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SIMULATION OF A WALL SYSTEM WITH DYNAMIC THERMAL INSULATION – IMPACT ON THERMAL COMFORT

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To my family

To my friends

“Don't settle for average. Bring your best to the moment. Then, whether it fails or succeeds, at least you know you gave all you had.”

Angela Bassett

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ABSTRACT

Current buildings follow regulations and standards that demand well insulated envelopes. By keeping heat inside, well-insulated buildings allow thermal comfort during winter months, but cause discomfort by overheating during summer. For that reason, overheating is, currently, a phenomenon of great concern and importance. In addition, with climate change, the weather conditions have become more severe and extreme, both in summer and in winter, making overheating even more problematic.

The building envelope is responsible for maintaining thermal comfort. It should allow heat exchanges with the outside in summer, avoiding situations of overheating, but prevent such exchanges in winter. Therefore, and to meet both situations, adaptive façades have arisen. This type of façade incorporates a system which enables them to adapt to the conditions of the exterior environment depending on the interior needs, in order to provide comfort to the occupants. Dynamic thermal insulation systems (DTIS) are an example of adaptive façades. These systems allow the control of heat transfer, varying between a state of insulation and a state of conduction. However, due to its complexity and lack of standardised evaluation procedures, developing and implementing an adaptive façade is challenging and the assessment of its behaviour is, sometimes, based on unreliable results.

In this study, twelve months and July simulations were performed hourly on *DesignBuilder* to assess the impact of a dynamic thermal insulation system on indoor thermal comfort. A parametric analysis was carried out by modifying several parameters like the envelope configuration, the thermal transmittance coefficient, the climate conditions, and the shading and cooling systems. It was then possible to obtain hourly results of operative temperatures and energy consumption for seventy-four different scenarios. Through the exported simulation results, two discomfort performance indicators (DPIs) were calculated, to assess the severity and the percentage of time with discomfort by overheating. The results showed that the use of a dynamic U-value can be effective to mitigate the effects of overheating. A U-value of 1 W/(m^2.ºC) reduce the percentage of hours with discomfort by overheating by a maximum of 27% and the severity by a maximum of 18%. It was also discovered that the implementation of a DTIS in a high mass building has greater impact than in a low mass building.

Subsequently, hourly simulations per orientation were carried out, exporting internal and external surface temperatures that were analysed by the calculation of four DPIs. The optimization of the operational performance of the dynamic thermal insulation system under study, was discussed. This way, the use of a DTIS in a façade can be beneficial to the performance of the building, being interesting to have a high U-value during around 46-70% of the simulated hours, without shading, and around 23-33% when an exterior shading is used. In addition, it was discovered that with the use of an exterior shading system the relevance of having a high U-value decreases around 50%.

Finally, it was analysed the impact of the time step on the results, and it was found that they were approximately equal when simulated hourly and sub-hourly. This way, it was not necessary to do simulations with more time steps in order to get reliable results.

KEYWORDS: adaptive façades, dynamic thermal insulation system, discomfort by overheating, optimization of the operational performance, simulation.

RESUMO

Os edifícios construídos atualmente seguem regulamentos e normas que exigem envolventes bem isoladas. Ao manter o calor no interior, os edifícios bem isolados permitem o conforto térmico durante os meses de inverno, mas provocam desconforto por sobreaquecimento durante o verão. Assim, o sobreaquecimento é, atualmente, um fenómeno de grande preocupação e importância. Para além disso, com as alterações climáticas, as condições meteorológicas tornaram-se mais severas e extremas, tanto no verão como no inverno, tornando o sobreaquecimento ainda mais problemático.

A envolvente dum edifício é responsável pela manutenção do conforto. A envolvente deve permitir trocas de calor com o exterior no verão, evitando situações de sobreaquecimento, mas impedir essas trocas no inverno. Assim, e para que ambas as situações sejam satisfeitas, surgiram as fachadas adaptativas. Este tipo de fachadas incorporam um sistema que permite a sua adaptação às condições do ambiente exterior em função das necessidades interiores. Os sistemas de isolamento térmico dinâmico (DTIS) são um exemplo de fachadas adaptativas. Estes sistemas permitem o controlo da transferência de calor, variando entre um estado de isolamento e um estado de condução. No entanto, devido à sua complexidade e à falta de procedimentos de avaliação normalizados, o desenvolvimento e implementação de uma fachada adaptativa é um desafio e a avaliação do seu comportamento baseia-se, por vezes, em resultados pouco fiáveis.

Neste estudo foram realizadas simulações horárias, para doze meses e para julho, no *DesignBuilder* para avaliar o impacto de um DTIS no conforto térmico interior. Foi efetuada uma análise paramétrica, modificando diversos parâmetros como a configuração da envolvente, o coeficiente de transmissão térmica, as condições climáticas, e os sistemas de sombreamento e de arrefecimento. Foi então possível obter resultados horários das temperaturas operativas e do consumo de energia para setenta e quatro cenários diferentes. Através dos resultados exportados das simulações foram calculados dois indicadores de desempenho de desconforto (DPIs), para avaliar a gravidade e a percentagem de tempo com desconforto por sobreaquecimento. Os resultados mostram que a utilização de um U dinâmico pode ser eficaz na mitigação dos efeitos do sobreaquecimento. Um valor U de 1 W/(m^2.ºC) reduz a percentagem de horas com desconforto num máximo de 27% e a gravidade do sobreaquecimento num máximo de 18%. Descobriu-se também que a implementação de um DTIS num edifício de elevada inércia térmica tem maior impacto do que num edifício de baixa inércia térmica.

Posteriormente, foram efetuadas simulações horárias por orientação, exportando temperaturas superficiais internas e externas que foram analisadas através do cálculo de quatro DPIs. Foi discutida a otimização operacional do desempenho do DTIS em estudo. Desta forma, a utilização de um DTIS numa fachada pode ser benéfica para o desempenho do edifício, sendo que é interessante ter valor de U elevado durante cerca de 46-70% das horas simuladas, sem sombreamento, e cerca de 23-33% quando é utilizado um sombreamento exterior. Para além disso, descobriu-se que, com a utilização de um sistema de sombreamento exterior, a relevância de ter um valor U elevado diminui cerca de 50%.

Finalmente, foi analisado o impacto de diferentes intervalos de tempo nos resultados, tendo-se verificado que estes eram aproximadamente iguais quando simulados de hora em hora e de 15 em 15 minutos, não sendo necessário fazer simulações com diferentes intervalos de tempo para obter resultados fiáveis.

PALAVRAS-CHAVE: fachadas adaptativas, sistema de isolamento térmico dinâmico, desconforto por sobreaquecimento, otimização operacional do desempenho, simulações.

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SYMBOLS, ACRONYMS, ABBREVIATIONS

SYMBOLS

Cp – Specific heat capacity [J/(kg.K)]

CO_2 – Carbon dioxide

g-value – Solar heat gain coefficient

λ – Thermal conductivity [W/(m.K)]

n – Number of hours simulated

N – Number of hours with discomfort

R – Thermal resistance (m2.K/W)

T – Temperature (ºC)

U-value – Thermal transmittance [(W/(m2.ºC)] or [W/(m2.K)]

ΔT – Difference of temperature (ºC)

θ_{rm} – External running mean temperature (ºC)

θ_{o} – Operative temperature (ºC)

θ_{c} – Comfort temperature (ºC)

θ_{ed-i} – Daily mean external temperature for the i-th previous day (ºC)

θ_{ul} – Upper temperature limit of comfort (ºC)

$\theta_{ext.\ sur.}$ – Exterior surface temperature (ºC)

$\theta_{int.\ sur.}$ – Interior surface temperature (ºC)

ACRONYMS

AFs – Adaptive Façades

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

CAD – Computer-Aided Design

CCF – Close Cavity Façades

DB – DesignBuilder

DIMs – Dynamic Insulation Materials

DPI – Discomfort Performance Indicators

DSF – Double Skin Façade

DTIS – Dynamic Thermal Insulation System

E+ – EnergyPlus

EAS – Exhaust Air Façade

EEA – European Economic Area

EN – European Standard

EPS – Expanded Polystyrene Insulation

EPW – EnergyPlus Weather

EU – European Union

GHG – Green House Gases

HM – High Mass

HVAC – Heating, Ventilation and Air-conditioning

IEA – International Energy Agency

KPIs – Key Performance Indicators

LM – Low Mass

MDF – Medium Density Fibreboard

MSAW – Mediterranean Smart Adaptive Wall

NZEB – Net-Zero Energy Buildings

PCMs – Phase Change Materials

SAF – Supply Air Façade

SCE – Sistema de Certificação Energética dos Edifícios

UK – United Kingdom

US – United States

VIP – Vacuum Insulation Panels

WHO – World Health Organization

WMO – World Meteorological Organization

1

INTRODUCTION

1.1. BACKGROUND

Thermal comfort is often associated with the exclusive use of technologies that regulate the temperature of the thermal environment. However, it implies an enormous energy consumption, increasing the cost for the users. This way, in order to have more efficient buildings and reduce the cost, it is necessary to guarantee indoor thermal comfort by reducing and optimising the building's energy needs. Because of climate change, the temperature in the planet has been increasing over the years, which has led to various recent problems in the society. One of these complications is the overheating of buildings. Recently, several solutions have been developed to mitigate overheating in buildings and consequently reduce energy consumption, without jeopardising the thermal comfort of users.

The building façade separates the interior and exterior environment and is responsible for maintaining indoor comfortable temperatures to occupants. During winter, heat exchanges with the exterior environment should be avoided to maintain the heat inside the building, providing comfort to its occupants. However, these exchanges are desirable in summer to maintain the interior temperatures between the comfort temperature limits, allowing the heat release through the façade, mitigating overheating.

Adaptive façades have emerged to address both challenges: to provide thermal comfort and to reduce energy consumption. This high-performance type of façades includes a system that allows it to adjust to the outer environment conditions based on the interior demands. There are a lot of different categories and typologies of adaptive façades with different purposes, such as dynamic shading, chromogenic glazing, active solar façades and active ventilation façades. However, due to the complexity of these types of façades and the lack of standards to evaluate their performance, developing and implementing an adaptive façade is still challenging and the assessment of its behaviour is, sometimes, based on unreliable results.

Based on the results of building energy simulations, this dissertation will go deeper into the evaluation of the performance of a dynamic thermal insulation system (DTIS), assessing the impact of a DTIS on indoor thermal comfort, through the use of discomfort performance indicators (DPIS). Furthermore, the operational performance optimization of the system is discussed.

1.2. MOTIVATIONS AND GOALS

The main objective of this dissertation is to evaluate the impact of a DTIS on a building's thermal comfort and discuss the optimization of the operation performance of a dynamic insulation system, based on discomfort performance indicators. A dynamic thermal insulation system makes it possible to control heat exchange according to the needs of the building, thus reducing the energy consumed by cooling and heating systems, while providing comfort.

The secondary goals of this dissertation are the following:

- Study the importance of adaptive façades to reduce energy consumption and increase thermal comfort and underline the most important aspects of what has already been studied;
- Select and create a generic building model that includes the most common building components implemented in Portuguese construction;
- Assess the impact of a variable U-value in façade walls on the thermal comfort and on the energy consumption for the created model, using *DesignBuilder* as a simulation tool;
- Simulate for durations with different detail levels, a twelve month simulation and a July simulation;
- Assess the periods when it is interesting to have a high U-value in the façade;
- Analyse the impact of the time step on the quality of the results.

1.3 DISSERTATION STRUCTURE

This dissertation is structured into seven main chapters, with the objective of highlighting the content of the work in a logical and consistent way.

