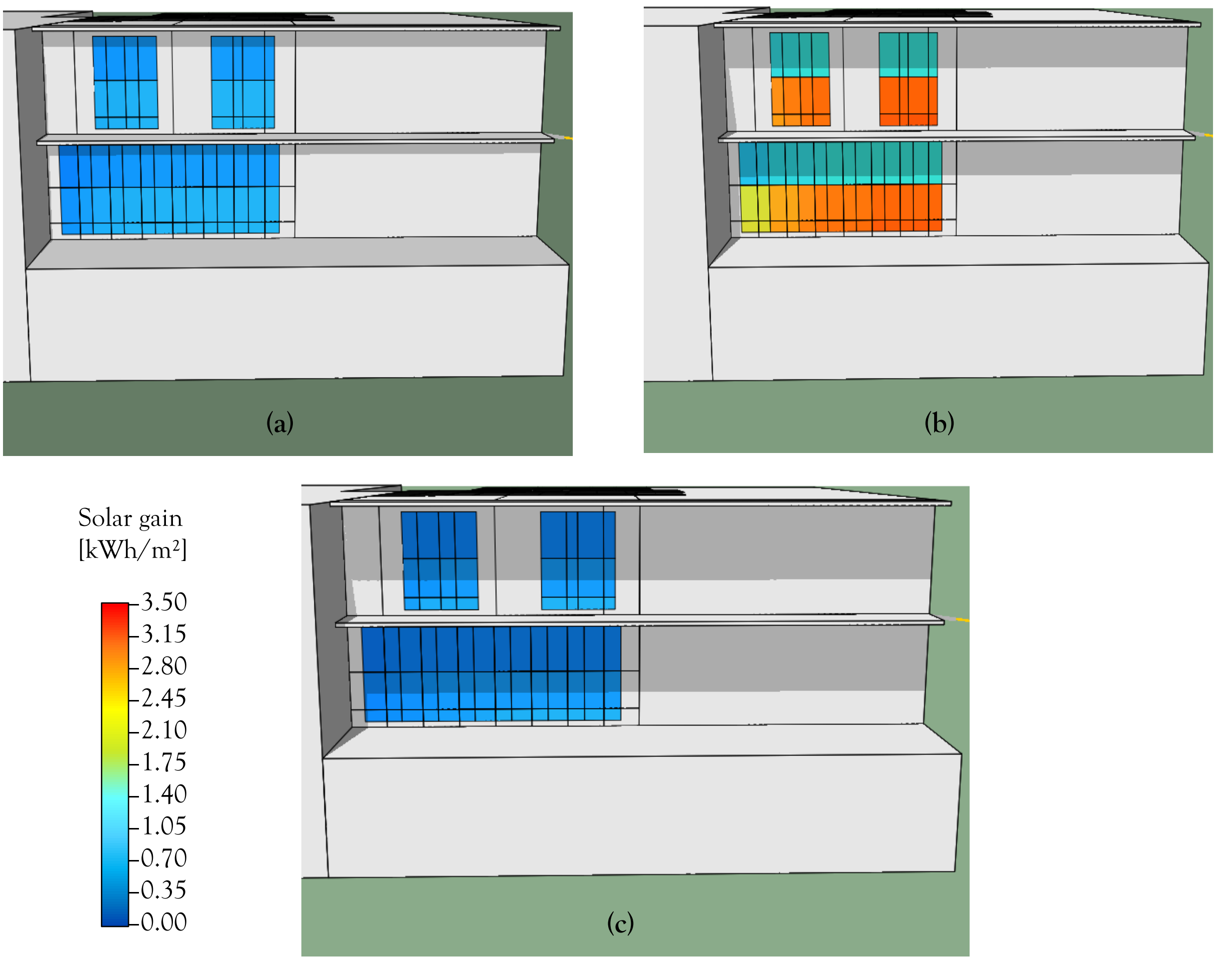


Figure 23 – Impact of external shading on solar gains (a) 15th February (b) 15th April (c) 15th June.



5.3.3. Solar glazing

The second improvement is the use of a solar glazing for the South facade. Solar glazing is a glazing with a low-emissivity coating that reduces heat gains as well as heat losses. Panes absorb solar radiation selectively, more in the near infrared and less in the visible spectrum to ensure a good transmissivity in the visible range. With the absorbing pane facing the environment, a large portion of the absorbed radiation is rejected back to the outdoor environment resulting in a low solar factor. Compared to shutters, solar glazing has the advantage to preserve an acceptable indoor illuminance while controlling both direct and diffuse radiation. Although reducing glare and thermal discomfort in summer, such widows are not convenient during winter when it would be desirable to make use of all the available solar energy to reduce heat load [52]. The solar glazing can be modelled simply by modifying the solar factor of the window from 0.5 to 0.3.

Feuermann & Novoplansky studied the interest of reversible low SHGC windows. In winter, during the heating season, the window can be turned by 180°, for the absorbing pane to face the room. In that case, a large fraction of the otherwise lost solar radiation can be recovered. Those types of glazing are not suitable for all climates, there must be a need for both cooling and heating. Moreover, making the window reversible comes with a cost that should be compared with the related energy savings. It was shown that the larger the difference between the summer and winter SHGCs, the greater the potential energy savings. In this case, a reversible window could help avoiding the purchase of an active cooling system and its efficiency shall be measured in terms of thermal comfort improvement. During the heating season, the window is supposed to have a SHGC of 0.7. When the window is reversed, from 1st May to 30th September, the SHGC falls to 0.3.

5.3.4. Thermochromic smart windows

Switchable glazing can vary its optical properties in a dynamically controlled fashion, allowing opportunities to manage building incident solar gains according to ever-changing boundary conditions and building requirement. 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. Switchable glazing, embedding such smart materials, can be categorised into two typologies according to the way they are controlled during building operation: active switchable glazing and passive switchable glazing. In active switchable glazing, the modulation of the optical properties of the functional layers can be actively triggered by means of an external actuator such as current, voltage or magnetic field. The optical property variation of passive switchable glazing is induced passively by introducing materials that are sensitive to a variation of boundary condition such as UV radiation or temperature. The most commonly known active switchable glazing are electrochromic and gasochromic, while the passive ones are thermochromic and photochromic [53].

The most interesting glazing in the context of the present work is the thermochromic glazing as it does not need extra power to operate. Energy-efficient glass windows have been steadily developed over the years, resulting in a rapid development of thermochromic glazing. Thermochromic coatings tend to be vanadium oxide (VO_2) based. Across a critical transition temperature, VO_2 undergoes a structural transformation from a semiconducting to a metallic state. These states are referred to as "light" and "dark" states since the former is relatively transparent to infrared radiation while the latter is absorptive (or opaque) to such radiation. What makes this material feasible is that this process is highly reversible [54].

Nonetheless it should be noticed that thermochromism being a passive system, it offers no possibility of being manually controlled by the user. For this reason, electrochromic glazing has been identified as commercially more attractive and has benefitted from more research until now, even though more expensive than thermochromic glazing. Initially designed to limit overheating issues by stopping infrared radiations, thermochromic glazing also influences indoor illuminance by affecting the transmitted visible radiations. Therefore, as a dynamic and adaptive process, thermochromism brings the question of visual comfort for occupants [55].

The thermochromic coating is applied on the outer surface of the glazing. In their master thesis, Rickard Tallberg [56] and Stéphanie Bertrand [57] defined some modelling parameters for thermochromic glazing, they are given in Table 8. The glazing is in its clear state when the outer pane temperature is 10°C and in its dark state when this temperature reaches 65°C. In winter, the outer pane temperature is relatively close to the outdoor air temperature. In summer however, the film temperature can be much higher than the indoor temperature due to intense solar irradiation and high absorptivity, which can justify such a high transition temperature [58].

Table 8 – Thermochromic glazing characteristics of clear state and dark state.

	Solar transmittance	g-value	Outer pane temperature
Clear state	0.40	0.50	10°C
Dark state	0.11	0.14	65°C

VE has an option to model electrochromic windows by separating the outer pane into two panes, one corresponding to the clear state and the other to the dark state. By default, VE keeps the same glazing type for light and dark states. The transmittivity, reflectance and emissivity coefficients can be varied to obtain the desired solar coefficient for the dark state.

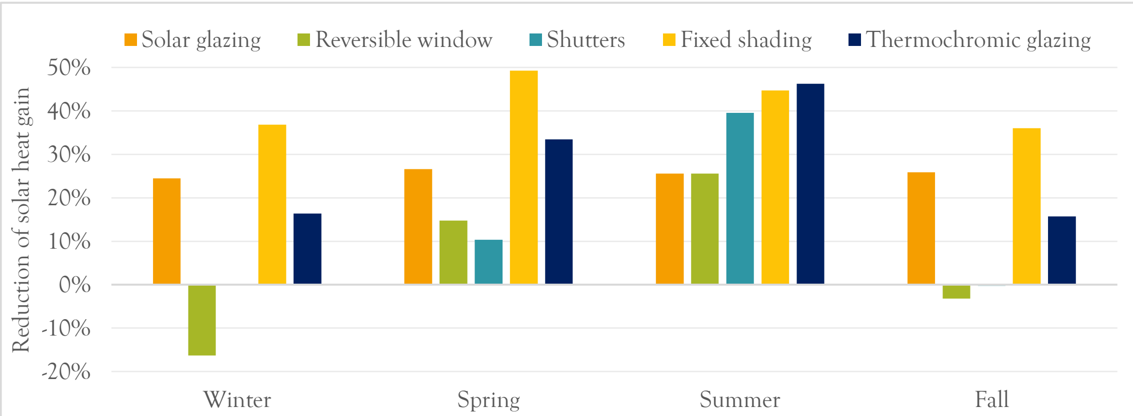
The transition from clear to dark state is specified through a control function, whose evaluation should result in a number between 0 and 1, 0 corresponding to the light state and 1 to the dark state. The properties of the glazing vary continuously between the two specified conditions. For the electrochromic glazing, the default control function is based on the incident irradiance. Below 400 W/m^2, the pane is in its clear state, dark state is reached at 800 W/m² and for incident irradiances between those values, the solar factor decreases continuously.

Thermochromic windows can be modelled by using the temperature in the control function instead of the incident irradiance. However, VE does not give access to the temperature of the glazing itself. The control function has been generated based on the indoor temperature of the room. In winter, when the outdoor temperature is around 10°C, the indoor temperature is 20°C and the glazing should be in clear state to maximise the solar gains. The dark state is reached when the external surface of the window is about 65°C, which can be assumed to coincide with an indoor temperature of 32°C, which is the highest indoor temperature reached in the baseline simulation. During the transition from clear to dark states, the glazing characteristics vary continuously, which is one of the advantages of thermochromic glazing. The properties of the glazing can be adapted continuously to respond to the needs of the building. Moreover, it can handle both direct and diffuse irradiation.

5.3.5. Comparison

Figure 24 shows the reduction, in percentage of solar gains offered by the tested solar protections compared to the traditional venetian blinds. As a reminder, the venetian blinds are the solar protections chosen in Chapter 4 for the baseline scenario and the efficiency of the improvements should be established by a comparison with those results. Only the southern facade has been considered in this analysis as this is where the solar gains primarily need to be decreased. The reduction is shown separately for the four seasons because if important solar gains should be avoided in summer, they should be preserved in winter so that the heating power can be kept low. As expected, fixed shading device and solar glazing decrease solar gains in winter too. Thermochromic glazing is the most effective protection in summer. Its strength is to be able to adapt to the environment conditions while preserving a more significant illuminance than fully closed shutters. Compared to other protections, reversible windows have the advantage to increase the solar gains in winter, allowing a decrease in heating energy consumption.

Figure 24 – Impact of the solar protections on solar gains through Southern windows depending on the season. The percentage of decrease of solar gains is calculated compared to the solar gains obtained when the windows are protected with internal venetian blinds.