Firstly, in Chapter 1 a brief introduction to the topic is given, describing the issues related to the overheating phenomenon and highlighting the benefits of implementing an adaptive façade to minimize this problem. The concept of adaptive façades is presented and the DTIS is explained in detail. The main objectives of this dissertation are also stated. Finally, the structure is detailed by showing the organization of the document.

Secondly, Chapter 2 presents the main concepts related to thermal comfort, necessary for a better understanding of this document, followed by the definition of adaptive model, used to evaluate thermal comfort. Then, is it made a description of the overheating problem and some statistics about energy consumption. A brief description of some mitigation measures of this phenomenon in buildings is also presented.

In Chapter 3 the definition of adaptive façade is given, showing that it is possible to maintain interior thermal comfort and to improve the building efficiency at the same time, by discussing the results of studies available in the literature. The problem of the performance assessment of this type of façade is also explained. Then, the characterization, typification and categorization of the adaptive façades is presented. The dynamic thermal insulation system, one of the possibilities for the adaptive façades, is explained in more detail, since it is the focus of this study.

Chapter 4 presents and defines *DesignBuilder*, the software that was used for the simulations, settles the building models that were used and defines the simulated scenarios. The inputted parameters (envelope configuration, based on the configuration of different U-values, weather data, cooling system and shading system) are also detailed. Finally, the procedure of the data treatment is shown.

In Chapter 5 the simulation results are presented and deeply discussed for each scenario. The outputs that were considered in this analysis were operative temperature, to evaluate thermal comfort without any mechanical system, and energy consumption, when mechanical systems are used. The discussion is supported by an evaluation of the results based on the variation of the outputs over time and on discomfort performance indicators.

Chapter 6 presents the discussion of the operational performance optimization of a DTIS, based on new discomfort performance indicators that were established and analysed. The discussion if a DTIS on a façade is beneficial and the analysis of the periods when the system is indeed useful is given. Conclusions about the impact of the time step of the simulations are also presented.

Finally, in Chapter 7 an overview of the main conclusions from the previous chapters is presented. A description of future works on this topic is also made.

2

THERMAL COMFORT

2.1. FUNDAMENTALS ON THERMAL COMFORT

A building´s quality – whether it is residential, commercial, or industrial – is determined not only by its physical attributes but also, and perhaps most importantly, by how efficiently it satisfies the needs of its intended users. Thus, the design and construction of a building must satisfy seven essential requirements including mechanical strength and stability, fire safety, hygiene, health and environmental protection, safety and accessibility during use, as well as noise protection, energy efficiency and thermal insulation, and sustainable use of natural resources.

Thermal comfort is defined, by ASHRAE 55, as a *condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation* [1]. This definition highlights that comfort evaluation is a cognitive process impacted by physiological, psychological, and other factors [2]. Thermoregulation is the ability of an organism to maintain its internal body temperature within certain boundaries, even when the external environment changes. In mammals, thermoregulation is maintained through a complex interplay of physiological and behavioural mechanisms, such as sweating, shivering, and variations in the blood flow to the skin. Thermoregulation is crucial for the normal functioning of the body, and disruptions to this process can lead to serious health problems. Afferent sensing, central control, and efferent reactions are the three mechanisms of thermoregulation. The hypothalamus in the brain acts as the body's "thermostat", monitoring the body's temperature and triggering appropriate responses to maintain a stable internal temperature. The human body contains receptors for both hot and cold. These receptors allow afferent sensing to assess whether the body's core temperature is too high or too low [3][4].

Three parameters are involved in the energy exchanges necessary to find equilibrium: the heat created by the human body, the heat that is transported to the environment, and the heat that is stored by the body [4]. Heat is exchanged between the human body and its surroundings through radiation, convection, and evaporation. Both internal and external sources have an impact on the thermal environment indoors. All these factors will affect how people perceive their surroundings and, consequently, how comfortable they are. In fact, it is challenging to please everyone in the same space due to the significant physiological and psychological differences between individuals. Not everyone needs the same kind of environment to be comfortable. Six variable elements that are primarily responsible for affecting thermal comfort must be balanced to maintain occupant satisfaction with their surroundings, such as air temperature, mean radiant temperature, air velocity, humidity, clothing insulation, and physical activity level or metabolic rate [5]. The metabolic rate is defined, by ASHRAE 55, as the *rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually* *expressed in terms of unit area of the total body surface (met units)*. Clothing insulation is defined as the *resistance to sensible heat transfer provided by a clothing ensemble (clo units)* [1].

The term "adaptation" may be described as the process by which the organism adjusts to its surroundings to increase its chances of survival and reproduction. Human beings' adaptation involves physical, physiological (organism's ability to adjust to thermal conditions), and psychological changes (different perceptions of the environment) [6].

To access thermal comfort, there are analytical and adaptive models. This dissertation will focus on the adaptive model, which considers the adaptations made by human beings to adjust to the environment and the influence of exterior meteorological conditions in the thermal perception of the interior ambient.

2.2. ADAPTIVE MODEL

The adaptive model is based on the fact that the thermal conditions of a room are mostly adjusted by the inhabitants through the window opening and closing during the summer or in-between-seasons. Several field studies have shown that occupants' thermal responses in such spaces differ from those in buildings with mechanical cooling systems, due to differences in the occupant's thermal experience. To be able to use this methodology, the spaces must have windows or analogous façade components that open to the exterior environment and are operated by the users. These components should be built and positioned in such a manner that occupants can fine-tune the indoor air speeds on warmer days. There must be no mechanical cooling in operation in the space and the windows must be the primordial mechanism to regulate thermal conditions, even though mechanical ventilation with unconditioned air may be utilized (in summer) [7].

According to the standard EN 16798, the average air temperature of a room can be used to establish the design indoor temperature. However, if the temperatures of the room surfaces deviate greatly from the air temperature, or if the building inhabitants are frequently exposed to direct sunlight, the indoor operative temperature must be calculated [7].

The standard defines the thermal comfort upper and lower temperature limits, during the summer season and the between-seasons (spring and fall), based on research conducted in office buildings, which fluctuate with the running mean external temperature. This methodology can only be applicable when the inhabitants have metabolic rates ranging from 1,0 to 1,3. It is also necessary to ensure that the building occupants can adapt their clothes to indoor and/or outdoor temperature conditions within a range of at least 0,5 to 1,0 clo [7].

Fig. 1 shows the upper and lower limits allowed for the operative temperatures plotted against the running mean external temperature θ_{rm} (equation 1) between 10ºC and 30ºC. The limits presented below should be used for dimensioning passive means to prevent thermal discomfort. EN 16798 recommends the use of four categories to describe the yearly indoor environmental performance of a building or to establish different levels of criteria for the design of buildings [7]:

- **Category I:** High level of expectation also recommended for spaces occupied by very sensitive and fragile persons with special requirements like some disabilities, sick, very young children, and elderly people, to increase accessibility;
- **Category II:** Normal level of expectation;
- **Category III:** An acceptable, moderate level of expectation;
- **Category IV:** Low level of expectation. This category should only be accepted for a limited part of the year.

The following equation was used to calculate the external running mean temperature (ºC) which was in turn used to calculate the indicators utilized in the analysis and treatment of the results:

$$\theta_{rm} = \frac{\Theta_{ed-1} + 0{,}8 * \Theta_{ed-2} + 0{,}6 * \Theta_{ed-3} + 0{,}5 * \Theta_{ed-4} + 0{,}4 * \Theta_{ed-5} + 0{,}3 * \Theta_{ed-6} + 0{,}2 * \Theta_{ed-7}}{3{,}8} \quad (1)$$

Where:

θ_{rm} – external running mean temperature (ºC)

Θ_{ed-i} – daily mean external temperature for the i-th previous day (ºC)

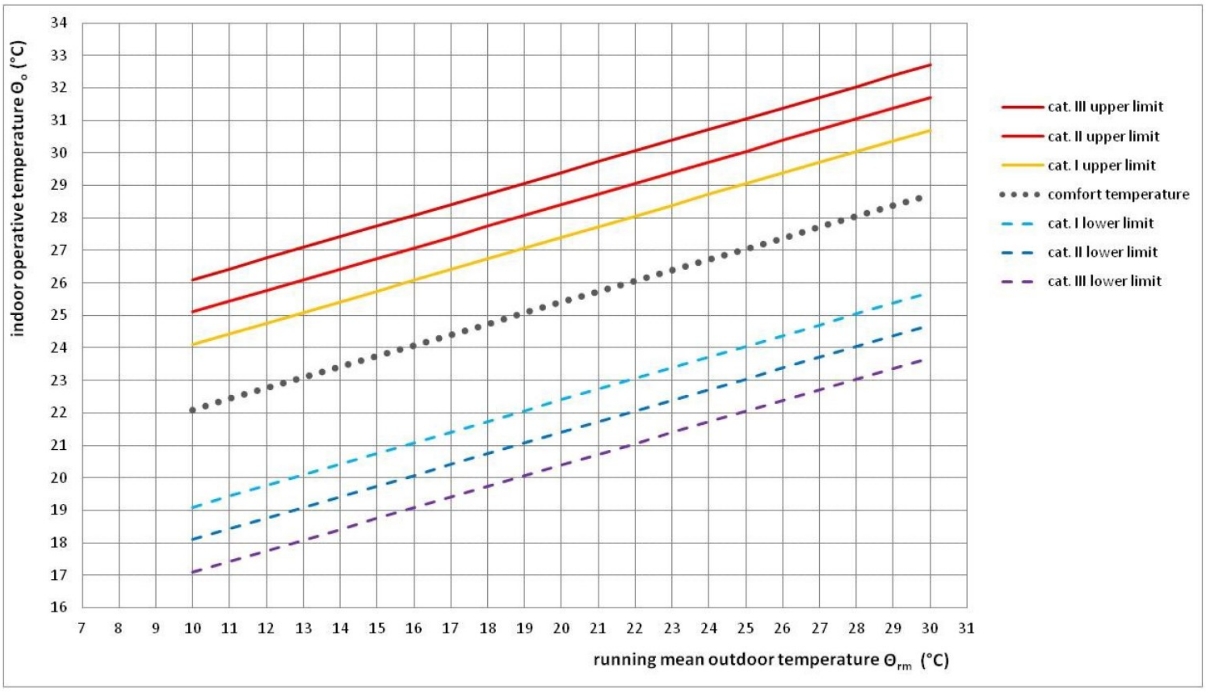


Fig. 1 - Design values for indoor operative temperature [7].

EN 16798 [7] defines a model based on the relation between the operative temperature (θ_o) [ºC] and the running mean outdoor temperature (θ_{rm}) [ºC]. The indoor operative temperature, to ensure occupant comfort, is obtained by the following equations (2-8), for buildings without mechanical cooling systems, depending on the category:

Category I: upper limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 + 2$ (2)

lower limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 - 3$ (3)

Category II: upper limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 + 3$ (4)

lower limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 - 4$ (5)

Category III: upper limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 + 4$ (6)

lower limit: $\theta_o = 0{,}33\theta_{rm} + 18{,}8 - 5$ (7)

The dotted line in the centre of Fig. 1 represents the ideal operative temperature or comfort temperature. The equation for this line is: $\theta_c = 0{,}33\theta_{rm} + 18{,}8$ [7]. (8)

Where:

θ_{rm} – external running mean temperature (ºC)

θ_0 – operative temperature (ºC)

θ_c – ideal operative temperature or comfort temperature (ºC)

2.3. Overheating

2.3.1. Climate Change, Energy Consumption and GHG Emissions

Climate change is one of the greatest environmental, social, and economic threats faced by the planet and humanity today. Several organizations have tried to define objectives for the reduction or even extinction of the emission of greenhouse gases (GHG), to avoid a dangerous anthropogenic interference in the climate system (the global temperature must not exceed the increase of 2ºC concerning pre-industrial levels). Various sectors and activities emit GHGs, which is why different policies and mitigation measures have been imposed by the European Council based on the Paris Agreement to make EU climate-neutral by 2050 [8][9].

The residential and building construction sectors play an important role in energy consumption. In fact, in 2021, the use of fossil fuels in buildings accounted for approximately 8% of global energy-related and process-related CO_2 emissions, with another 19% resulting from the generation of electricity and heat used in buildings, and an additional 6% resulting from the manufacture of cement, steel, and aluminium used in building construction. As a result, the building sector is responsible for about a third of the total global final energy consumed and process-related CO_2 emissions (Fig. 2) [10].

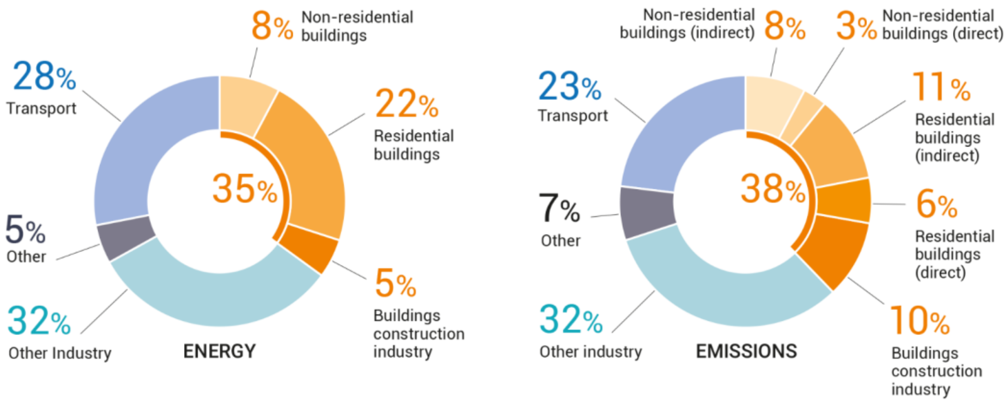


Fig. 2 - Global share of buildings and construction industry final energy and emissions, in 2019 [11].

These emissions are partly due to the use of fossil fuels to produce electricity and heat in said buildings. Some measures to improve buildings, such as installing insulation and more efficient heating and cooling systems, can reduce these emissions. The energy consumed must be produced by renewable energies or decarbonized energies, to reduce emissions. GHG produced by buildings decreased by 29% between 2005 and 2019 and it should continue to decrease due to EU decarbonization strategies and the strong increase in the renewal rate [12]. Fig. 3 shows the downward trend of greenhouse gas emissions in the construction and residential sectors.

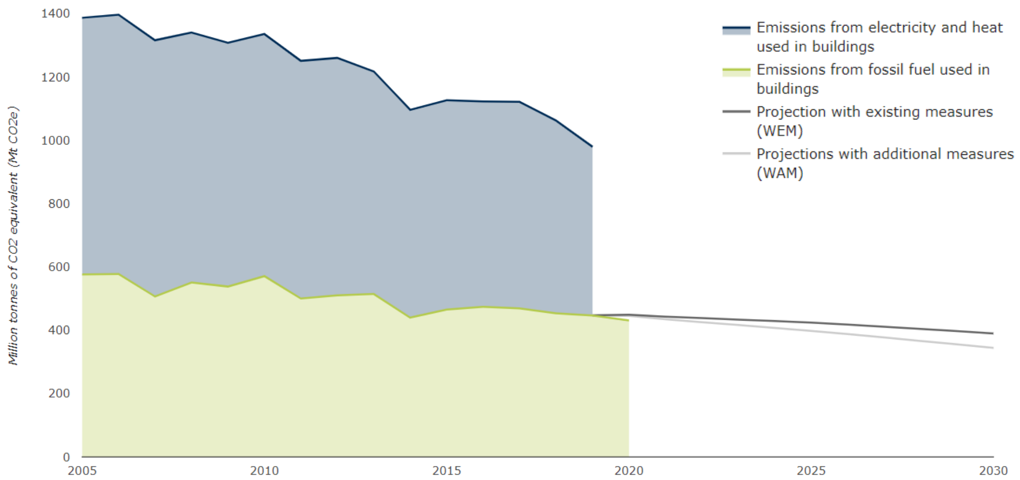


Fig. 3 - GHG emissions, by the residential and construction sectors, between 2005 and 2020. Future forecast [12].

Although it was expected a continuous decline in the GHG prodution, the expectations were not met. Following the reduction in 2020 from Covid-19 restrictions, both energy consumption and emissions increased to levels higher than in 2019. To accomplish a Net Zero Scenario, carbon emissions from building operations must be cut in half by 2030, which will imply considerable efforts to reduce energy consumption through clean and efficient technology in all end-uses. To accomplish this scenario, it is necessary to improve the buildings' envelope in order to reduce thermal energy needs, to use the best available appliances, to use clean technologies, etc., and the coordination between building strategies and infrastructure development is essential, including the electricity grid. Governments may entice action by shaping market regulations to enable access to finance, de-risk clean energy investment, and expand the availability of market-based instruments that lower transition obstacles and increase the attractiveness of building sector investment [13].

The emission of GHGs contribute to the worsening of climate change and air pollution. According to the World Health Organization (WHO), approximately 12,6 million annual deaths can be attributed to preventable environmental risk factors. Climate change and environmental pollution (in particular air pollution) are closely linked, with around 6,5 million deaths a year due to air pollution. In fact, air pollution is a contributing factor in one in three deaths from lung cancer, stroke or heart disease. According to statistics, 92% of people worldwide do not breathe clean air. And climate change is predicted to cause an additional 250.000 deaths between 2030 and 2050 if mitigation and adaptation measures are not taken [14].

Furthermore, with climate change, the earth's average temperature has increased and is estimated to continue to rise if no action is taken [15]. Extremely high air temperatures contribute to deaths from cardiovascular and respiratory disease, particularly in the elderly people. Despite evidence of the effect of the environment and climate on health, political action and investments remain largely insufficient, with only 3% of resources being invested in prevention and 97% spent on treatment, increasing health costs [14].

According to the six leading international datasets consolidated by the World Meteorological Organization (WMO), the last seven years (2015-2021) have been the warmest ever and 2021 in particular being one of the hottest on the record (Fig. 4) [16].

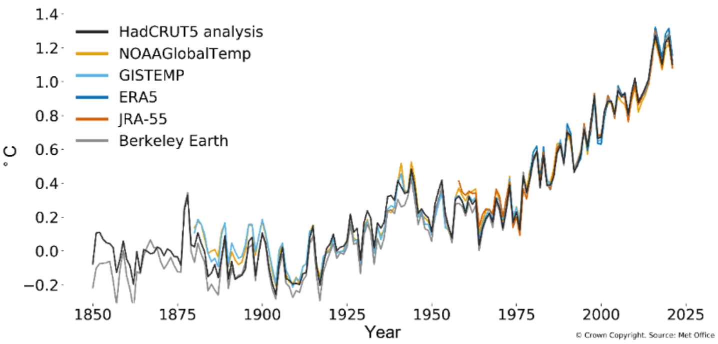


Fig. 4 - Global mean temperature difference from 1850-1900 (ºC) [16].

In Fig. 5 it is possible to observe the heating degree-days (left images) and cooling degree-days (right images) from 1981 to 2100, considering two different scenarios, for all cooperating countries of the EEA (European Economic Area). Degree-days are used to determine the thermal needs for heating or cooling. Thus, it is concluded that indoor heating and cooling needs will be higher in 2100 than in 1981, because the world's climate has become more severe both in the heating and in the cooling season due to global warming.

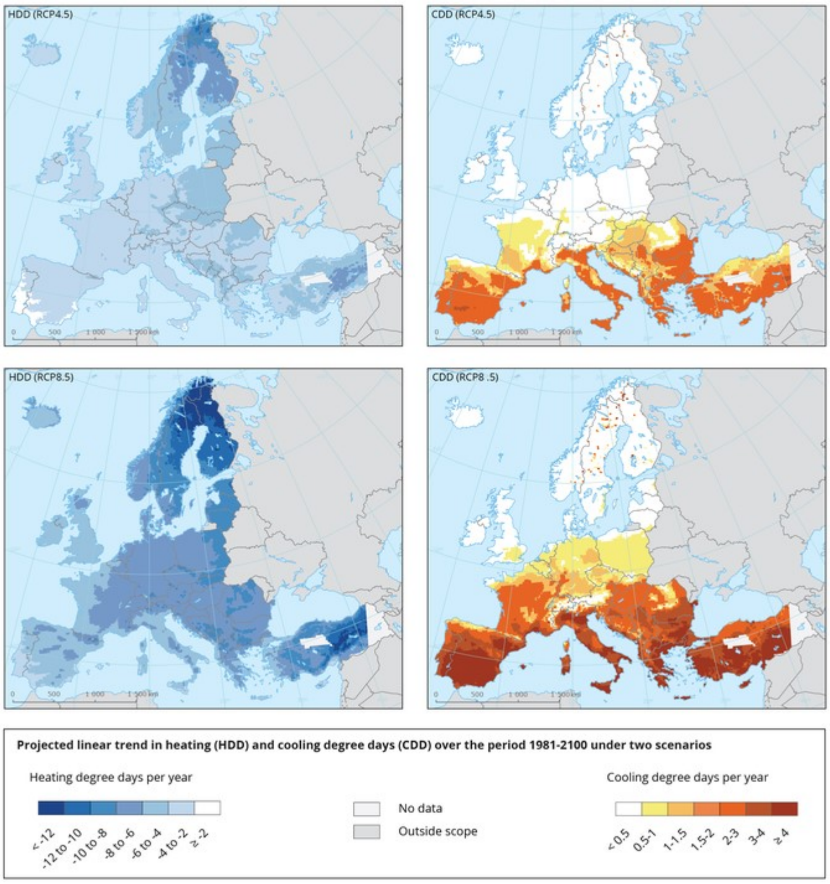


Fig. 5 - Heating and cooling degree days from 1981 to 2100 [17].

The map in Fig. 6 shows that cities located in southern Europe experienced extremely hot daytime conditions between 1961 and 1990. The risk of mortality, particularly for the young, elderly and sick, increases with thermal discomfort. In the future, an increase in the number of tropical nights and extremely hot days is expected both in the south and in the rest of Europe. In cities these conditions will be intensified due to the heat island effect [18].