5.4. Cooling through natural ventilation

While the main goal of the solar shading techniques is to decrease the solar gains to reduce the risk of overheating, the second passive cooling method consists in increasing the losses occurring through ventilation in summer to limit temperature rise during the day. This section is mainly based on the *Ventilative Cooling Design Guide* which is the work of Heiselberg *et al.* published by the IEA [59].

Ventilative cooling uses the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by active cooling in buildings, while guaranteeing a comfortable thermal environment. The outdoor air driving force can be either natural, mechanical or a combination of both.

Ventilation is already present in most buildings through mechanical and/or natural systems and by adapting them for cooling purposes, cooling can be provided in a cost-effective way. Ventilative cooling can both remove excess heat gains as well as increase air velocities and thereby widen the thermal comfort range. However, the cooling challenge can be addressed most effectively through a combination with other passive measures such as solar shading and thermal mass activation.

Ventilative cooling performances vary between countries due to climate variations, energy prices and other factors. In countries with a cold climate, ventilative cooling can mitigate the trend to use air conditioning in new buildings, which has occurred in response to the heavily insulated and airtight building designs. Heiselberg *et al.* showed that ventilative cooling can have a considerable impact on the risk of overheating in all climates. In cold and moderate climates, this risk can be eliminated, while in warm and hot climates supplementary cooling solutions are needed to ensure acceptable comfort levels.

As already mentioned in the theory of adaptative comfort in section 4.1, the degree of user control also has an influence on the perceived indoor environmental quality and productivity. Allowing occupants to adapt to their thermal environment can expand the comfort range in buildings. This adaption can be important to guarantee the thermal satisfaction of building occupants. However, the occupants' behaviour can sometimes have a negative impact on the ventilation strategy and some limitations or constraints on the use of natural ventilation may be necessary to prevent overheating or overcooling. When adopting user control, the window opening can be either a mix between manual and automated or purely manual. A purely manual system could require the training of building occupants.

In the present work, both natural and mechanical ventilation are studied. Mechanical ventilation is more convenient for night cooling since it does not require user interaction. The two strategies compared are day cooling and night cooling. As a reminder, natural ventilation is modelled through a MacroFlo module which calculates the incoming air flow rate based on the wind speed and direction and the opening characteristics. The mechanical ventilation is handled by ApacheSystem, in which the air flow rate at any time can be defined by the user.

5.4.1. Day cooling through natural ventilation

Unlike radiators that are controlled automatically by the thermostat, the opening of a window is, in most buildings, a manual action that occurs when decided by the occupants of the building. Modelling natural ventilation thus means modelling the occupants' behaviour.

Generally, in energy building simulation software, the opening of the window is a phenomenon that occurs when a criterion based on the internal temperature is satisfied, meaning that the window opening is a static model. Four implementation approaches of occupants' behaviour model have been defined [60].

- **Direct input or control**: this approach defines occupant-related inputs in the same way as other model inputs by defining some schedules. All the occupants' actions should be pre-calculated by the user to create some schedules that can be inputted in the program. This model is static and deterministic.
- **Built-in occupant behaviour model**: some building performance simulation programs offer the possibility to use pre-implemented occupant behaviour models.
- **User function or custom code**: the user can write functions or custom codes, as a part of a building energy model input file, to implement new building operation and supervisory controls. This approach provides more flexibility to the user by defining some conditions under which an action takes place depending on environmental conditions calculated by the software. This approach allows both stochastic and deterministic occupant behaviour models.
- **Co-simulation**: this is a simulation methodology that allows distinct components to be simulated by several simulation tools running simultaneously and switching information in a combined routine. This approach is most efficient when dealing with probabilistic and stochastic models.

In the case of VE, the only approaches that apply are the *direct input or control* and the *user function or custom code*. The user function is defined by creating a profile for the window opening. The window opening profile consists in giving a value to the control signal s that commands the opening of the window. The value can be set directly to 0 or 1, if we are to model a regular airing of the apartment for example, or it can be defined by a formula considering some room variables. In the latter case, the action only occurs when some conditions are satisfied. Two natural ventilation strategies have been investigated.

a. Static & deterministic strategy

The first method to model natural ventilation is simply based on the indoor and outdoor temperature. This approach is deterministic because if the conditions are met, the window is open. 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 is commanded by a control signal s. A value of 1 means that the window is open.

$$s = \begin{cases} 1\,, & if\ Ta > 24°C\ and\ Ta > To\ and\ To > 18°C \\ 0\,, & else \end{cases}$$

The main drawback of such method is that the window closes as soon as the indoor temperature falls below 24°C, making further natural cooling impossible. When performing a simulation, VE does not give access to the results of the previous time steps, and it is thus impossible to implement a hysteresis.

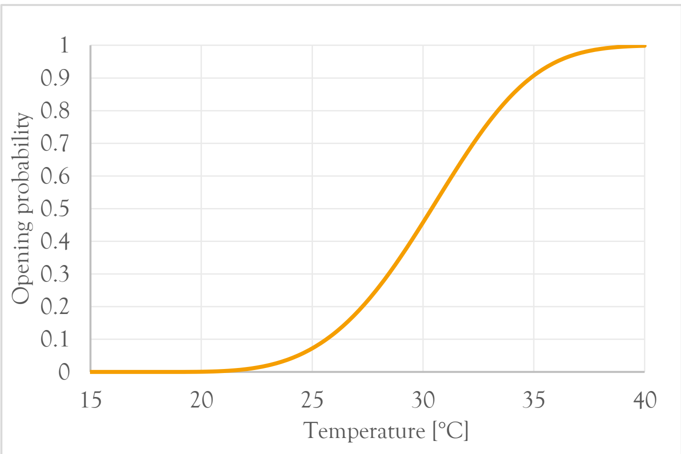
b. Stochastic strategy: memoryless hypothesis

The first way of implementing natural ventilation does not consider the occupants' behaviour. The occupants are not necessarily aware of the indoor temperature nor of the outdoor temperature. Instead of putting an arbitrary threshold at 24°C, the window opening can be implemented as a stochastic model. Naspi *et al.* used a regression model consisting in a general formula to evaluate the probable occupants' behaviour in relation to environmental conditions. Based on a memoryless hypothesis, the probability is influenced only by the current environmental conditions and not by previous states [61]. They considered two variables as relevant stimuli to drive the opening of a window, the indoor temperature and the outdoor temperature. This probability is thus used in VE as the probability to find a window open or closed at a specific moment. In this case, it has been decided to use the probability depending on the indoor temperature. The occupants generally react to the indoor temperature rather than to the outdoor temperature. The probability to find a window open is written as

$$P(T_{in}) = \begin{cases} 1 - \exp\left(-\dfrac{\left(\dfrac{T_{in} - 18}{8.6}\right)^{3.9} \Delta t}{t}\right), & if\ T_{in} > 18°C \\ 0\,, & if\ T_{in} \leq 18°C \end{cases}$$

where $T_{in} = 18°C$ is the limit above which the user starts to react to discomfort. $\Delta t/t$ provides the temporal frequency. Δt is the discrete time step in the simulation (here 10 minutes) and t is a time constant fixed at 60 minutes. Figure 25 shows the evolution of the opening probability depending on the temperature.

Figure 25 – Illustration of the opening probability depending on the indoor temperature.



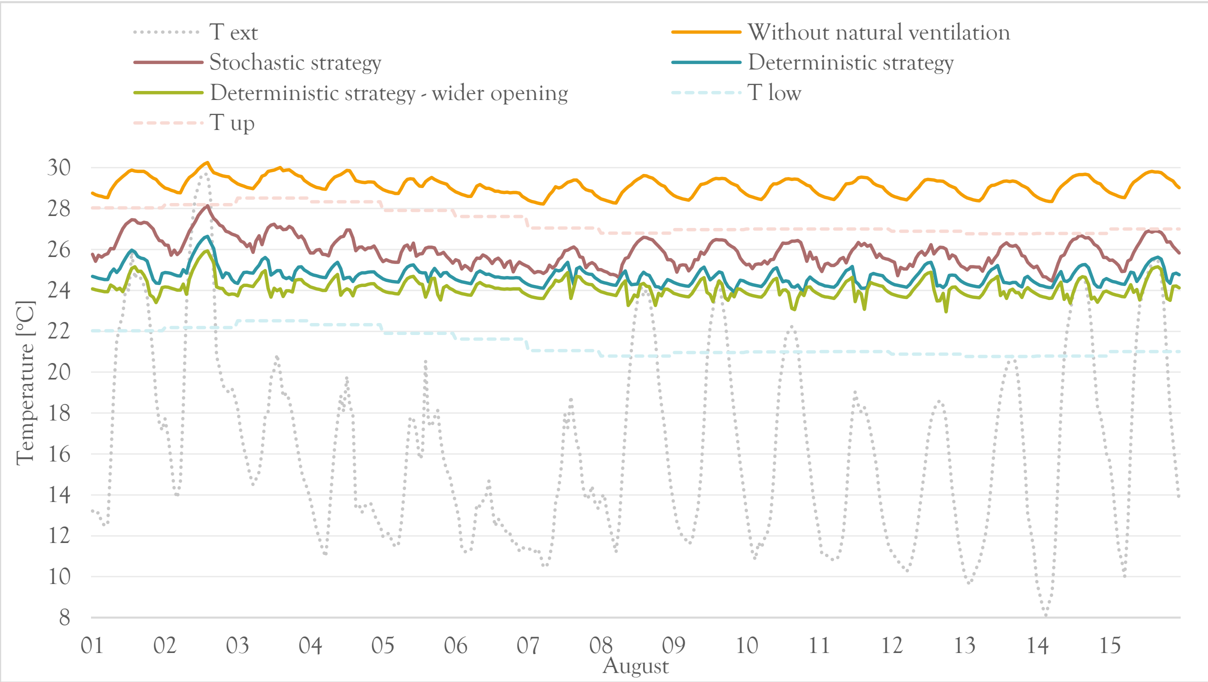
This stochastic strategy is the natural ventilation strategy that has been implemented in the baseline to account for occupants' behaviour.

The second method is more complete than the first one, but it only allows to take one variable into account, and it gives the probability to find a window open at a specific moment. To date, the most complete model of occupants' behaviour has been designed by Haldi & Robinson, who studied the interactions with window openings by office occupants for seven years [42]. They modelled those interactions as a Markovian process. However, as already mentioned, VE does not allow to access previous states and this model could not be implemented. More information about Haldi & Robinson's occupants' behaviour modelling can be found in Appendix D.1.

Those two strategies have been implemented to show that the occupants' behaviour can sometimes be detrimental to thermal comfort and that the occupants training could be necessary to reach thermal comfort. Figure 26 shows a comparison of the temperatures obtained in the kitchen with the two natural ventilation strategies. The opening area of the window has also been varied. When developing their Markovian model for window opening, Haldi & Robinson did not consider the opening angle of a window as a relevant variable and there is no predictive model for it so far. In the first case, it is considered that the window is open at 20% of the total opening area and at 90% in the second one. The temperatures are also compared with the scenario without natural ventilation to emphasise its benefit, regardless of the strategy. The kitchen has been chosen for this analysis. As aforementioned, it is one of the rooms that is the most subject to overheating and the only parameter that can be acted on to limit overheating is the ventilation.

It can directly be seen that adding natural ventilation brings the temperatures within the acceptable range calculated according to the theory of adaptative comfort (between T_{low} and T_{up}). All three methods considerably decrease the risk of overheating. The deterministic model is more efficient than the stochastic one. The occupants' behaviour is based exclusively on indoor temperature, and they will thus not consider closing the window when the outdoor temperature is higher than the indoor temperature and natural ventilation could only worsen the situation. The deterministic models give temperatures 1.5°C lower than the stochastic model on average but the difference is less marked between the two deterministic models, meaning that the opening area is not a major variable for the temperature decrease, even though the air flows at stake are much more significant.