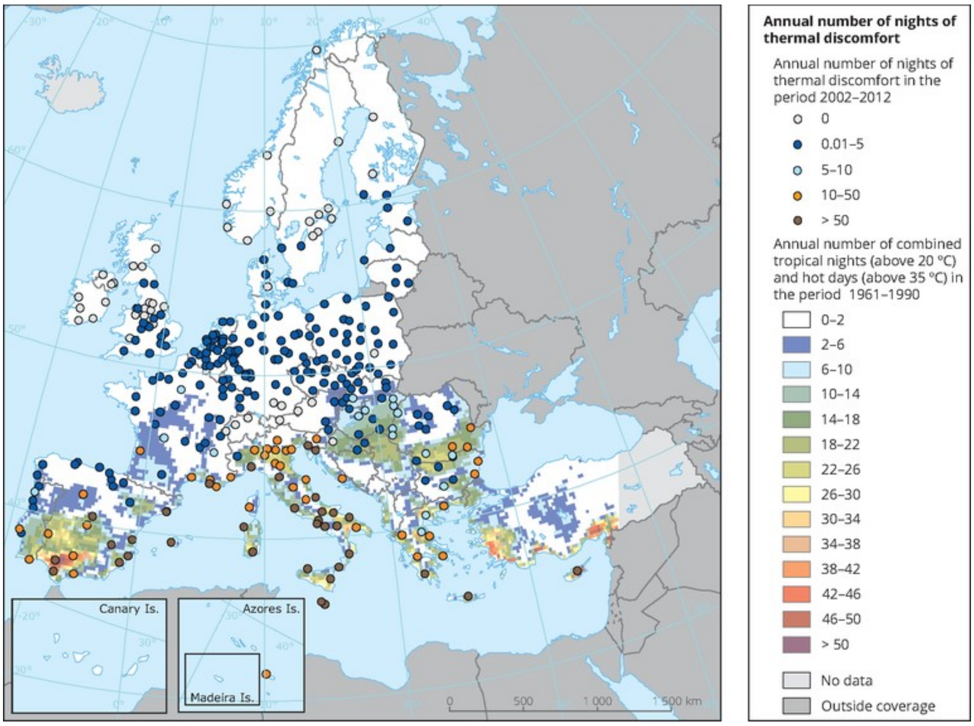


Fig. 6 - Number of nights with thermal discomfort and hot days with temperatures above 35ºC [18].

Climate change causes increasingly frequent heat waves and extreme weather events. In June and early July 2022 record-breaking temperatures were seen in Europe, North Africa, the Middle East and Asia. For the first time, 40°C was exceeded in the UK, and a strong heat wave was reported in the US in late July [19]. April 2023 was the fourth hottest month on record in Portugal, and temperatures were above normal, particularly in southern Europe. A 78-year-old record was broken in Mora when the thermometer reached 36,9ºC, breaking the previous record for that month, which dated from April 1945 [20].

2.3.2. MITIGATION MEASURES

2.3.2.1. Active Measures

Overheating occurs especially in the presence of extreme heat events, causing thermal discomfort. It depends on the characteristics of the building and on the behaviour of the occupants [21]. As the earth heats up, it is critical to ensure that cooling requirements are addressed fairly. To avoid overheating problems, the efficiency standards applied to systems together with passive, nature-based and alternative solutions to air conditioners, and improved design of buildings and urban areas, are key measures [19].

Usually, a building is considered to be overheated when the indoor temperature is above 25°C. The mitigation methods are classified into two types: passive and active. Active solutions employ cooling techniques through mechanical means, whilst passive solutions use techniques and properties of materials and components to reduce overheating [22].

This way, the overheating problem is frequently prevented by cooling devices (active measures) that consume enormous quantities of energy, jeopardising the planet's sustainability. According to Stauffer [24], about 40% of the energy consumed worldwide by buildings is used for regulation of the interior temperature and these numbers tend to increase, since with climate change and population growth, levels of cooling and dehumidification, necessary to satisfy the conditions of comfort and to protect human health will increase abruptly. According to the IEA (International Energy Agency), the use of air-conditioning and electric fans is responsible for almost 20% of the total electricity used in buildings worldwide. In the next three decades, the use of air-conditioning is expected to increase, becoming one of the main drivers of global electricity demand [23]. Since 1990, energy demand for space cooling has more than quadrupled at an average pace of 4% per year since 2000, with substantial implications for power systems [19]. Space cooling demand grew at the fastest rate in all construction end-uses in 2021, accounting for over 16% of total building sector final power consumption (about 2 000 TWh) [16].

In service buildings, the amount of energy used for cooling is higher than in residential buildings because service buildings have more people, working during the hotter hours of the day, and have equipment's that emit heat. This phenomenon can be aggravated by the architectural choice for the service building (offices usually have a large percentage of windows to provide daylight to workers). In a typical office building, HVAC systems use about 40% of the total energy consumed by the building and 70% of the base energy is consumed by it [25]. Fig. 7 shows the typical end-use breakdown in HVAC system, showing that the cooling system represents 27% of the energy consumed for the various HVAC systems, highlighting the importance of the cooling on the energy consumption.

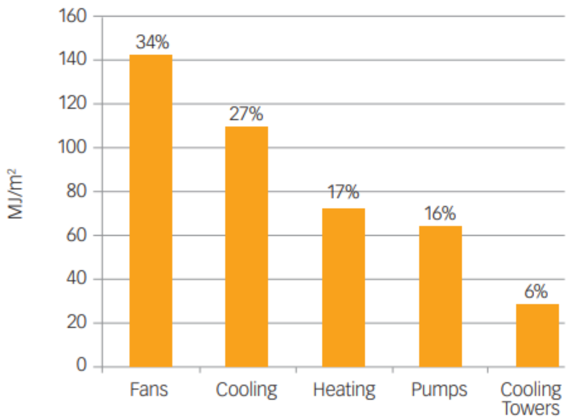


Fig. 7 - Use of energy by the various HVAC systems [25].

Households in the EU use energy for a variety of purposes: for space and water heating, space cooling, cooking, lighting, household appliances and other end-uses. Data on household energy consumption has been collected and published by Eurostat since 2017 [26] and it is shown in Fig. 8 that only 0.4% of the energy consumption is for space cooling. However, even if there isn't a high consumption for this purpose, the overheating phenomenon is still a problem. These buildings can not use energy for cooling, but users can feel discomfort inside the buildings. This way, it is necessary to implement measures to reduce the energy consumption, but, above all, to reduce the user's discomfort.

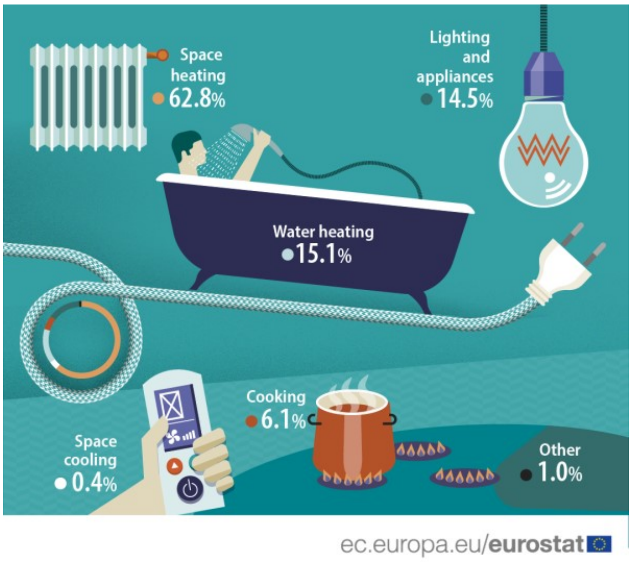


Fig. 8 - Household energy consumption in the EU [26].

2.3.2.2. Passive Measures

The need of constructing domestic buildings to perform well in terms of energy efficiency and comfort in both winter and summer is nowadays recognised as fundamental to excellent design, so it is essential to develop and optimize the passive solutions [21]. In the summer, well-insulated buildings have overheating risks, which is expected to rise as a result of climate change, offering potentially major health concerns to occupants [22]. The façade is part of the envelope of a building and separates the interior from the exterior. Most of the heat exchange between the internal and external environments takes place through this element. Thus, the façade has great impact in the thermal behaviour of a building and is critical in keeping a comfortable internal temperature. In cold-weather countries, technologies that insulate the interior are employed to reduce heat exchange with the outside. Thus, overheating can be a severe issue for several European countries. While heat exchanges in winter must be prevented, in summer these exchanges are desirable (the value of the thermal resistance of the system must be as low as possible), allowing the tackle of the overheating phenomenon [27].

Solar radiation and external air temperatures are examples of external gains. Knowing a building's orientation and surroundings can give helpful insight into how sunlight can heat up the indoor environment [28]. In order to tackle overheating and minimize the amount of energy required for space cooling it is necessary to utilize passive design strategies to reduce the amount of heat that enters the building. This can include measures such as shading, heavy thermal mass, that provides the ability to maintain the interior conditions stable, for example by insulating building components by the exterior or using heavy materials, and enable natural ventilation or night-time cooling, whenever the outside temperature is lower than the inside temperature [29].

The study made by Morten proved that to reduce the overheating risk, it is necessary to increase the ventilation by opening windows, installing shading devices and installing new glazing to limit solar gains. The study shows that the most effective measure is the use of external blinds, which help in the regulation of summertime comfort, by preventing the entrance of solar radiation, without affecting solar gains during the winter. Fixed shading devices or low g-value glass, for example, require no input from the occupant yet are judged to be significantly less effective. They also risk restricting solar benefits in the cold season [22].

According to the same author, night-time ventilation will become increasingly more ineffective in the future as the outdoor temperatures become warmer due to climate change, reducing the cooling effect. However, it is still a highly effective method of passive cooling. This is especially relevant in high thermal mass structures. The study concludes that it is important to prepare the buildings for the future climate scenarios in order to prevent overheating. Therefore, passive strategies are desirable because they don't require the use of energy. In addition, strategies that don't require the occupant input are considered by this study to be more consistent but less effective [22].

"Thermal mass" describes the material's capacity to absorb, store and release heat in response to internal conditions. Materials that have high thermal mass, have a high capacity to store heat, such as concrete, brick and stone. Materials with low thermal mass are typically lightweight construction materials. A correct implementation of thermal mass in buildings can improve the performance of the building, guaranteeing that it is more comfortable and decreasing the use of energy for summer cooling (Fig. 9), especially in climates where there is larger temperature difference during the 24-hours of the day. Thermal mass reduces the amplitude of the higher and lower temperature peaks, allowing a mismatch between them. In winter, thermal mass can absorb heat during the day from direct sunlight and release it into the indoor environment throughout the night. During summer, thermal mass can be used to keep the interior space cooler, because most of the unwanted heat gains will be absorbed by the thermal mass during daytime, preventing an excessive temperature rise. At night, buildings can be ventilated to draw out heat from walls or other high mass components [30][31].

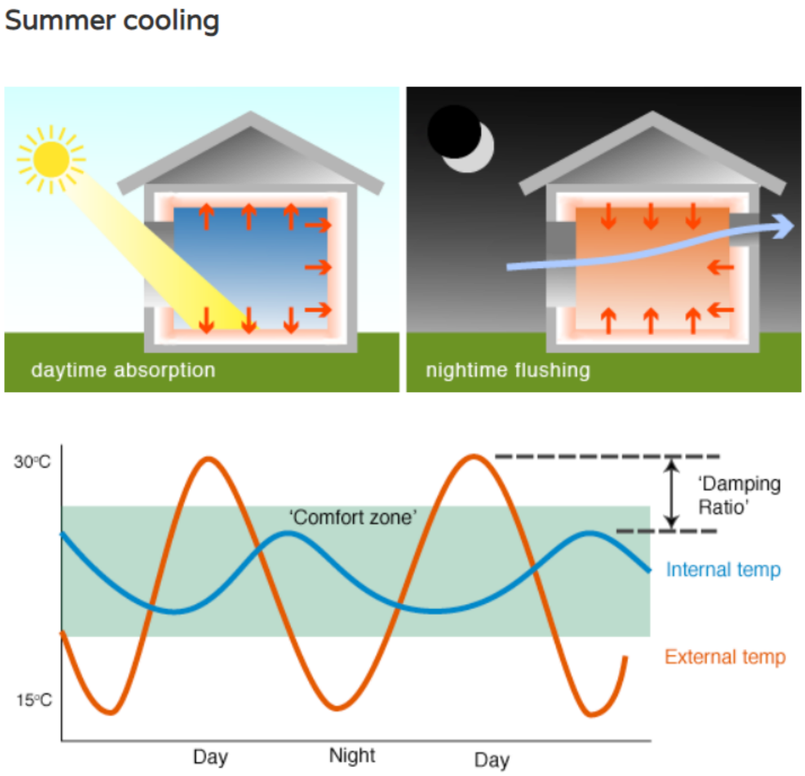


Fig. 9 - Thermal mass effect during summer [31].