Figure 26 – Comparison of the natural ventilation strategies and impact on adaptative thermal comfort in the kitchen from 1st to 15th August.



However, the results obtained with MacroFlo are to be taken with great care. Petrou *et al.* [62] investigated the existing differences in overheating risk prediction of flat typologies between two commonly used and widely validated BPS tools: Energy Plus and IES VE. Their study mainly focused on the impact of ventilative cooling on overheating reduction. They selected the default algorithm options in either tool to represent what is expected to be the most popular choices within the modelling community. They concluded that IES VE generally predicts higher air flows than Energy Plus, resulting in the prediction of a lower overheating risk in IES VE than in Energy Plus. They could however not determine which tool is the more accurate because of their inability to empirically validate their models.

5.4.2. Night cooling

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 thus 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 [63]. The efficiency of night cooling has essentially been demonstrated in Europe. Artmann *et al.* showed that there is a high potential for night cooling in Northern Europe and a significant potential in Central and Eastern Europe, as well as some Southern Europe regions. 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 [64].

Night cooling can be performed either by natural or mechanical ventilation. When using natural ventilation, night cooling should also be modelled with the MacroFlo module. 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 [63].

$$s = \begin{cases} 1, & if\ Ta > To\ and\ Ta > 20°C \\ 0, & otherwise \end{cases}$$

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. It could also create a risk of discomfort in the bedrooms due to draught, as well as a risk of acoustic discomfort, especially in large cities. 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. Generally, the ventilation systems do not work at full power to avoid acoustic discomfort. However, they could be used at a higher percentage of their capacity in summer.

Night cooling through mechanical ventilation is modelled with the same criterion as for natural ventilation. When the signal s is 1, the supply air flow rate reaches 100% of the fan capacity and when it is 0, the installation is used at 50% of its capacity, *i.e.* it provides the hygienic air flow rates.

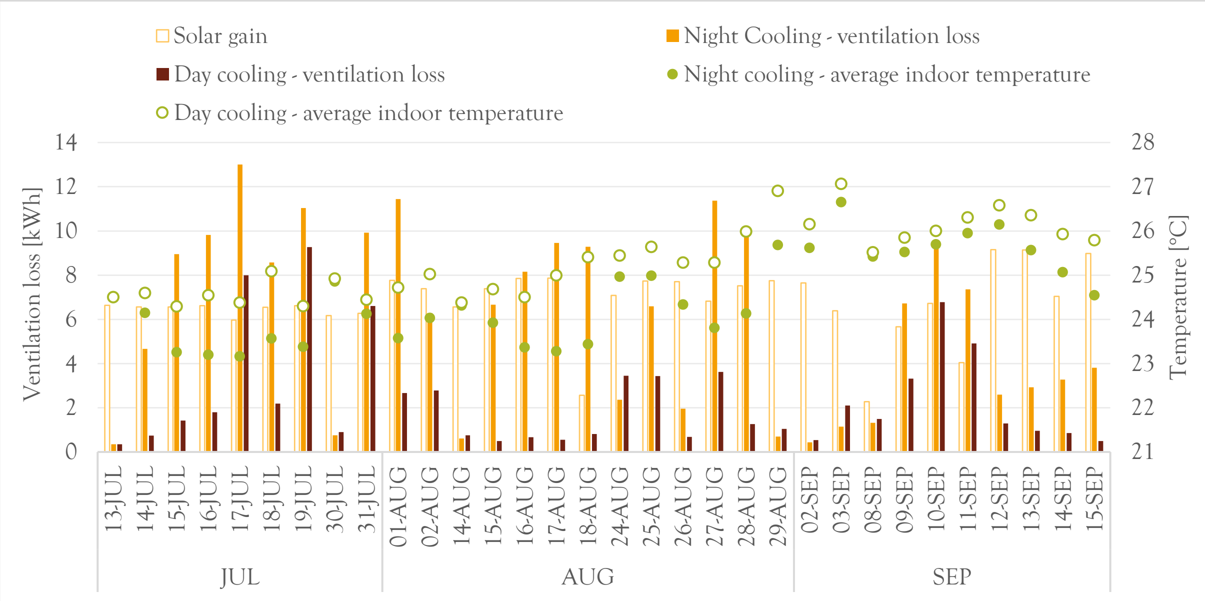
The advantage of using mechanical ventilation is that it ensures a constant air flow all night long and it avoids draughts. This solution could be more convenient for bedrooms. However, it could cause some noise issues due to the ventilation fans running at high rotational speed. One major drawback of overventilation is that it comes with an increased electricity consumption. The fan power consumption increases as the cubed air flow rate, resulting in a significant increase of electricity consumption.

5.4.3. Comparison

Figure 27 shows the potential of ventilative day and night cooling and the comparison of the resulting average daily temperature for the warmest days of 2020. The graph shows the losses induced by natural ventilation for both day and night cooling. Those losses are compared to the solar gains of the same day.

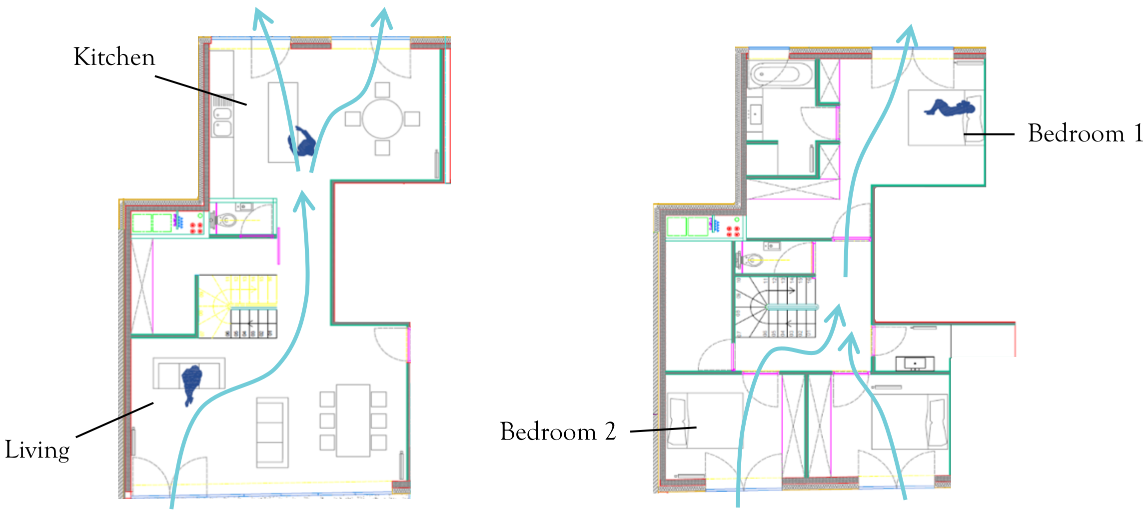
Night cooling is globally more efficient than day cooling to decrease the indoor temperature. It allows to restore the thermal inertia of the building by taking advantage of the cooler night temperatures. On average, night cooling decreases the average indoor temperature by 1°C compared to day cooling. However, if the outdoor temperature becomes too high even during the night, ventilative cooling becomes useless and other passive cooling techniques should be investigated to ensure thermal comfort.

Figure 27 – Comparison of the potential of day cooling ventilation and night cooling ventilation.



The efficiency of ventilative cooling strongly depends on the dwelling inner geometry. The building should be designed to foster cross ventilation. The openings size and position should be determined based on wind direction. For example, Liege often has a South-westerly wind. The associated pathway is shown in Figure 28. The geometry of the studied building enables a rather good circulation of air, especially on the first floor.

Figure 28 – Wind cross ventilation pathway.



5.5. Adiabatic cooling

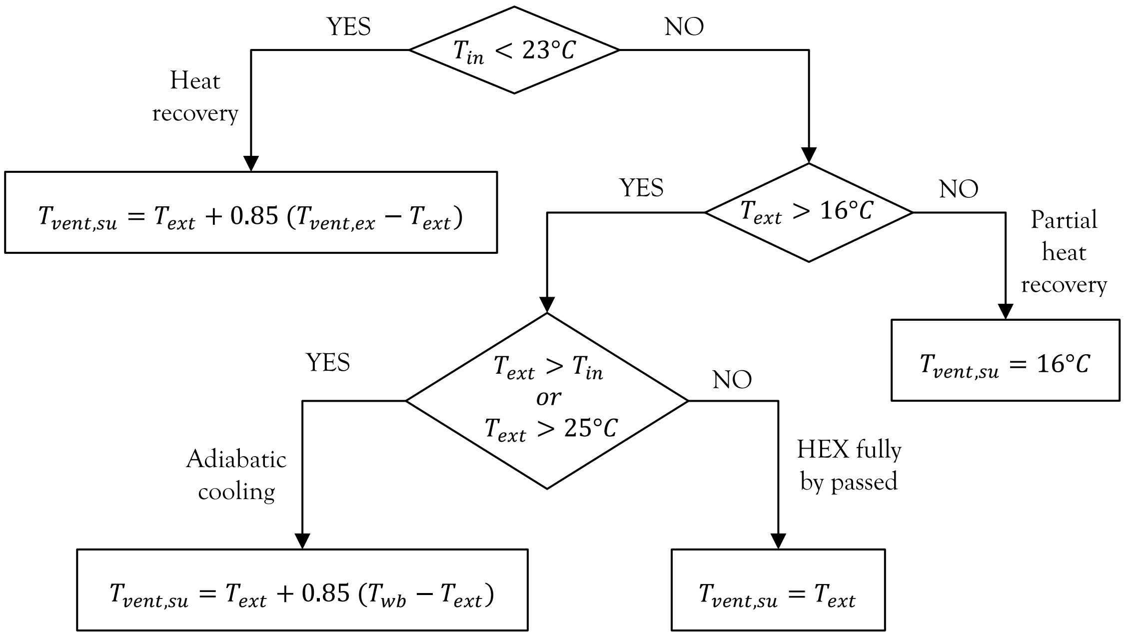
Adiabatic cooling can be either direct or indirect. In the direct adiabatic cooling, the outdoor air which is to be cooled is humidified, causing an increase in ambient humidity. A possible contamination of the supply air due to the humidification also must be considered. Therefore, this system is used only in few applications, *e.g.* in industrial buildings. In the indirect adiabatic cooling, the exhaust air is humidified and cooled and then, via a heat exchanger, it cools down the incoming outdoor air. The supply air is not humidified, and a possible contamination is ruled out. In summer, this technology provides gentle air conditioning and consumes a minimum energy as it can be coupled with the mechanical ventilation system [65].

The water consumption of this type of systems is very modest during the cooling operation, otherwise there would be no point in substituting a large electricity bill for cooling with heavy water consumption. Typically, the water cost would be approximately 16 € per year per m^3/s design air volume [66], or about 1.4 € per year for the considered apartment.

Adiabatic cooling is modelled by changing the conditions of the supply ventilation air. When the temperature of the outdoor air becomes too high, the latter needs to be cooled down before entering the building to avoid heating through ventilation in summer. Adiabatic cooling is used when the outdoor air temperature either exceeds 25°C or is higher than the indoor temperature. Figure 29 shows the chart flow diagram used to compute the supply ventilation temperature. This temperature depends on the indoor and outdoor temperatures, respectively T_{in} and T_{ext}. $T_{vent,ex}$ is the exhaust air temperature and T_{wb} is the wet bulb temperature of the exhaust air. It is assumed that the efficiency of the heat exchanger is not impacted by the humidity contained in the exhaust air.

The advantage of adiabatic cooling is that it can be coupled with overventilation during the day to avoid relying only on the building inertia all day long.

Figure 29 – Flow chart diagram of the supply ventilation temperature when introducing adiabatic cooling.



5.6. Building envelope improvements

5.6.1. Cool materials

Cool materials are also known as highly reflective materials and are a cost-effective, environment-friendly, and passive technique that contributes to achieving energy efficiency in buildings. They can reduce the energy demand for cooling and improve the urban microclimate by lowering surface and air temperature [67]. Cool materials are characterised by:

- High solar reflectance (SR). Solar reflectance is a measure of the ability of a surface material to reflect solar radiation and refers to the total reflectance of a surface, considering the hemispherical reflectance of radiation, integrated over the solar spectrum, including specular and diffuse reflection. It is measured on a scale from 0 to 1.

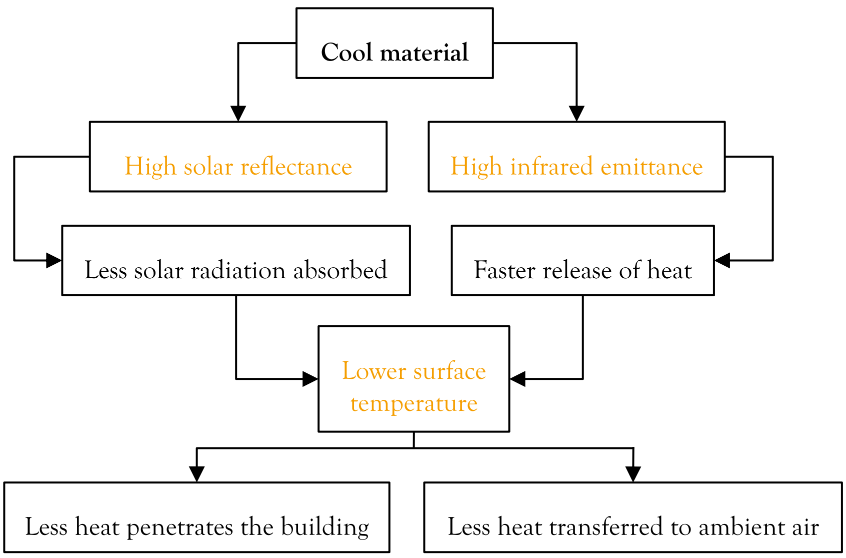
- High infrared emittance (e). Infrared emittance is a measure of the ability of a surface to release absorbed heat. It specifies how efficiently a surface radiates energy away from itself as compared with a black body operating at the same temperature. Infrared emittance is measured on a scale from 0 to 1.

When a surface with high solar reflectance and infrared emittance is exposed to solar radiation, it will have a lower surface temperature compared to a similar surface with lower SR and e values. If the cool surface is on the building envelope, the heat penetrating into the building will decrease. For a surface in the urban environment, this would contribute to decrease the temperature of the ambient air as the heat convection intensity from a cooler surface is lower. The basic principle of cool materials is illustrated in Figure 30. High solar reflectance and high infrared emittance can typically be reached by applying a white coating on the external surface of the building (SR = 0.7-0 .85 and e = 0.8-0 .9).

Generally, cool materials are applied to roof surfaces as they are the most exposed to sun irradiation. If the building is not air-conditioned, the reduced heat transfer from the cooler roof results in lower indoor temperatures and improved thermal comfort conditions. Cool materials are generally more efficient in older houses with little or no insulation. When reflective roofs are installed in high rise buildings, the expected climatic impact and mitigation potential is very limited. And even though they have been shown to be useful in various climate conditions, they can potentially lead to an increase of heating energy demand [68].

The benefits of cool materials have been assessed at building, city and global scale. When used at larger scale in a city, cool materials could contribute to increasing the urban albedo and it is considered as one of the most promising and powerful techniques to mitigate the urban heat island effect. The effect of an increased urban albedo as also been studied, even though it cannot be directly acted on at building scale. The albedo has been increased from 0.2 to 0.3.

Figure 30 – The basic principles of cool materials.



5.7. Conclusion

All the passive cooling techniques investigated in this work have been described and some comparisons have been made between the passive techniques belonging to the same category. In the next chapter, the efficiency of all the passive cooling techniques is evaluated, and the most effective ones are combined to minimise overheating. The resilience of the building is assessed by studying its behaviour during an intense period of heat.

6. COMPARISON OF PASSIVE COOLING TECHNIQUES

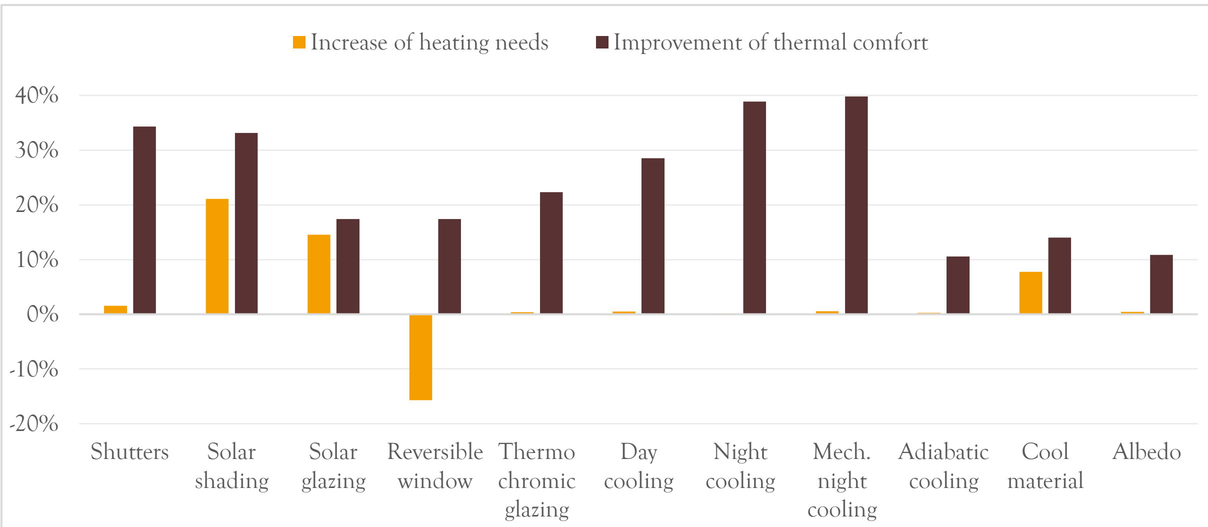
In the previous chapter, various passive techniques were introduced, and their strengths and limitations were overviewed. Four categories of passive cooling techniques were investigated based on their purpose. Solar techniques aim at decreasing the solar gains, preventing the heat to come in. Ventilative cooling is used to increase the heat losses through ventilation by taking advantage of the cooler outside air. Adiabatic cooling is a direct cooling method that uses the latent energy of water. The last technique consists in acting directly on the building envelope to decrease the solar gains through the external walls and, if used at global scale, tackle the urban heat island effect. In this chapter, it is shown how to combine those passive cooling techniques to improve thermal comfort and ensure the resilience of the building to global warming. First, the impact on energy consumption and thermal comfort of the studied passive cooling techniques is assessed to identify the most promising ones. Then possible combinations are discussed depending on the room orientation and usage. Those combinations are then tested during a period of intense heat to evaluate the resilience of the building. Finally, the limitations of the passive cooling techniques are reviewed.

6.1. Impact of passive cooling techniques on energy consumption and thermal comfort

Figure 31 shows how heating energy demand and thermal comfort are impacted by the implemented passive techniques. The increase in energy consumption and thermal comfort is calculated compared to the baseline scenario, *i.e.* with venetian blinds and when natural ventilation is controlled by the user in a stochastic way. The improvement of thermal comfort is shown for the living room, as it is the room that is the most likely to be subject to overheating. This room is South-oriented and thermal comfort should be guaranteed during the day when the solar gains and the internal gains are the highest. If thermal comfort is reached in the living room, it can be assumed that it is reached everywhere else.

The techniques that are considered as the most efficient are those that do not change the heating energy demand and significantly improve thermal comfort, hence the techniques that can be applied exclusively in summer. Some of the studied passive techniques are also likely to affect the global energy consumption of the building by consuming energy either directly or indirectly. Night cooling through mechanical ventilation requires more important air flow rates and the electricity consumption of the fans is proportional to the cubed air flow rate. Shutters and thermochromic glazing alter the daylight illuminance, resulting in the increase in lighting energy consumption. Finally, adiabatic cooling increases the water consumption of the building, but to a negligible degree.

Figure 31 – Impact of passive cooling methods on heating energy consumption and thermal comfort.



6.2. Combining passive cooling techniques

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 protections against solar gains that can be useful in the living room are the fixed external shading, the solar glazing and the thermochromic glazing. None of these solar protections spoils the outside view from the living room or has a strongly negative impact on room illuminance, unlike the shutters. External movable solar shades would be a better fit for a bedroom, since it would also allow to keep an acceptable level of darkness in the morning when the occupants are still asleep. And even when they should remain closed all day long, it has a lesser impact than in the living room, since the bedroom is supposed to be unoccupied.

As far as ventilative measures are concerned, day cooling should always be applied, since there are no restrictions on the occupants to open the windows. Guidelines might be useful to guarantee the occupants' thermal comfort. Night cooling is used only during heat waves, otherwise it would result in overcooling. In the living room, natural ventilative cooling can be used rather than mechanical ventilative cooling to avoid increasing the electricity consumption of the building. In the bedrooms, however, mechanical night cooling should be preferred. The opaque device, such as shutters or curtains, can interfere with the incoming outdoor air and reduce the efficiency of night ventilation.

The impact of all the combined passive cooling techniques is shown during a period of intense heat when the risk of overheating is the highest and an active cooling system might be the most useful method to prevent that risk. If thermal comfort can be guaranteed during a heat wave, it can be assumed that the risk of overheating has been sufficiently reduced. Moreover, as explained in the next section, it also allows to study the resilience of the building.

6.3. Resilience of the building to global warming

The present work aims at ensuring the resilience of nZEBs to global warming using passive cooling techniques. The definition of a resilient building was given in the introduction. One of the characteristics of a resilient building is its capacity to withstand extreme weather events. In Western Europe, the extreme meteorological event that is the most likely to occur and that is enhanced by global warming is the heat wave, as explained in section 2.5.5.

The efficiency of the passive cooling techniques is tested over a period of prolonged heat to find out if they contribute to withstand the risk of overheating. A heat wave, according to the current definition, occurs in the medium simulation during the year 2100. This period spreads from 30th August to 12th September. The results are shown for the period from 27th August to 14th September to see how long it takes to the building to recover from that period of intense heat.

Figure 32 shows the evolution of the temperature in the living room during the period of intense heat. The grey dotted line shows the evolution of the outdoor temperature over that period. To visualise the impact of the cooling methods, the temperature obtained without any passive cooling technique is taken as a reference (green solid line). All the improvement combinations include a cool reflective roof. Nowadays, cool materials are the most often used technique to counter overheating and it is the easiest one to implement in practice. It is thus assumed that the dwelling has a reflective roof. However, the impact of reflective roof on temperature is rather limited compared to the other cooling techniques. For this reason, it was not illustrated in the graph, as it would have lessened the legibility of the graph.

The improvements have been added one by one to visualise the improvement generated by each passive cooling technique and determine at which point 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 are suitable for the living room.