Vernacular architecture was developed during centuries and entails design and constructive procedures based on locally accessible materials and people's environmental, cultural, and historical backgrounds [32]. The vernacular architecture was centred on the construction of high mass buildings that are usually constructed with natural resources. Then came the industrial revolution and the relationship between building and nature dissipated, severely modifying building systems [33].

Nowadays, construction must be done the quickest and the most economical way. In Portugal, and in other countries around the world, the construction sector faces a manpower problem. Therefore, equipment's have been developed to improve the efficiency of construction and to reduce the workforce need. This way, the vernacular architecture is changing to a modular architecture that uses prefabricated constructive elements that tend to be lighter, increasing the risk of overheating. It is, then, necessary to return to the origins of construction as an overheating mitigation measure.

Another possibility to reduce overheating is to include organic materials in the façade and roof. These green façades and roofs allow better thermal insulation and the reduction of heat conduction to the interior of the buildings, with a consequent reduction of the surface temperature. This type of structure has been adopted in various cities around the world and in some of them the use of green roofs is required. The heat transfer to the interior of a building is lower as the soil have a high capacity for thermal heat storage, improving the indoor comfort. If the green roof incorporates foliage, it can also serve as a shade mechanism by absorbing some of the thermal energy used for photosynthesis and decreasing heat exchange beneath the vegetation. Green roofs reflect around 20% of solar energy and absorb approximately 60% of heat through photosynthesis, with just 20% being delivered to the growth media below. As a result, depending on the climate zone, they restrict heat flow by 70% to 90% in summer and 10% to 30% in winter [34].

Another building technology used to dissipate heat in the façade and improve thermal comfort is ventilated façades. Ventilated façades are composed by two opaque layers a ventilated space between them, and an insulation layer [21]. Ventilated façades have potential on increasing the building's energy efficiency. These systems can reduce heat transfer, lowering energy consumption, by combining an air barrier and a high-performance insulation [35]. In a study by Corrao et al., the ventilated façade showed a relevant energy saving, decreasing the heat flux in 70%, due to the effect of ventilation [36].

Glazing plays a relevant role in increasing indoor heat gains and should be the focal point of any mitigating measures [28][30]. In fact, a large part of the heat transfer between external and internal environments occurs through this element [21]. It is a good practice to use high-performance glazing to reduce the amount of solar radiation that enters the building. This can be achieved by using double or triple glazing, or by using special coatings (Low-E glass coating that reduces the amount of heat that can pass through the glass) [29]. In addition, shading devices should be used to block the entrance of solar radiation inside the building.

It is also possible to use cool roofs to minimise solar heat gains, by using materials that reflect the solar radiation and releases the absorbed heat [37]. Annual simulations conducted by Kolokotroni et al. show that interior ceiling surface temperatures are decreased by 3,2-5,5ºC on average, while internal air temperatures are reduced by 0,75-1,2ºC [38]. According to the literature review by Rawat et al. the average energy-saving impact of these roofs is from 15% to 35,7% in different climate zones and that this technology can reduce average roof temperatures from 1,4ºC to 4,7ºC [39].

In the research conducted by Rana, the optimum combination of passive design solutions were identified and evaluated in an effort to improve thermal comfort performance in a naturally ventilated home. The case study was a two-story dwelling in Washington, US. The thermal comfort performance was evaluated using the *DesignBuilder* software. It was, then, possible to reduce 50% in yearly discomfort hours from the reference simulation model to the final intervention model. Some of the measures already mentioned to reduce overheating were used, such as, the incorporation of triple glazed, low-emissivity, and argon filled openings, the integration of overhangs in south-facing windows, the minor reduction of openings in the east and west façades, and addition of blinds for window shading. To optimise natural ventilation, the most successful intervention was customising the window operating schedule depending on seasonal air temperature changes. This study shows that passive cooling solutions may increase occupant thermal comfort, decreasing energy consumption and the environmental effect of buildings [29].

However, even if it is utilized passive measure to mitigate discomfort, the environment can be uncomfortably hot. Then, it is always an option to use air-conditioning and mechanical ventilation to provide cool air during hot weather or to make behavioural changes, such as adjusting clothes or change activities.

3

ADAPTIVE FAÇADES

3.1. DEFINITION

Façades are one of the most essential aspects of a building's structure that may induce energy savings and a minimal environmental impact. They are crucial not only for a building's architectural look, but also for determining the quality of its interior spaces, since they serve as the interface between the inside and outside of the building structure.

On the one hand, these elements are subjected to uncontrollable meteorological variations throughout the year, such as solar radiation, precipitation, wind, and extreme temperatures, which have a relevant impact on interior comfort and energy consumption. Aelenei et al. found that solar radiation and external temperature are the most prevalent external factors that are considered as trigger for the adaptive façades (AFs) available in the market, Fig. 10. The same author also points that, because these characteristics are recognised for having a direct impact on thermal and visual comfort, as well as in the building energy performance, the present AFs have the improvement of human comfort as their major goal [40].

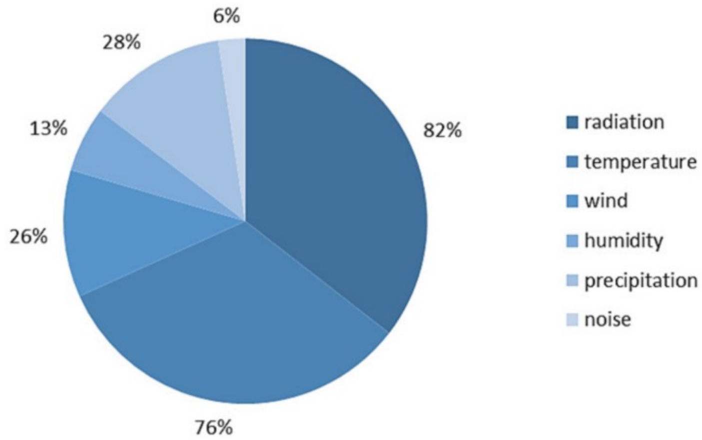


Fig. 10 - Global distribution of external meteorological variations [40].

On the other hand, façades must respond to several functional scenarios that may contradict one another: shade vs. artificial lighting, views vs. privacy, solar gain vs. overheating, daylight vs. glare [41]. This way, during the design stage, a lot of parameters should be considered [42]. In Fig. 11 [43], the influence of external factors in human comfort is shown, as well as the correspondent façade requirements.

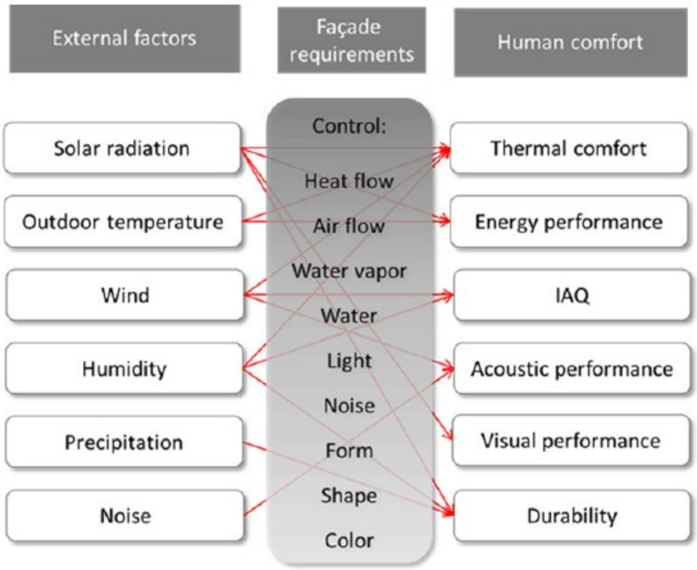


Fig. 11 - Schematic role of adaptive façades [40].

To improve the building energy efficiency and guarantee a more suitable behaviour, AFs have emerged. Several types of concepts of adaptive façades have been investigated, and are expected to increase in the future [40]. They are multi-parameter high performance building envelopes that can change their behaviour, mechanically or chemically, in real time according to external climate, by means of materials, components, or systems to meet occupant needs [40][41][44]. The ventilation and renewal of the interior air, the absorption or reflection of solar radiation, and the exchange of heat between the interior and exterior are factors that can be ensured in a controlled and efficient manner by a façade of this type. This way, it is possible to satisfy several functional requirements in terms of heat transfer, air and water vapour flow, rain penetration, solar radiation, noise, fire, strength, stability and aesthetics [40]. AFs can have a significant contribution to accomplish the NZEB Scenario because reductions in building energy consumption and in CO_2 emissions can be accomplished, while preserving the thermal and visual comfort of occupants [40].

3.2. Performance Assessment

Nowadays, there is a growing interest in AFs technologies in order to tackle problems of overheating inside the building and promote the occupant's well-being [45]. The nature and the human being adapt, so it is interesting to transform a building envelope in a living system [42]. It is difficult to make an AF assessment as there are not defined evaluation procedures to be implemented because of their complexity. Adaptive façades are composed of several subsystems and various technologies and solutions that interact with each other in different ways. As a result, immensely complex systems and subsystems emerge, with controls and interactions that are difficult to predict. In addition, the existing building energy standards and rules, that are being used to assess AFs, have limited relevance for such advanced façade systems, leading to a low reliability of the results. There is not sufficient research regarding standardised design, construction, operation and assessment of AFs, according to Attia et al. [44]. The author refers that there is a need to produce unique experimental datasets to serve as reference standards for revolutionary façade technologies and performance monitoring methodologies that may be compared to traditional façades. It is referred that it is essential to develop a database on advanced façade monitoring, performance modelling and assessment [46].

Attia et al. [46] investigated the trends of AFs and their performance assessment starting from the characterization and classification network. The first barrier to hinder the use of AFs in the market is the performance quantification and evaluation of a building with an AF. The second barrier is the multiple stages which AFs must pass until they are used, as shown in Fig. 12. In order to increase the market of AFs it is important to study ways of reconciling high technical performance with profitable options for both the client and the industry.