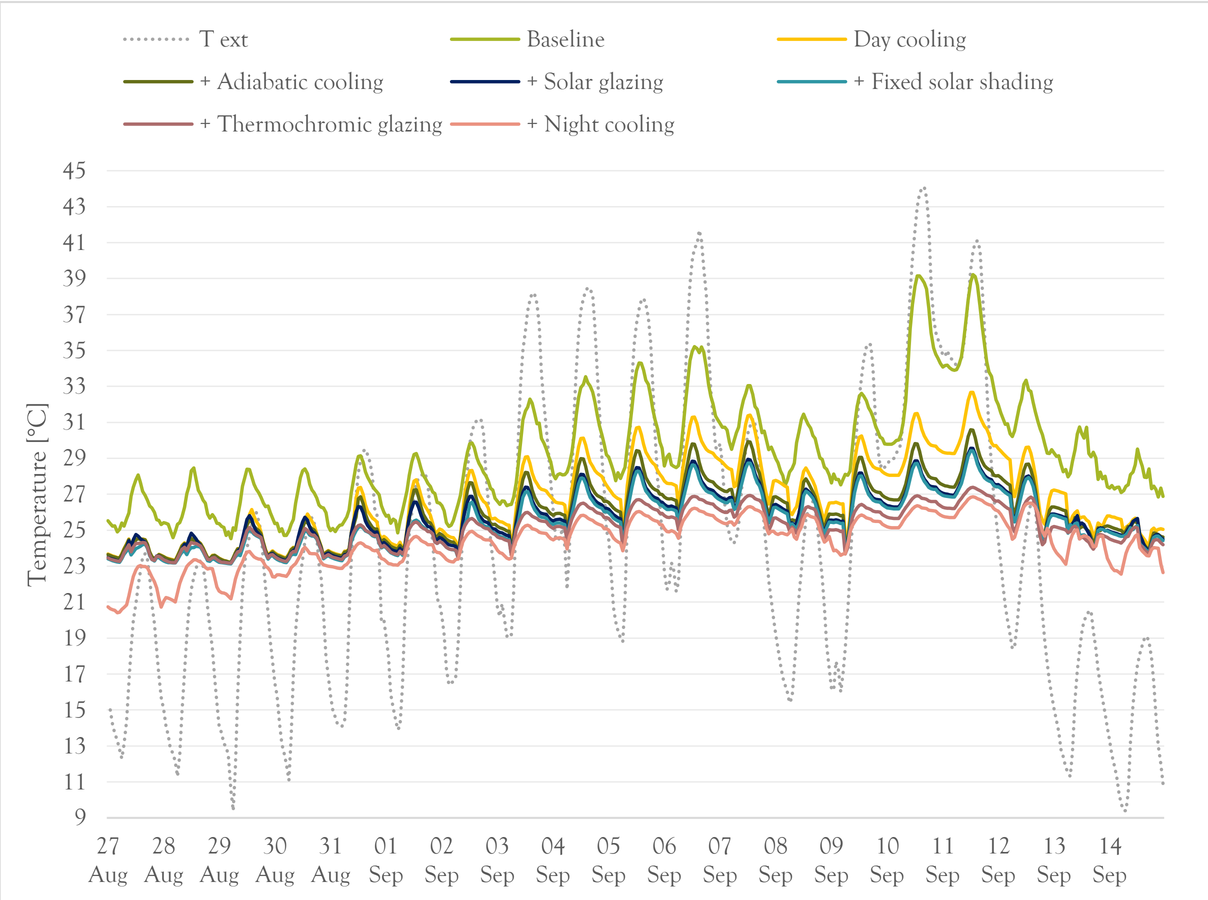
The first improvement is day cooling, used with the deterministic method described in section 5.4 (yellow solid line). The efficiency of day cooling appears even before the heat wave. Contrary to the case without improvement, the building has not stored heat within its walls all summer. The thermal inertia 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°C on average.

The next added improvement is adiabatic cooling (dark green solid line). When combined with day cooling, it allows to decrease the temperature by another 0.95°C on average. Adiabatic cooling is expected to become more efficient in the future as the outdoor air will become drier, as explained in section 2.5.4. If the outdoor air, and *a fortiori*, the indoor air becomes drier, the temperature decrease associated with humidification would be more significant, resulting in a more efficient cooling. If the outdoor air temperature becomes too dry, direct adiabatic cooling could also be considered.

Adiabatic cooling and day cooling have then been combined with the three solar protections that were considered as the most relevant for the living room. Solar glazing (dark blue solid line) and fixed solar shading (blue solid line) have almost the same impact on the indoor air temperature. On average, they further decrease the indoor temperature by 0.43 and 0.64°C respectively. Thermochromic glazing (purple sold line) allows a temperature reduction of 1.1°C and is thus the most efficient technique to decrease solar gains. The characteristics of the glazing are changed continuously depending on the indoor environment conditions. 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 day cooling, adiabatic cooling and thermochromic glazing, the temperature is maintained at 27°C even when the outdoor temperature reaches 43°C.

Figure 32 – Evolution of the temperature in the living room during a heat wave depending on the implemented passive measures.



A further reduction of the temperature is possible by adding night cooling to the previous passive techniques. Night cooling is particularly efficient because of the temperature drop during the night, which could even result in overcooling if used at full capacity all night long. 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 temperature does not fall below 25°C during the night, making night cooling useless. Since the building had 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. However, 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 thanks to day cooling. The temperatures could easily be further decreased by letting the windows open for a longer period (until the temperature reaches 23°C for example). However, as already mentioned, VE does not allow to define profiles containing hysteresis and the temperature decrease is limited to 25°C.

6.4. Limitations of the 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, adiabatic cooling. With those combined techniques, the temperature peaks are smoothed out and the temperature remains 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 simulation, the windows are open and closed exactly when necessary, to avoid overheating during the day and overcooling during the night. The sometimes detrimental occupants' behaviour has already been discussed in section 5.4 and it was concluded that occupants could require training to operate the building correctly.

Brown & Cole [69] 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. From a practical or design point of view, the systems usability or accessibility for the users can strongly impact the building regulation. The users can also 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. The findings also suggest a desire to learn more about how buildings work and comfort is provided, with a higher interest level in "green" buildings. 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.* [70] 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 technical manual where occupants would be able to learn about and understand its main components, their interactions, and with a user guide towards a better building performance. The key element to excellence in energy and environment building performance is the one that has been neglected in each one of the existing rating systems, i.e. the occupants' behaviour. Occupants' behaviour thus appears as the missing element to reach building resilience.

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 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 [71]. 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. When the sun sets or rises, it is low in the sky, resulting in highly penetrating solar irradiation that can cause overheating, even though the outdoor temperature begins to decrease. The passive cooling techniques should also be adapted depending on the orientation.

One other factor that can affect the overheating risk is the concentration of internal gains in the room. In this case, the internal gains are spread uniformly in the duplex even if in reality, there can be peaks of internal gains, especially in the kitchen. It could be a good practice to install supply ventilations vents in the rooms with higher internal gains to dissipate the heat more rapidly.

7. FUTURE WORK AND CONCLUSION

7.1. 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 of 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 by improving thermal comfort by 35% on average. It is followed by solar protections (+30%) and solar glazing (+25%). The use of cool reflective materials has also been studied as it is the most promising technique to mitigate the urban heat island effect. It allows to increase thermal comfort by 14% but its potential is rather limited for high-rise buildings. Finally, the last cooling technique studied was indirect adiabatic cooling which allows a reduction of only 11%, since adiabatic cooling is used only during intense periods of heat when the outdoor temperature exceeds 25°C. Its efficiency has been proved by studying the behaviour of the building during a heat wave.

The resilience of the building has been assessed by analysing its behaviour during a period of intense heat under various passive cooling combinations. It was shown that by combining night ventilation, indirect adiabatic cooling and thermochromic glazing, a reduction of 10°C in the indoor temperature could be achieved.

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 adaptative 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.

7.1. Future work

The present work was performed when the global warming simulations were still ongoing. Therefore, the warm scenario could not be used in this work. It would be interesting to see how the studied dwelling would behave with a weather file that predicts even higher temperatures than the medium simulation.

It was also shown in this work that current nZEBs are not designed to prevent overheating, even with nowadays climate. My intention was to use a weather file containing meteorological data for the year 2000 to see if this design flaw is already due to climate change. However, the reverse simulations started by Sébastien Doutreloup were not yet achieved. He intended to use the MAR to perform historic simulation with the considered scenario, but the 2000 simulation was not yet ready to be used in this work.

Once the apartment will be built, it would also be interesting to perform a testing campaign and to calibrate the VE model. The lack of experimental data is the biggest flaw of the present work. Nevertheless, it forced me to question the VE model and not to take the results for granted, which pushed me to develop a mathematical model with EES. The measured data would also offer the possibility to help developing a more robust EES model for further building performance simulations.

And obviously there are plenty of other passive cooling techniques that could be investigated. They were not considered in this work as they are less commonly used even in warmer climates, not adapted to the studied building or particularly difficult to model. All along this work I realised that passive cooling techniques are generally underestimated and underused. It would be worthwhile to develop some passive cooling techniques simulation models. The VE software is very traditional, and the model rapidly becomes complicated when faced with unusual improvements. For example, green roofs are particularly difficult to model due to the presence of vegetation even though they become more and more in use.

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APPENDIX A

A.1. Building envelope

Table 9 – Description of the wall construction with layers given from inside to outside.

WALLS		
	λ *[W/(m·K)]*	*Thickness* *[mm]*
External Wall		
Plaster	0.520	10
Masonry	1.200	190
Insulation	0.024	150
Air + Brick		
U =	*0.152*	*W/m²·K*
U_{max} =	0.240	*W/m²·K*
Adjacent Wall		
Plaster	0.520	10
Masonry	0.900	150
Insulation	0.034	160
U =	*0.198*	*W/m²·K*
U_{max} =	*1*	*W/m²·K*
Internal Wall		
Plaster	0.520	10
Masonry	0.900	150
Insulation	0.034	Min 60
U =	*0.452*	*W/m²·K*
U_{max} =	*1*	*W/m²·K*
Elevator Wall		
Concrete	1.7	200
XPS insulation	0.035	150
U =	*0.225*	*W/m²·K*
U_{max} =	*1*	*W/m²·K*

ROOFING		
	λ *[W/(m·K)]*	*Thickness* *[mm]*
External Roofing		
Structure	1.700	250
Concrete screed (max 800kg/m³)	0.23	110
Insulation	0.026	300
Sealing/finish		
U =	*0.081*	*W/m²·K*
U_{max} =	0.240	*W/m²·K*

FLOOR SLAB		
Floor Slab		
Flooring + screed	0.840	100
Sprayed PUR	0.028	200
Structure	2.200	300
U =	*0.132*	*W/m²·K*
U_{max} =	0.24	*W/m²·K*

A.2. ISO 17772: Energy performance of buildings – Indoor environmental Quality – part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings

Table 10 – Occupants' schedule for energy calculations for a residential apartment.