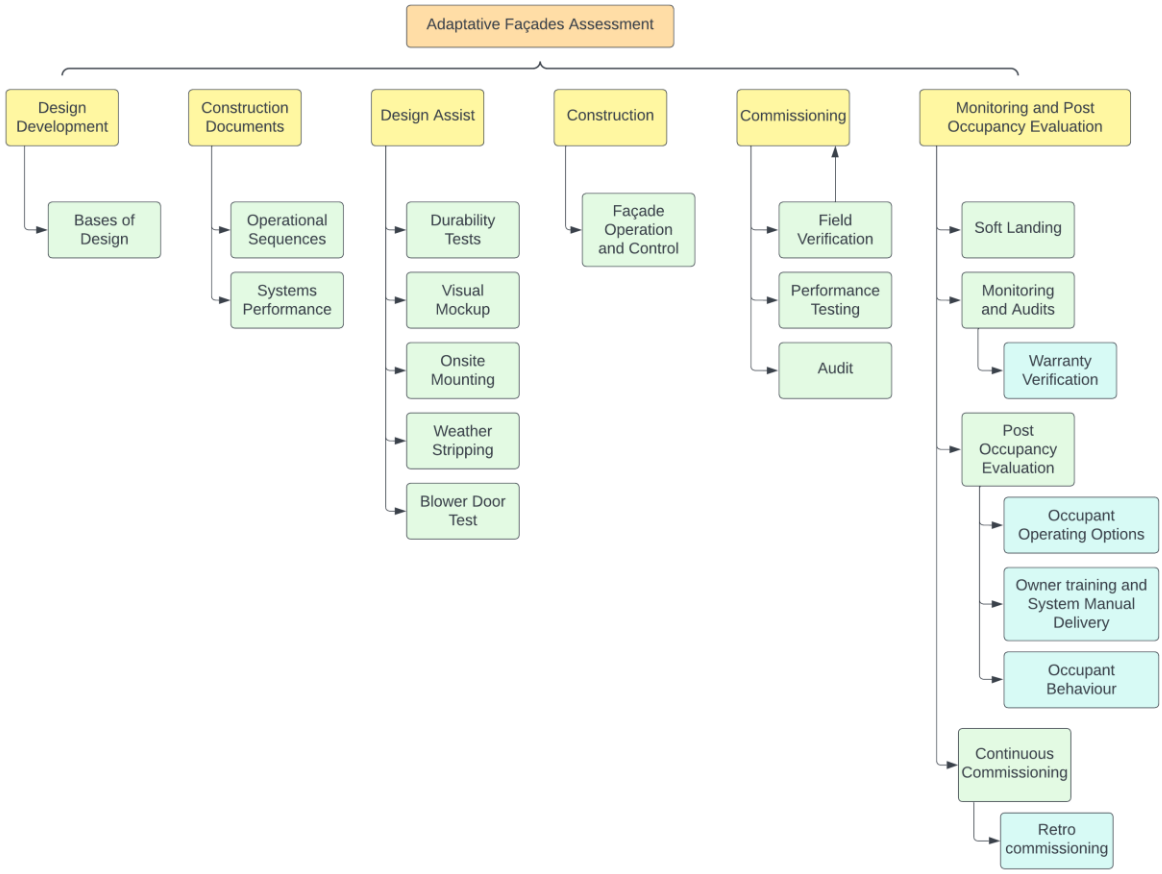


Fig. 12 - Design process of AFs [44].

The same author identified the gaps related to adaptive façade performance evaluation requirements and presented a novel assessment framework, that distinguishes AFs on the material, component, type of system and building level, defining key performance indicators (KPIs). According to the findings of this study, one fundamental issue with AFs is that these systems are typically designed at the product or component level and the heterogeneity of components and materials raises the potential of performance failures [46]. It is also showed that static performance measures (e.g., U-value, g-value, etc.) cannot adequately define the performance of AFs. Thus, their performance should be assessed through comparative tests, in which the energy consumption (and/or environmental quality) of a space protected with an AF is compared to another protected with a static façade, with identical boundary conditions [44]. Testing, inspection, and assessing operation performance of these systems in terms of thermal comfort and energy savings is very important, as well as long-term monitoring, although it is rarely done, so little is known about the accuracy of simulation results for AFs. Another important factor is the lack of awareness about how to use or interact with an AF, which continues to be a barrier to occupant satisfaction and comfort [46]. It is very important to provide occupants the possibility to control the indoor environment, improving thermal and visual comfort as well as their satisfaction with the air quality. It is necessary, according to Attia et al., to develop a behavioural model of occupant adaptability that may be used in simulation models. Unlike the adaptive hypothesis, this model sees an occupant's influence as changing not just its surroundings but also its experience of comfort [44].

Tabadkani et al. reviewed a simulation-based study which employed automatic shading control methods. In previous studies it was found that automatic control for dynamic movements in shading elements is more beneficial to control lighting and energy loads, while ensuring adequate comfort. If users can overrule these systems and change them to their preferences, they would feel more satisfied. It was, then, concluded that most of the literature is focused on automatic control shading systems to reduce the energy used, that few of them were oriented for thermal comfort and that none of them investigated the main five objectives together (thermal comfort, daylight, view, glare and energy saving). In the author's opinion, the design of these systems for an AF must cover human comfort and energy saving objectives altogether [47].

For the assessment and performance evaluation of AFs it is essential to select KPIs and set up a priority. The KPIs identified by Attia et al. [44] were: (i) maintenance, durability, and life cycle; (ii) user control and experience; (iii) building control and services; (iv) protective performance; and (v) energy and environmental performance.

On the other hand, Tabadkani et al. [42] suggest different methods to assess AFs after implementation: (i) by field observations and tests, which is the most accurate method, but it involves higher costs and it is time consuming; (ii) numerical simulations that are fast and cost-effective methods; and (iii) modelling the building performance, which is a fast and an economically effective approach but, as it uses many assumptions and simplifications, may lead to lower accuracy.

3.3. Typologies and Categorization of AFs

Several authors have divided AFs in sub-groups, such as adaptive glazing, phase change materials, solar façades, and daylight systems, to identify correlations between different systems and increase the understanding on their behaviour [40]. Loonen et al. characterized AFs in different categories, based on the purpose, the responsive function, the operation procedures by the users, the materials or building components that include, the response time, the scale of implementation, the degree of the visibility by the user, and the degree of adaptability (Fig. 13) [43].

Tabadkani et al. [42] identified ten different types of AFs, that can overlap, based on its adaptability and technological controlling criteria, namely: Active façades, passive façades, biomimetic or bio-inspired façades, kinetic façades, intelligent façades, interactive or media façades, movable façades, responsive façades, smart façades, and switchable façades. In Table 1, the requirements, limitations, and potentialities of these typologies are described.

Another way to characterize AFs is based on their motion typologies [42]. They can be classified as:

- **Simple motion:** Traditional AFs (as roller shades and venetian blinds), are confined to translational or rotational movements, ensuring compliance with many users demands simultaneously (glare, daylight, etc.).

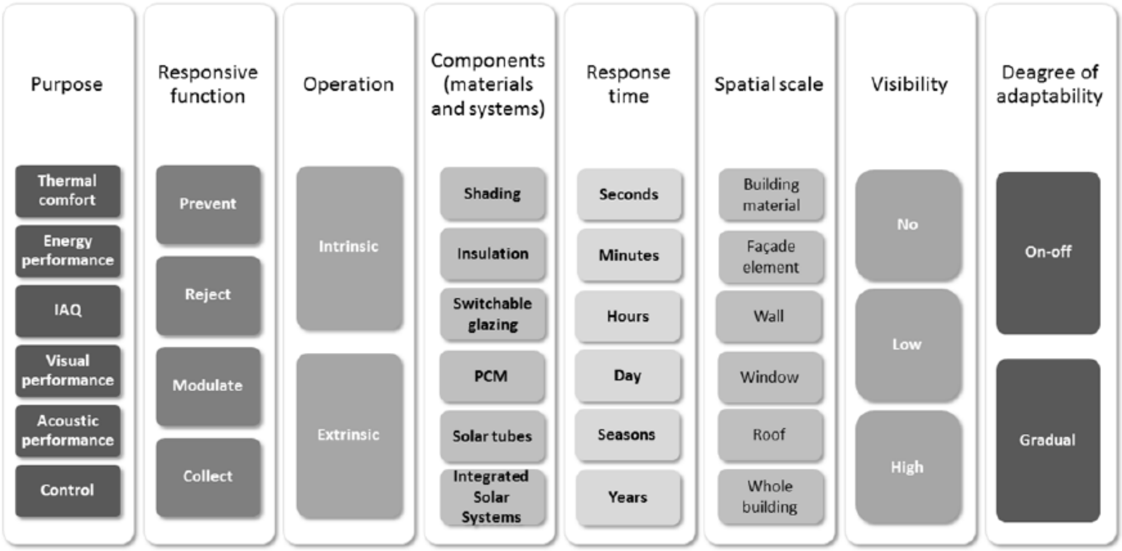


Fig. 13 - Overview of characterization concepts for envelope adaptivity [40].

- **Complex motion:** Non-traditional AFs are frequently based on complex motion types and allow individual adaptation to different parts of the façade, which might create more innovative design solutions. Three key adaptable typologies may be considered: (i) fundamental motions (rotational, translational or both motions), when AFs move in reaction to mechanical actuator energy input, with high installation costs, the need for periodic maintenance, and the need for synchronisation between sensors, controllers, and shade elements; (ii) folding structures, which allow 3D adjustments, changing the solar radiation, lighting, and the outside view; and (iii) biomimetic skins that consists on biological-inspired materials, being able to change their characteristics, responding to an external and internal stimulus with little to no energy (passive or no-tech technique).

Also, Attia, et al. categorized AFs into four families based on expert knowledge, market presence and sales volume. One of them is dynamic shading, which presents a diverse range of solutions and the largest market share. Due to the increasing risk of overheating and the implementation of more demanding cooling requirements, they will become increasingly relevant. Smart technology is being coupled with the dynamic solar shading devices, but its total implementation is being restrained by the complexity in operation procedures. Another family defined by Attia et al. [45] is chromogenic glazing, which is a relatively new technology that only in the future, when production costs decrease, will reach a critical mass of market sales. Nowadays, only a small part of the glazing industry is investing and researching their use for increasing the well-being and thermal comfort of users. However, automation and intelligence remain the biggest challenge. Active solar façades, which is another family defined by Attia et al. include double façades, green envelopes and phase change material (PCM) envelopes. Its performance depends on the reaction of the materials to the sun and temperature changes with minimal electromechanical intervention. Currently, this family does not have much market penetration. Finally, active ventilation façades are an emerging family with a high potential in the future. They include not only actively ventilated Close Cavity Façades (CCF), but also actively ventilated envelopes with heat recovery units and automatically operated windows. In addition, in order to achieve thermal and solar control, they also include active ventilation cooling as a key feature.

Table 1 - Characteristics of Adaptive Façade's Typologies [42].

Façade type	Requirement(s)	Limitation	Potential	User interaction	Upgraded version
Active	active technologies without sophisticated electronics	controlling indoor environment is not the aim	self-adjustment of façade that can be controlled by internal and external environment	No	–
Passive	passive design	a passive design makes it an adaptive façade	weather-protective layer that can improve indoor comfort condition	No	Intelligent façade
Biomimetic	mimicking natural inspirations	only responds to outdoor environmental condition and certain thresholds	uses biomimetic principles of nature with least energy involvement	No	–
Kinetic	complex mechanical or electro-mechanical mechanisms	corresponds only to outdoor environment	allows a wide range of possible motions	No	Responsive façade
Intelligent	Integrating automated and manual controlling through intelligent components	requires sensors, actuators and controllers to control indoor environment and computational technology to predict	has the ability to learn and respond over time either by learning facilities or real-time controllers	Yes	Responsive façade
Interactive/ Media	sensors, actuators and controllers in combination with direct human interventions	do not influence indoor comfort	responds in real-time by human-based signals	Yes	–
Movable	mobile systems in façade scale to quickly respond to climatic changes	user comfort is not the aim	has the ability to produce energy	No	Kinetic façade
Responsive	sensors, actuators and controllers to control indoor environment	need an act to response	allows real-time environmental perception and user-oriented operations	Yes	–
Smart	smart materials for intrinsic control	limited to materials with specific physical properties that are time-dependent	no need for external energy to generate movements	No	Intelligent façade Responsive façade Switchable facade
Switchable	adaptive materials for intrinsic control	limited to transparent components with specific physical properties	can be controllable either actively by users or passively by outdoor environmental condition	Yes	–

3.4. DYNAMIC THERMAL INSULATION TECHNOLOGIES (DTIS)

Thermal insulation is a material already widely used in construction and its behaviour is easy to predict and control with high confidence. The concept of dynamic thermal insulation has been primarily used in warm regions. However, in recent studies there is a growing interest in incorporating it into buildings to counterbalance the few disadvantages of intense thermal insulation or to allow buildings to adapt to varying seasonal climate conditions [48].

Nowadays, the increasingly stricter demands for building's thermal insulation are reflected on EU member's regulations. It is proven that thermal insulation is an effective way to reduce the heating energy consumption of a building while providing indoor thermal comfort. Yet, its effects on the cooling time are rather disputed, and the answer to the long-standing question of whether it enhances building performance or worsens the overheating phenomena is dependent on a variety of criteria. However, this prevalent question is no longer relevant if the façade could react and adjust to the prevailing environmental conditions, through the use of AFs [48].

Because of their capacity to vary their thermal resistance based on the surrounding conditions, dynamic insulation technologies are included in the adaptable façades category, modifying the heat flux between the internal and external environments. The interest in an envelope being able to control the transmitted heat flux is rapidly increasing and the geographical distribution can be one reason for this phenomenon, as most of the studies from north regions focus on the heating needs, while those from warm areas are centred on the cooling performance [48]. According to Karanafti et al. [48] dynamic insulated façades are divided into four categories and into sub-categories that depends on the operating mechanism of each system, as shown in Fig. 14.

The classification proposed by Karanafti et al. [48] for the dynamic insulation systems is based on their energy consumption for their optimum operation, while a second sub-categorization depends on the operating mechanism of each system. Some mechanisms can even operate with different energy consumptions: both thermal diodes and movable insulation operate as a passive, hybrid and active system.

Passive Systems only use natural power sources to operate and can be divided in three sub-categories [48]: (i) thermal diodes, that regulate heat transfer using heat pipe diodes. In a study of Li et al. they concluded that by using thermal diodes, the heat transfer capacity of the north wall increased by 46 times when compared to an ordinary wall [49]; (ii) optical properties and latent heat that are composed by opaque thermochromic materials, that change the thermal performance of the system by changing the solar absorptivity of its external surface, and by Phase Change Materials (PCMs), that store or release latent heat by phase changing, reducing energy needs by 17% [50]; (iii) movable insulation that enables the envelope to either be insulated or not, which reduces the heating demands by more than 50% and the cooling demands in 80% [51].

Hybrid Systems use an automation system to operate, and it can be a simple or a complex automation [48]. Simple automation can be divided in movable insulation, air convection, mixed systems and thermal diodes. Movable insulation, such as a thermal screen or curtain, enabled the reduction of the annual loads in 30% [52]. Air convection is a system based on heat exchange by convection and it is used in double glazing units. The cooling demand using this system is 10% less compared to non-adaptive façades [53]. The mixed systems operation depends on a combination of mechanisms where special or advanced technology is used. It was found that, when using these systems, occupants were exposed to 20% less summer discomfort and that 43% less cooling energy was needed [54]. In another study, the cooling needs were reduced by 68% compared to non-adaptive façades [55].

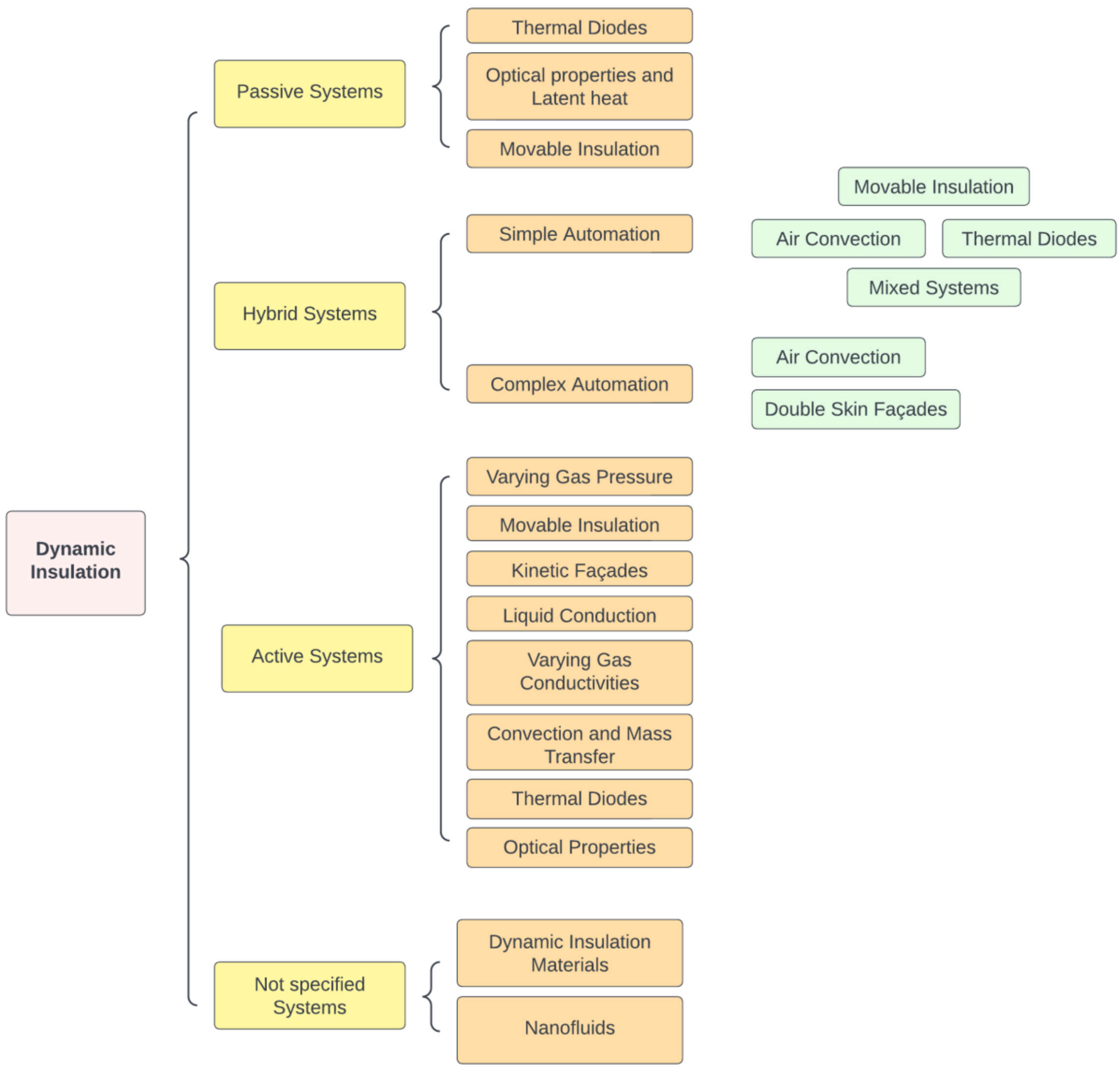


Fig. 14 - Classification of dynamic insulation systems and sub-categorization [42].

Complex automation in Hybrid Systems is divided into DSFs (Double skin façades) and air convection. In DSFs shading devices, either external or embedded inside the cavity, are frequently utilised to increase energy efficiency. The ventilation method used may therefore manage heat transfer owed to convection and conduction, and solar radiation gains can be modified according to internal circumstances and demands by tilting the blind's slat angle [48]. Air convection, such as the study by Koenders et al. [56], consists in two fans on the top and bottom of an insulating material layer inside an air cavity sealed with two aluminium foils, inducing air circulation. When the fans are turned off, it serves as a standard insulating layer. To function, this assembly requires a considerable temperature differential. The results of this study show that the amount of time in which occupants felt thermal discomfort was reduced by 72%-90% and that their heating needs were also reduced by 16%-22% [48].

Active systems depend on a constant power supply to operate and maintain their performance and are divided into eight sub-categories: varying gas pressure, movable insulation, kinetic façades, liquid conduction, convection and mass transfer, varying gas conductivities, optical properties and thermal diodes.

For example, varying gas conductivities is based on alternation of gas concentration on the material's pores to vary the thermal conduction. In the study by Park et al. [57], up to 39% of cooling loads and 10% of heating loads were reduced. Optical properties are based on electrochromic materials that can modify their visible transmittance and their solar gain coefficient under an electrical stimulation. It was found that with this system, 50% less CO_2 was emitted and 20% less energy loads were necessary [48][58]. Each one of the sub-categories of the active systems rely on constant power to operate and have the objective of changing the thermal conductivity or the thermal resistance, changing the thermal conduction through the façade and improving the comfort and energy efficiency.

Not specified systems is divided into Dynamic Insulation Materials (DIMs), which are materials that can modify their thermal resistance according to the prevailing conditions, and nanofluids that can be made from a variety of materials and allows enhanced heat transfer characteristics compared to conventional fluids [48]. Using DIMs, 7% to 42% less energy was needed [59].

Most of the studies on dynamic insulation systems focus on active technologies (60%) and are simulation-based (53%), rather than experimental. The simulations conducted refer to complex assemblies under development, testing the performance of a configuration under a specific aspect. This way, the simulation software and the procedure were assumed to be of vital importance. A whole-building simulation, rather than a component-only simulation, was the most adopted procedure to assess the systems' interaction with the rest of the envelope and other systems [48].

Before deciding on an active system to integrate into a structure, it is critical to do thorough research to determine whether the energy benefit outweighs the cost. Designers should bear in mind that the best option for said building may be a passive or hybrid system, which even though cannot achieve such a wide thermal resistance range, it can operate at a higher energy efficiency than an active system [48].

3.5. PREVIOUS STUDIES

3.5.1. NUMERICAL SIMULATION

Wieprzkowicz et al. [60] studied the feasibility of using latent heat storage by incorporating PCM into an exterior wall system in two cases of insulation components enhanced by a layer with increased latent heat capacity. Dynamic building simulation techniques employing *ESP-r* software provided the results. Thermal comfort and energy efficiency were evaluated using five indicators (number of phase transitions, frequency of being active, latent heat accumulation, latent heat storage efficiency, and dynamics of heat storage and release), and they discovered that the performance of the insulation with the PCM was dynamic and sensitive to the variation of the outside temperature. The authors also concluded that there is still demand for the development of assessment methods and guidelines for the performance of such components. A relation between phase change temperature, the external weather conditions, and the effectiveness of heat storage was found.

The performance of a closed loop forced convective dynamic insulation system was explored by Koenders et al. [61], using *EnergyPlus (E+)* as a simulation tool. The results revealed a U-value nine times higher when the system was in a conductive state than when the system was in an insulation state. A decrease of energy consumption was shown (the absolute reductions are between 1,5 and 3,0 kWh_{th}/m^2) and a boost of indoor thermal comfort in a typical residential building was observed (the hours when the operative temperatures exceed the comfort criteria were reduced in 80%), when compared with an equivalent passive cooling solution, like night ventilation. In addition, a dynamic insulation system applied to an exterior lightweight panel and an interior heavyweight panel façade resulted in the best performance.

Lee et al. [62] conducted a study to validate the changes in hourly shade states and envelope energy performance achieved by applying a control approach to an AF with a moveable folding type shading device. This device can have various shapes and movements and may alter the solar heat gain, the illuminance, and the discomfort glare. The paper proposes expressing the displacements of the shades with ten or more fixed states at constant intervals and provides a multi-purpose control technique in order to satisfy the occupant needs and requirements of heating, cooling, lighting energy conservation and glare prevention. The proposed method can block the entry of solar radiation while increasing the view factor in certain sections to promote the entry of diffuse solar radiation. Discomfort glare is a factor that can only be controlled with shades whereas indoor thermal comfort and illuminance can be supplemented via active systems. The findings of this study also illustrate that the heating, cooling, and lighting energy performance of the building envelope can vary depending on the orientation and on the prioritized objective of the control system. The movement of shades may bring economic benefit during intense cooling periods by lowering peak loads caused by strong solar radiation, while also eliminating uncomfortable glare. Yet, throughout the winter, there was a rise in energy use.