Parameters and setpoints

	Parameter	Value	Unit
Operation time	Hour at day, START	0	hour
	Hour at day, END	24	hour
	Breaks, inside range	0	hours
	Days/week	7	days
	Hours/day	24	hours
	Hours/year	8760	hours
Internal gains	Occupants	28.3	m^2/pers
	Occupants (Total)	4.2	W/m^2
	Occupants (Dry)	2.8	W/m^2
	Appliances	3	W/m^2
	Lighting (NBN EN 15193)	6	W/m^2
	Moisture production	2.12	g/m^2h
	CO2 production	0.66	l/m^2h
Setpoints	Min Top unoccupied hours	16	°C
	Max Top unoccupied hours	32	°C
	Min Top	20	°C
	Max Top	26	°C
	Ventilation rate (min)	0.5	l/s m^2
	Ventilation rate for CO_2 emissions	0.28	l/s m^2
	Max CO_2 concentration > outdoor	500	ppm
	Min relative humidity	25	%
	Max relative humidity	60	%
	Illuminance in working areas	0	lux
Other	Domestic hot water use	100	l/m^2 y

Usage schedule

h	Energy Calculation					
	Weekdays			Weekends		
	Occupants	Appliances	Lighting	Occupants	Appliances	Lighting
1	1	0.5	0	1	0.5	0
2	1	0.5	0	1	0.5	0
3	1	0.5	0	1	0.5	0
4	1	0.5	0	1	0.5	0
5	1	0.5	0	1	0.5	0
6	1	0.5	0	1	0.5	0
7	0.5	0.5	0.15	0.8	0.5	0.15
8	0.5	0.7	0.15	0.8	0.7	0.15
9	0.5	0.7	0.15	0.8	0.7	0.15
10	0.1	0.5	0.15	0.8	0.5	0.15
11	0.1	0.5	0.05	0.8	0.5	0.05
12	0.1	0.6	0.05	0.8	0.6	0.05
13	0.1	0.6	0.05	0.8	0.6	0.05
14	0.2	0.6	0.05	0.8	0.6	0.05
15	0.2	0.6	0.05	0.8	0.6	0.05
16	0.2	0.5	0.05	0.8	0.5	0.05
17	0.5	0.5	0.2	0.8	0.5	0.2
18	0.5	0.7	0.2	0.8	0.7	0.2
19	0.5	0.7	0.2	0.8	0.7	0.2
20	0.8	0.8	0.2	0.8	0.8	0.2
21	0.8	0.8	0.2	0.8	0.8	0.2
22	0.8	0.8	0.2	0.8	0.8	0.2
23	1	0.6	0.15	1	0.6	0.15
24	1	0.6	0.15	1	0.6	0.15

APPENDIX B

B.1. Detailed equations of the EES model

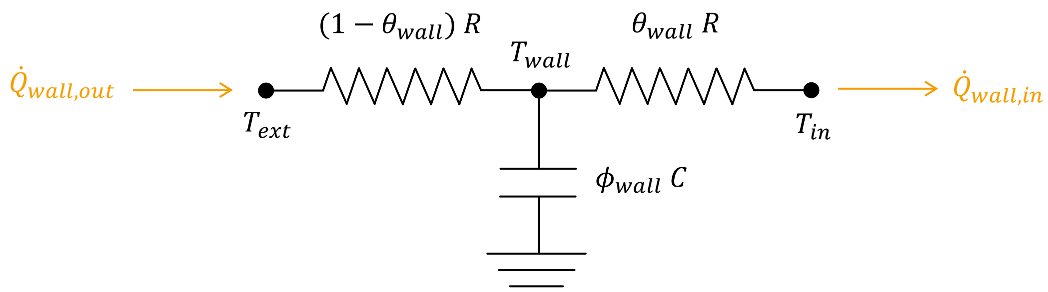
In EES, a thermal zone is entirely defined by a heat balance. Let z be the subscript for a thermal zone.

$$C_z \frac{dU_z}{dt} = \sum_{i=1}^{N_l} \dot{Q}_l + \sum_{i=1}^{N_s} \dot{Q}_{wall,i} + \sum_{i=1}^{N_z} \dot{m}_i \; cp \; \left(T_{z,i} - T_z\right) + \dot{m}_{inf} \; cp \; (T_\infty - T_z) + \dot{m}_{vent} \; cp \; (T_{su} - T_z) + \dot{Q}_{sys}$$

$C_z \frac{dU_z}{dt}$ is the amount of energy stored within the heat capacity of the zone at each time step.
C_z is the thermal capacity of the zone, taken at 6 times the thermal capacity of air to account for furniture and variation of air density.
U_z is the energy stored inside the zone.
$\sum_{i=1}^{N_l} \dot{Q}_l$ is the sum of the convective internal loads, aka internal heat loads.
N_l is the number of loads.
$\sum_{i=1}^{N_s} \dot{Q}_{wall,in,i}$ is the heat transfer by conduction through each surface of the zone.
N_s is the number of surfaces of the zone.
$\sum_{i=1}^{N_z} \dot{m}_i \; cp \; \left(T_{z,i} - T_z\right)$ is the heat transfer due to interzone mixing.
N_z is the number of zones in the building.
$\dot{m}_i$ is the air flow rate from zone i to the considered zone.
$T_{z,i}$ is the temperature in zone i.
$\dot{m}_{inf} \; cp \; (T_\infty - T_z)$ is the heat transfer due to infiltration of outside air.
$\dot{m}_{inf}$ is the infiltration air flow rate.
T_∞ is the outdoor air temperature.
$\dot{m}_{vent} \; cp \; \left(T_{vent,su} - T_z\right)$ is the heat transfer due to mechanical ventilation.
$\dot{m}_{vent}$ is the supply air flow rate.
$T_{vent,su}$ is the temperature of the supply air.
$\dot{Q}_{sys}$ is the additional heat from the heating system.

A wall is modelled with resistors and capacitors. The capacitor represents the thermal inertia of the wall, and this reservoir of heat can be accessed either from the inside or from the outside. The resistors R can be calculated as $1/U$. The parameter θ_{wall} defines the accessibility of the thermal capacity from the inside. The smaller θ_{wall}, the more accessible the capacity and the smaller the overheating risk. This is why insulation is generally the outermost layer. ϕ_{wall} is a parameter calculated based on the capacity of the wall to store and restore heat on a 24-hour period.

Figure 33 – Modellisation of a wall.



Based on this model, it is possible to distinguish three types of walls. If a wall separates two distinct zones or a zone from the outside environment, and has a thermal capacity, the above model can be used, and the associated equations are:

$$\phi_{wall}\, C_{wall} \frac{dU_{wall}}{dt} = \dot{Q}_{wall,out} - \dot{Q}_{wall,in}$$

For a heat transfer between two zone, $\dot{Q}_{wall}$ is expressed as

$$\dot{Q}_{wall} = A_{wall} \frac{U_{wall}}{\theta_{wall}}\, (T_{s,i} - T_z)$$

$T_{s,i}$ is the temperature at the node between the two resistors and the capacitor, *i.e.* the temperature inside the wall. The convective heat transfer coefficient between the surface of the wall and the zone temperature (or the outdoor temperature) is taken into account in the U_{wall} coefficient.

If the wall is considered as adiabatic, *i.e.* within the zone itself or adjacent to an unmodelled zone, the wall is modelled with only one resistance.

Finally, windows have a limited thermal capacity and are not supposed to store heat. They are thus modelled as follows:

$$\dot{Q}_{window} = U_{window}\, A_{window}\, (T_\infty - T_z)$$

The parameters used in the heat balance are given in the core of the report.

In EES, there are two ways to handle the solar gains. First, the solar gains can be directly injected in the thermal balance of the room, they are thus treated as internal gains. Physically, it means that the solar gains are heating the room and furniture and that they are then transferring this heat through convection to the walls, resulting in high temperature peaks. This approach is not realistic as air is transparent to irradiation, which stops only when hitting an opaque surface. It would be more accurate to inject the solar gains in the thermal balance of the walls. They are heated and then they transfer this heat to the room by convection. The solar gains can be spread between the walls according to the factors given in norm NBN EN ISO 13791 (2012). It is assumed that 10% of the solar irradiation is used to heat the furniture of the room. In the remaining 90%, 50% is injected in the floor, 40% in the vertical walls and 10% in the ceiling.

B.2. Comparison between the EES and VE models

<u>Solar gains</u>

Generally, when comparing the results of two simulation software, the main source of differences comes from the calculation of solar gains [35]. The distribution of the solar irradiation transferred through or re-emitted by glazing is not handled similarly by all software.

Before computing the solar gain of the room, it is necessary to calculate the irradiation on the window. This irradiation can be expressed as $I_{\gamma,i}$ which is the irradiation on a tilted surface with a tilt angle i and an azimuth γ. It is calculated as the sum of the irradiation directly coming from the sun, the diffuse irradiation from the sky and the reflected short-wave irradiation from the ground.

$$I_{\gamma,i} = I_{Dh} \cos\theta + I_{dh} \frac{1+\cos i}{2} + \alpha^* \,(I_{Dh} \sin h + I_{dh}) \frac{1-\cos i}{2} \;, \qquad \cos\theta > 0$$

I_{Dh} is the direct irradiation on a horizontal surface.

θ is the incidence angle, *i.e.*, the angle between the solar beam and the normal to the surface.

I_{dh} is the diffuse irradiation on a horizontal surface. It is assumed that all diffuse irradiation is uniformly distributed over the sky dome.

α^* is the albedo factor of the ground. It is assumed to be 0.2 in both models.

h is the solar altitude.

The solar irradiation arriving on the South and North-oriented windows can thus be calculated for each hour of the day based on the direct and diffuse irradiations on a horizontal surface provided by the meteorological files. The computation of the irradiation I_{North} and I_{South} is the same in both software. The main difference in the final solar gains is due to the irradiation handling.

a. Handling of irradiation in EES

In EES, the solar gains are calculated with a very simplified formula:

$$SG = g \cdot A_{window} \cdot I_{\gamma,i}$$

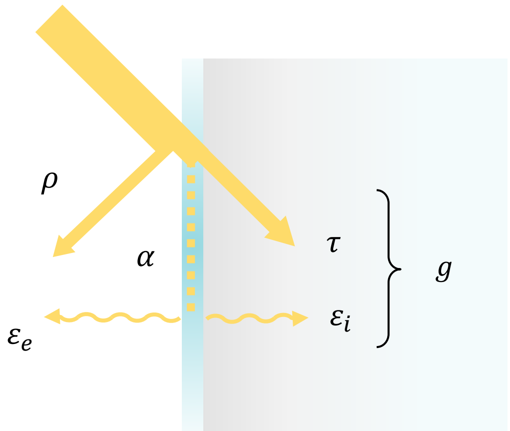
g is the solar factor of the window.

A_{window} is the area of the window in the considered room.

$I_{\gamma,i}$ is the irradiation on a tilted surface with a tilt angle i and an azimuth γ.

All the solar irradiation is not captured by the window. The irradiation that is not reflected (ρ) by the window can either be transmitted (τ) inside the room or absorbed (α) in the glazing. The absorbed irradiation is then re-emitted as short-wave irradiation (ε). The fraction of the solar irradiation that finally enters the room is given by the solar heat gain coefficient (SHGC), or solar factor (g). The process is illustrated in Figure 34. The solar factor offers a simple way to deal with solar gains by combining the direct and diffuse irradiations and it has the capacity to define the solar heat gains with acceptable precision while not taking convective heat transfer into consideration [72].

Figure 34 – Distribution of solar irradiation on a window



b. Handling of irradiation in VE

Contrary to EES, VE handles the diffuse and direct irradiations separately. When the transmitted direct irradiation enters the room, it hits the surfaces of the room that absorb some of the irradiation and reflect the rest. If it encounters a transparent surface, it can also be transmitted. The direct beam is tracked until it meets an opaque surface. The reflected part of the irradiation is further treated as diffuse irradiation.

The diffuse irradiation comes from three major sources: directly from the sky, where it is reflected in various directions by the clouds, radiation reflected from the ground and radiation attenuated by the sources of shading. This irradiation can be absorbed or transmitted through transparent surfaces. The transmitted part is redistributed to the walls of the room according to their view factor. The irradiation is then either absorbed or reflected by the internal surfaces. These steps are repeated up to 10 times to distribute diffuse irradiation through the room. In the end, some of the initial irradiation is lost through the window after reflection.

Once all the irradiation has been absorbed by an opaque surface, the walls heat up and release their heat through radiative and convective heat transfer. During this phase, further irradiation is lost as external walls transfer heat to the external environment. Finally, the *solar gains* calculated by VE are defined as the solar irradiation absorbed by the internal surfaces of the room and the solar irradiation absorbed in the glazing and transferred by conduction.

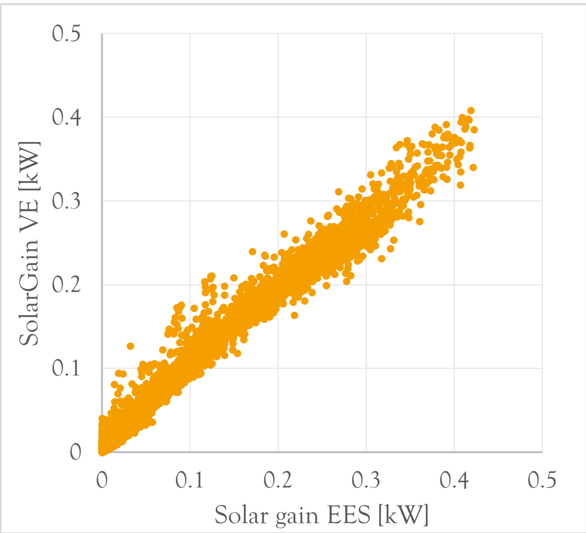
While in EES the solar factor is considered constant all year round, VE calculates the solar transmission, absorptance and reflectance parameters at 10 incidence angles spaced at 10-degree intervals. It accounts for the increasing reflectance with increasing incidence angle.

c. Comparison of the models

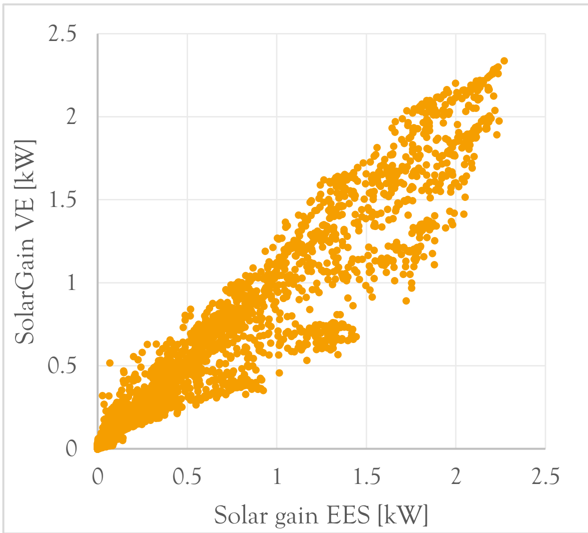
Part of the solar irradiation is lost during the distribution process of the irradiation inside the room. To cope with those phenomena that cannot be introduced in EES, a new solar factor has been computed. The solar factor of the windows has been defined to 0.5 in the EPB. Figure 35 shows a comparison of the solar gains calculated in EES and in VE when the solar factor of EES is decreased to 0.4, meaning that there is a difference of 20% between the solar gains of EES and those of VE, which seems reasonable. It can directly be seen that the solar gains perfectly fit in the North-oriented room where the coefficient of correlation is higher than 99%. In the South-oriented room however, the difference increases proportionally to the solar gains.

Several phenomena can explain this difference. First, in EES, the solar factor is considered constant while VE computes the solar transmission, absorptance and reflectance for several incidence angles. The portion of direct irradiation that is reflected is more important in summer than in winter when the sun is lower. However, the incidence angle does not seem to impact those coefficients at dawn and dusk, even though close to 90°. This could be due to the anisotropy of the glazing. Finally, even though the bedroom and the living room are both South-oriented, their solar gains significantly differ, the solar gains being more important in the bedroom than the living room when the irradiation increases. One possible explanation is that since the living room has an almost entirely glazed external surface, a large share of direct irradiation that enters the room is then reflected back outside. These phenomena are illustrated for three sunny days of the year in Figure 36.

Figure 35 – Comparison of the solar gains in EES and in VE (a) in a North-oriented room and (b) in a South-oriented room.



(a)



(b)

Results analysis

The EES model is rather simplified and does not consider heat exchange through radiation. When comparing the indoor temperature, it is thus important to compare the air temperature, not the operative temperature which considers radiative heat transfer.

Figure 37 shows a comparison of the evolution of the temperature inside a South-oriented room. The comparison has been made with the same solar gains for EES and VE to suppress the difference due to the changing solar reflectance with incidence angle. Results are shown for 15th August, a sunny day with a uniform cloud cover along the day. The graph shows a comparison of the solar gains, the indoor temperature, the conduction losses, and the ventilation losses. Infiltration losses are not showed as they are negligible.

Both models take account of the thermal inertia of the walls, introducing a delay between the irradiation peak and the temperature peak. Solar heat is in a first time stored within the walls and then progressively released. The temperature peak appears later in EES than in VE, suggesting that the dynamic behaviour of the room is handled differently.

Other sources of differences

There are of course other sources of differences between both models but their impact on the building behaviour is less significant. First, the EES model does not take radiant heat transfer into account. In VE, equipment, lighting and radiators are supposed to have a radiant fraction which can induce warmer air temperature in EES than in VE, since all the heat is supposed to be evacuated by convection in the indoor air. In VE, only the convective fraction of the internal gain is injected in the room balance. The radiant fraction is spread among the surrounding walls according to a view factor and is then injected in the thermal balance of the wall.

Another difference comes from the heat system controller. In VE, the heating load is calculated by an iterative process so that the desired indoor air temperature is reached at any moment. In EES however, the heating load is proportional to the temperature difference between the set point temperature and the room air temperature.

$$X_{valve} = C_{valve}(T_{set} - T_{in})$$

X_{valve} is the opening degree of the radiator thermostatic valve and C_{valve} is a coefficient whose value determines if the control is responsive to a small variation of temperature. This control strategy leads to abrupt variations in heating load, hence room temperature. To better regulate of the room temperature and remain at the desired temperature instead of having some oscillations around the set point temperature, it would be possible to use a PID controller. Figure 38 shows a comparison of the heat load profiles calculated with EES and VE for 15th November, a day with a heating demand. The graph shows the heating load of a bathroom as the heating demand is higher due to a larger set point temperature. With a PID controller, the behaviour of the radiators in EES could get closer to those of VE.

Figure 36 – Comparison of the solar gains in EES and VE for (a) 10th February (b) 14th April and (c) 13th June. The solar gains on the left are those in the living room and on the right in the bedroom.

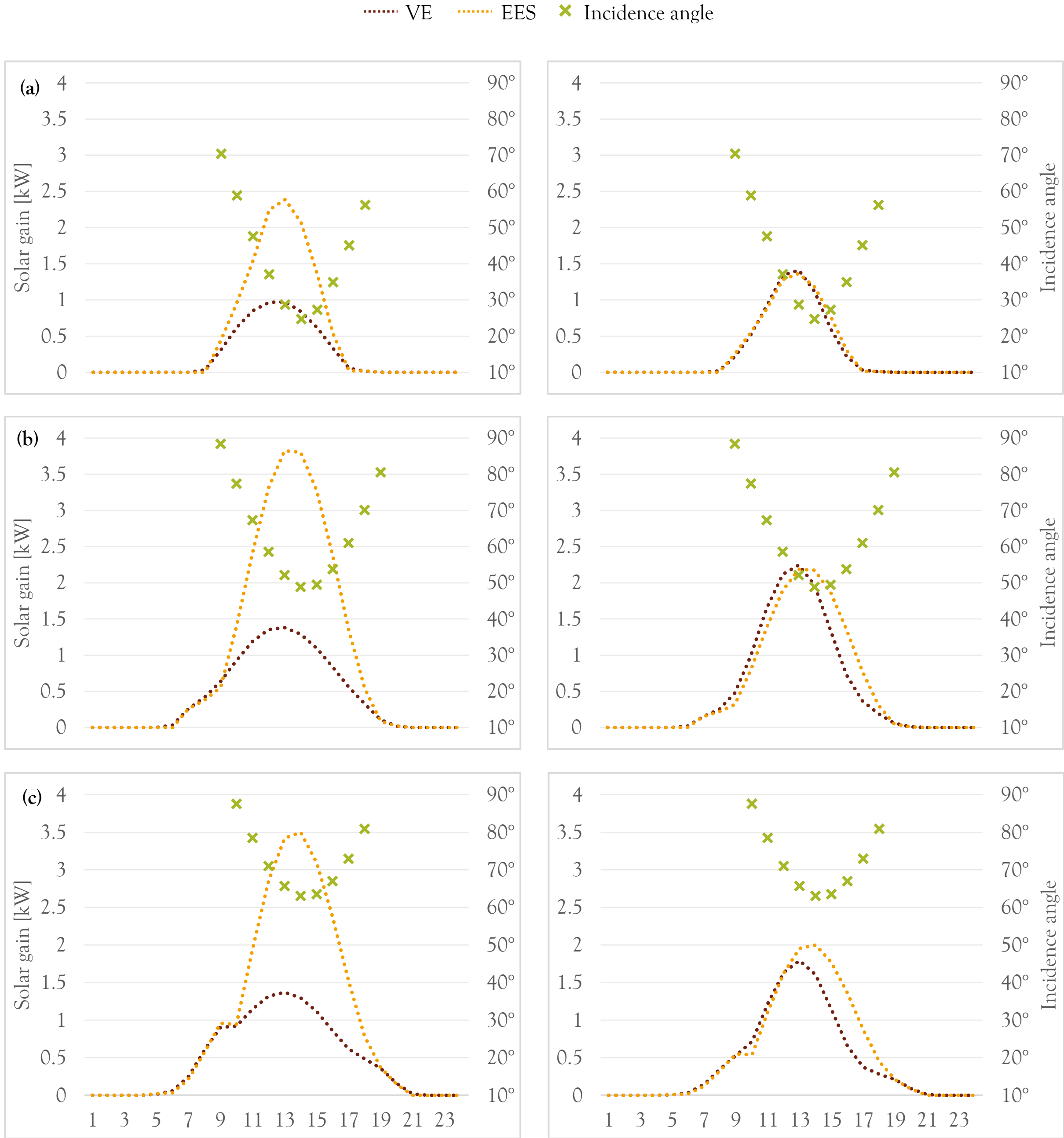


Figure 37 – Comparison of the behaviour of the living room in EES and VE. (a) Solar gains (b) Air temperature (c) Conduction losses (d) Ventilation losses.

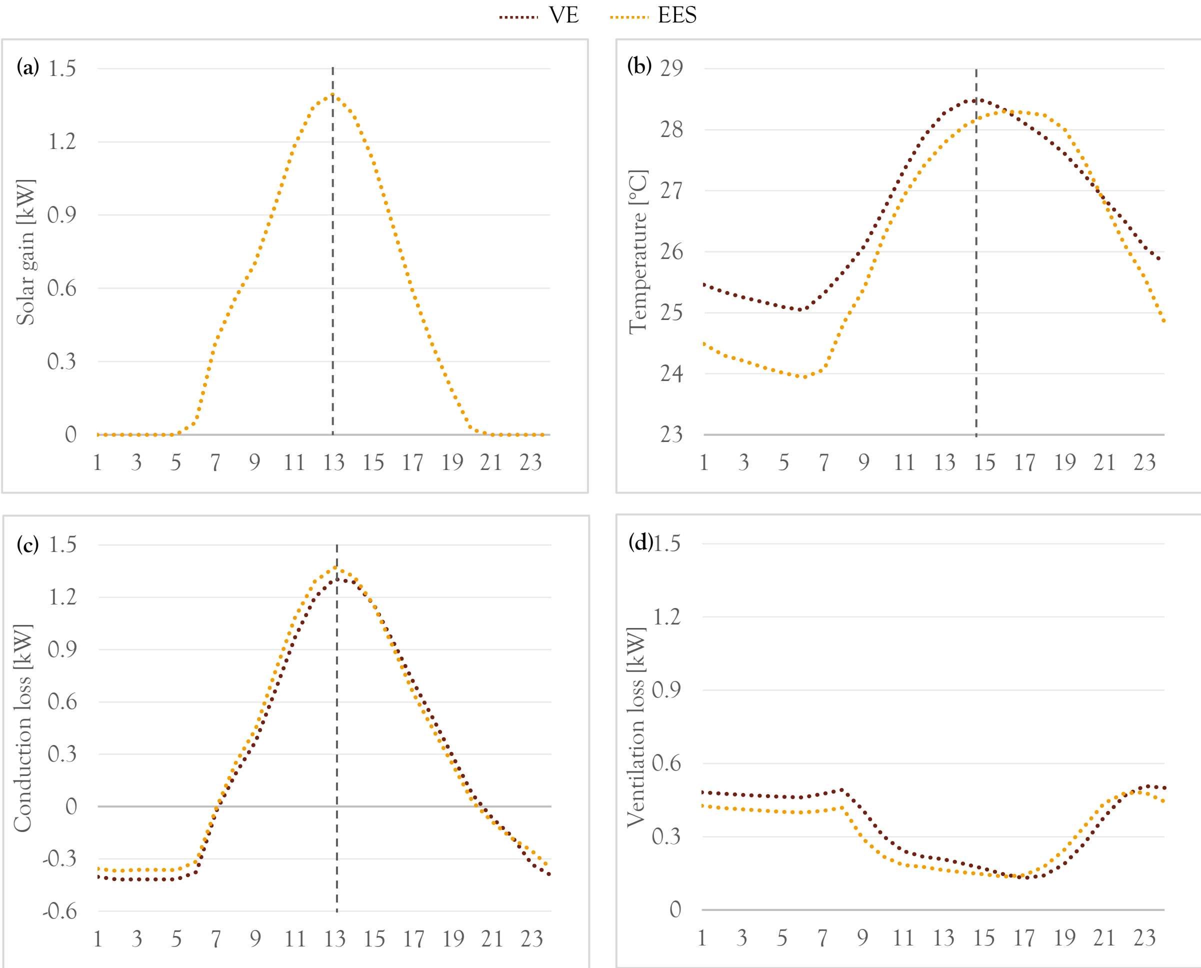
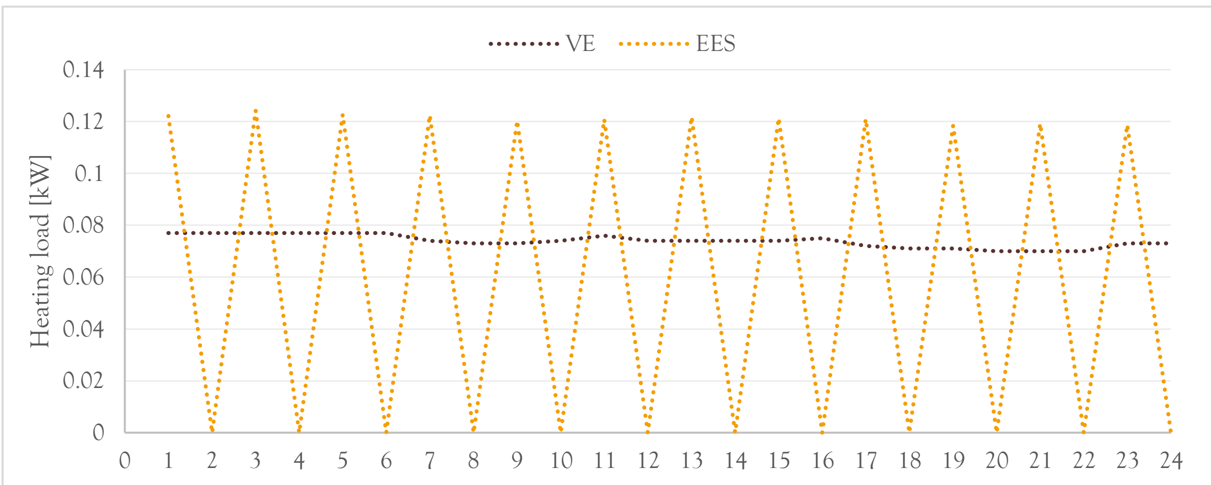


Figure 38 – Comparison of the heating load profiles of EES and VE in a bathroom.



APPENDIX C

C.1. Heating design and energy consumption analysis

There are several ways to perform the heating design. As already mentioned in section 2.3.4, the heating load of the radiators can be computed following the guideline of norm EN12831.

VE also offers the possibility to compute the heating load of the radiators in each room through a steady-state analysis according to the CIBSE design (Chartered Institution of Building Services Engineers). The CIBSE design is very similar to the norm EN12831 but is generally used in England. The steady-state analysis is made on the 10 coldest days included in the meteorological file and does not consider the internal gains of the room.

The dynamic simulation can also be used to compute the design heating load of the radiators by looking at the maximum power required to maintain the room at the desired temperature. Contrary to a steady-state analysis, the dynamic simulation allows to consider the heat gains from equipment, lighting, people, and solar irradiation, thus reducing the design heating load of the radiators.

As can be seen in Table 11, the heating capacities obtained with a static analysis are quite similar. When considering the internal gains however, the heating load is reduced by half. In nZEBs, the energy coming from internal gains, solar gains and heating load are generally of the same order of magnitude.

The annual energy consumption is 9.3 kWh/m² and is below the notional 15 kWh/m² imposed by the norm. To decrease the energy consumption, it is possible to heat only during the day. The annual consumption is decreased by 35%, but this measure increases the design heating load by 50% due to the morning heat up. All in all, a trade-off has to be found between temperature set point and heating capacity to decrease at most the energy consumption and the investment and operation cost of the installation.

The norm EN12831 also offers the possibility to install a heating-up capacity in the case the heating system would be shut off for the night. For a heating-up time of 1h, a setback period of 8h and a high thermal inertia, the heating-up capacity is 10 W/m². If the heating-up time is doubled, the heating-up capacity falls to 3 W/m². It is interesting to note that the heating-up capacity does not depend on the set-point temperature of the room. In VE, the heating-up time is approximately two hours and is strongly dependent on the temperature set point. The bedrooms have a lower heating-up capacity than the other rooms and it is maximum in the bathrooms where the heating set point is 23°C.

This analysis shows the importance of considering internal gains when designing a heating system, especially in nZEBs. A static analysis can lead to oversized heating systems, hence to an increased energy consumption. Standards such as CIBSE and EN12831 were initially developed to ensure that the radiators could reach the desired heating set point even in the worst-case scenario, even though this situation is very unlikely.

When considering the internal gains, the heating capacity is negligible for most of the rooms. Therefore, it would be interesting to invest in a less consuming heating system, for example by decreasing the temperature regime. When choosing a heating system, it is important to consider all the characteristics of the building. In this case, the heating needs can rapidly fluctuate due to the large share of internal gains and solar gains in the energy requirement. So, when the solar gains are suddenly large, the heating system should stop rapidly, and vice versa, meaning that its thermal inertia should be low. In passive buildings, heating through ventilation is often recommended by the PHPP as it is responsive and adapted to low heating loads.

Table 11 – Comparison of the heating load designs.

Heating load [W] ([W/m²]) Room	EN12831	CIBSE	Dynamic simulation Constant heating	Dynamic simulation Day only heating
Living	783 (19)	696 (17)	402 (3)	652 (16)
Kitchen	357 (11)	317 (10)	147 (5)	267 (8)
Bedroom 1	256 (11)	247 (10)	0 (0)	33 (1)
Bedroom 2	339 (13)	402 (16)	169 (7)	204 (8)
Bathroom 1	286 (32)	303 (34)	230 (26)	341 (39)
Bathroom 2	236 (50)	189 (40)	141 (30)	211 (45)
Total	*2256 (13)*	*2154 (12)*	*1089 (6)*	*1708 (10)*

APPENDIX D

D.1. Modelling occupants' behaviour for window opening based on Haldi & Robison stochastic model

The stochastic model used in section 5.4.1 for window opening only allows to take one variable into account, and it gives the probability to find a window open at a specific moment. Haldi & Robinson [42] studied the interactions with window openings by office occupants. They built a stochastic model over a measurement period of 7 years. They found out that the probability that an occupant opens a window varies depending on whether the occupant is arriving in the room, is leaving the room, or has already been in the room for a certain amount of time. Their model is thus separated in three distinctive probabilities. At each time step, the probability to open or close a window is calculated based on occupancy and on the state of the window at the previous time step. The probability is compared to a random number $r \in [0; 1]$ from a uniform distribution. The Markovian chain is illustrated in Figure 39.

The probabilities take new factors into account, which also have a significant importance on the occupants' behaviour. For example, the departure probability considers the running mean temperature, the absence factor and the robbery factor. If it has been hot lately, there is a higher probability that the occupant opens the window even when leaving. Conversely, if the occupants know they will not come back before another eight hours or if the room is on the ground floor and is likely to be robbed, they will probably be more reluctant to leave the window open. Those probabilities also express the fact that there is a higher probability that an action takes place when the occupants leave or arrive in the room, rather than when being in the room for a while.

It should also be noted that this model has been developed for office occupants, so the applicability of this model to residential building occupants could be questioned. In residential buildings, occupants can react to some other stimuli that cannot apply in an office. For example, occupants can open the window when internal gains become too high because of cooking.

$$p_{01,arr} = \left(1 + \exp\left(-\left(-13.7 + 0.308\,T_{in} + 0.0395\,T_{out} + 1.826\,f_{abs,prev}\right)\right)\right)^{-1}$$

$$p_{10,arr} = \left(1 + \exp\left(-(3.95 - 0.286\,T_{in} - 0.05\,T_{out})\right)\right)^{-1}$$

$$p_{01,int} = \left(1 + \exp\left(-\left(-11.78 + 0.263\,T_{in} + 0.0394\,T_{out} - 9 \cdot 10^{-4}\,N_{pres}\right)\right)\right)^{-1}$$

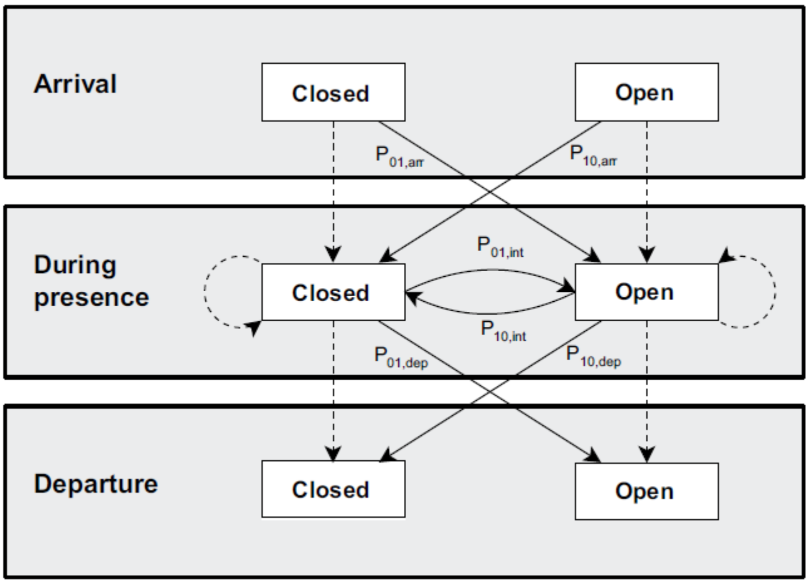
$$p_{10,int} = \left(1 + \exp\left(-(-4.14 + 0.26\,T_{in} - 0.0625\,T_{out})\right)\right)^{-1}$$

$$p_{01,dep} = \left(1 + \exp\left(-\left(-8.72 + 0.1352\,T_{rm} + 0.85\,f_{abs,next} + 0.82 f_{GF}\right)\right)\right)^{-1}$$

$$p_{10,dep} = \left(1 + \exp\left(-\left(-8.68 + 0.222\,T_{in} - 0.0936\,T_{rm} + 1.534\,f_{abs,next} - 0.845 f_{GF}\right)\right)\right)^{-1}$$

T_{in} is the temperature inside the considered zone
T_{out} is the outdoor temperature
T_{rm} is the running mean outdoor temperature
$f_{abs,prev}$ is a parameter whose value is 1 when the occupant has been absent for at least 8 hours
$f_{abs,next}$ is a parameter whose value is 1 when the occupant will be absent for at least 8 hours
N_{pres} is the number of presence hours
f_{GF} is a parameter whose value is 0 if the zone is likely to be robbed (if located on the ground floor for example)

Figure 39 – General scheme of the Markov process **[42]**.



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