When fabric shades with a solar transmittance of 0,5 were used, the total primary energy consumption decreased by 10%-20% and the cooling energy was reduced by about 45% for all orientations for both control schemes, when compared with the use of opaque shades. This way, it was concluded that this difference in energy proportions can effectively be reduced by adopting translucent shades [62].

3.5.2. Experimental Tests

A prototype of a smart and adaptive façade module (MSAW – Mediterranean adaptive smart all), based on a dry wooden modular constructive system, including PCMs and high insulation materials, was developed by Iommi [64]. They addressed energetic and environmental issues.

This prototype allows the modification of the sequence of the internal layers in relation to the different thermal performance's requirements, coupling high thermal capacity with reduced thickness. It was made to be a smart constructive solution, easily manageable, with fast and smart assembly process on site and with customizable external finishes. The façade module is made up of a modular frame made of plywood timber sheets with modular components that offer the wall form in the absence of additional vertical structural elements. The modular structure is separated into two major levels, which were made by vertical and horizontal wooden pieces as well as internal and external plywood sheets. Wood wool insulation, a polyethylene vapour barrier layer, PCM, and VIP (vacuum insulation panels) insulation are all installed in the frame. An air gap is included to adapt the performance of the system, by providing a ventilated façade or by increasing the thickness of insulating material [64].

This study conducted by Iommi concluded that this type of envelope solution can guarantee cost and time savings due to the production process, materials used, and the easy and smart assembly process. It can have a good environmental impact as it is a dry and light construction process with a DFD - design for disassembly - approach. The acquired findings for thermal insulation and thermal capacity reveal a overall performance, as well as good results for thermal bridges. The PCM layer provides a good thermal inertia with a reduced mass wall. In addition, the heat storage capacity is effective. The thermal analysis performed by the simulations, both for stationary and dynamic computations, demonstrate thermal characteristics that outperform the most current solutions (the U-value of the MSAW is better than 55% of the case studies analysed by the author) [64].

Fantucci tested a ventilated opaque double skin façade in laboratory. The DSF was made of an exterior panel made of EPS, MDF, and brick, a ventilated air cavity and an internal panel made of a brick layer and a structural brick wall. This Dynamic Insulated Façade had two configurations: an exhaust air façade

(EAF), which uses the façade as an air heat recovery system, and a supply air façade (SAF), which uses the façade as a supply air pre-heater. In a EAF the hot air enters the air cavity through a hole in the base of the interior panel and reaches the external environment through an upper hole. In a SAF the cold air from the exterior enters the air cavity through a hole in the base of the external panel and enters the building through an upper hole in the internal panel. A preheating efficiency between 9% and 20% was achieved using the SAF configuration, whilst a heat loss reduction between 43% and 68% was recorded when using the EAF configuration. In addition, the extra insulation that the ventilated gap offers, provides heat loss reduction and a higher level of indoor air quality [65].

Teixeira [66] developed a dynamic thermal insulation solution that utilizes a ventilation system to control the heat flow through the façade in an attempt to provide internal comfort for the users. The solution, constructed by Grupo FARCIMAR, consists of a reenforced concrete panel, an insulation layer, an air cavity and a reinforced concrete layer, from the exterior to the interior connected by threaded rods. The theoretical thermal transmittance coefficient of the system is 0,35W/(m^2.ºC). The wall system had two cavities in opposite corners, in the exterior panel, for placing computer fans to force the air circulation in the air cavity. Without the air currents the system is in an insulation state, but with the air currents the system is in a conductive state. This prototype was experimentally analysed, in a laboratory, in a variety of heat settings, with and without ventilation, in order to assess its performance as both an insulating and conductive system. For the conductive state, tests were performed in which the ventilation system's settings were modified in the interest of analysing the effect of air flow on the prototype's thermal transmittance. The results showed a higher thermal transmittance for the tests with the two computer fans in the lower hole with a U-value of 0,50 W/(m^2.ºC), instead of 0,26 W/(m^2.ºC) without the ventilation. In addition, it was discovered that the transmittance was directly related to the intensity of the air flow [66].

Guimarães [67] tested the same constructive solution prototype for overheating, with the temperature in the climatic chamber (exterior) lower than the temperature in the laboratory (interior), to verify the thermal behaviour. For the exterior temperature settled as 5ºC, the heat resistance is 6,14 m^2.ºC/W without ventilation, and with ventilation it is 1,67 m^2.ºC/W. For an exterior temperature of 10ºC, the heat resistance is 6,52 m^2.ºC/W without forced ventilation, and it is 1,47 m^2.ºC/W with forced ventilation. It was concluded that the heat resistance was lower in situations in which the ventilation system was turned on than in scenarios without the ventilation system, showing its capacity to reduce building overheating. It was also noticed that a higher difference of temperature between the exterior and the interior contributes for a lower heat resistance of the wall solution.

Bakker et al. [63] utilized another approach and studied the user satisfaction with the interaction with automated dynamic façades. For the experiment, 26 participants were exposed to different scenarios with varying control strategies and occupant influence options. The study focused on dynamic daylighting and visual performance aspects, and it revealed that a high risk of disturbance and discomfort didn't occur, and that less frequent discrete transitions (when it relates to a clear cause) were more appreciated than smooth ones (without apparent reason) at a higher frequency. It was also found that, for having high-performance operation, manual override is a requirement.

4

MODELLING METHODOLOGY

4.1. OVERVIEW

The goal of this study is to verify if a dynamic thermal insulation system (DTIS) is able to greatly impact the problem of overheating, by considering different exterior climates, and, therefore, different locations, different U-values and different thermal mass. To accomplish this objective, it is necessary to:

- understand the interior discomfort that users feel, based on the adaptive model proposed in EN 16798-2 [7]
- and get to know the energy use for systems required for cooling, to guarantee a comfortable environment.

The software *DesignBuilder (DB)* [68] was used to simulate the response of the building to the different scenarios that were stablished. To simulate in *DB*, two scenarios of envelope configurations for a residential building, a low mass envelope and a high mass envelope, were used. Three different U-values were used, to assess the building performance varying between the state of insulation and the state of conduction. To assess the impact of the exterior environment, simulations were run in Bragança, Porto and Faro, three portuguese cities with different climate conditions. The effect of shading and the existence or not of a cooling system were also evaluated. In total, 74 scenarios were considered in this work. The schematic description of the inputs and outputs of the simulations that were run to assess the behaviour of a dynamic thermal insulation system is shown in Fig. 15. Twelve months and July results were exported hourly from *DB* and then the data was treated and presented in Chapter 5.

The following steps were taken from the initial development of the model until the result analysis:

- Identify the key parameters for the simulations;
- Input the residential building defined by ASHRAE Standard 140 [69] and change/adapt the model to the parameters already identified;
- Run the simulations for the 74 scenarios;
- Export hourly results, for twelve months and July, of energy consumption and operative temperatures;
- Data treatment to evaluate the thermal discomfort, using two discomfort performance indicators (DPIs);
- Analyse and discuss the results for all the scenarios;
- Discuss the operational performance optimization of the performance of a DTIS.

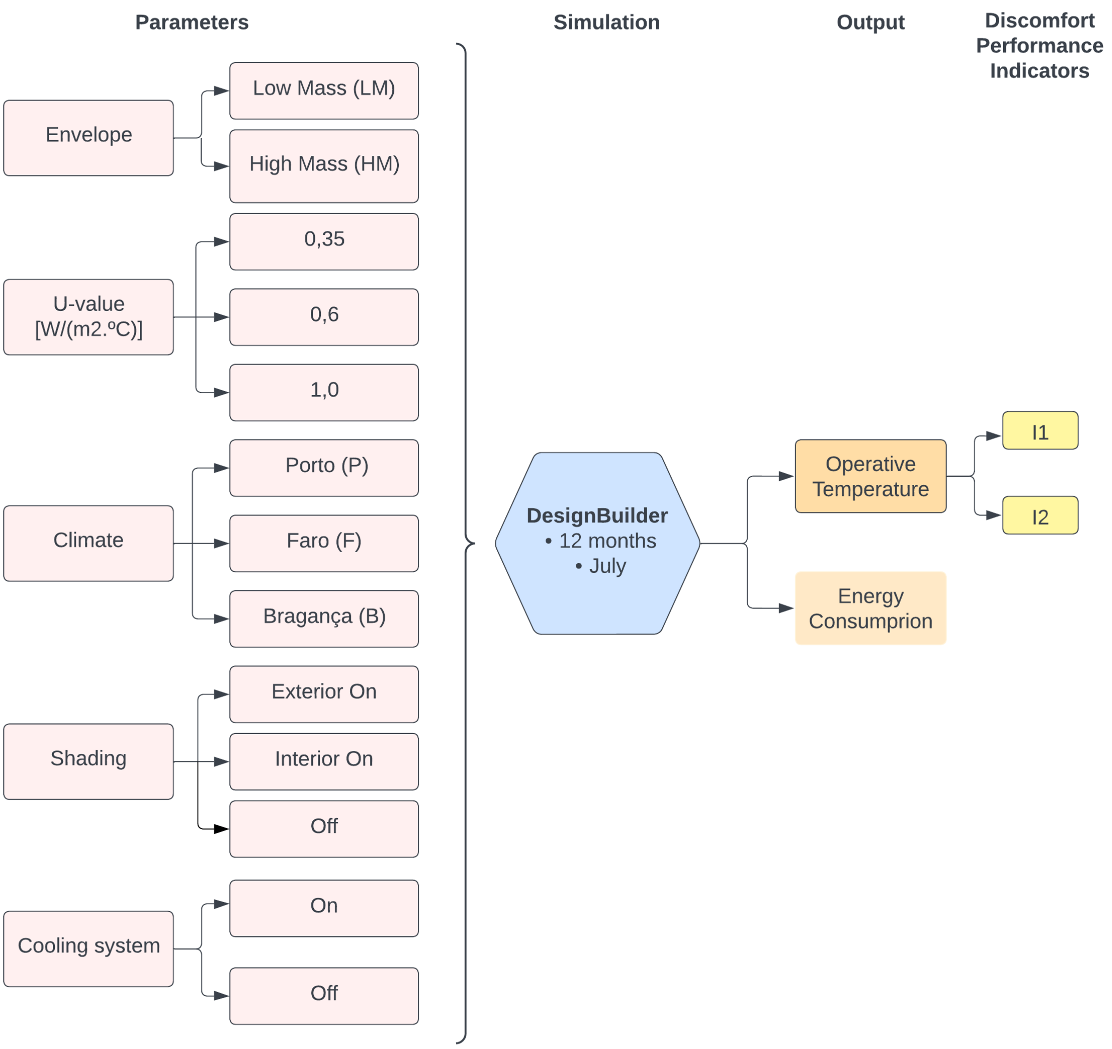


Fig. 15 - Study overview.

4.2. Modelling in *DesignBuilder*

4.2.1 Envelope Configurations and Properties

In the ASHRAE Standard 140-2004 the procedures to be applied to test a software are specified, with the goal of easily detect any flaws and limitations when comparing to different programmes. To do the simulations in this study, two models of buildings that are defined in this standard were used: the Low Mass Basic Test Case 600 and the High Mass Basic Test Case 900. In both cases, a single unpartitioned building, with 8m x 6m x 2,7m and two 6 m^2 of double-glazed windows in the south facing wall, was considered (Fig. 16). The infiltration rate used is 0,5 a.c./h and the glazed windows are composed of two panes of 3,175mm and an air-gap thickness of 13mm. The U-value of the glazing units is 3 W/(m^2.K), and the solar heat-gain coefficient is 0,789. More detailed information about the glazed windows properties can be found on ASHRAE Standard 140- 2004 [69].

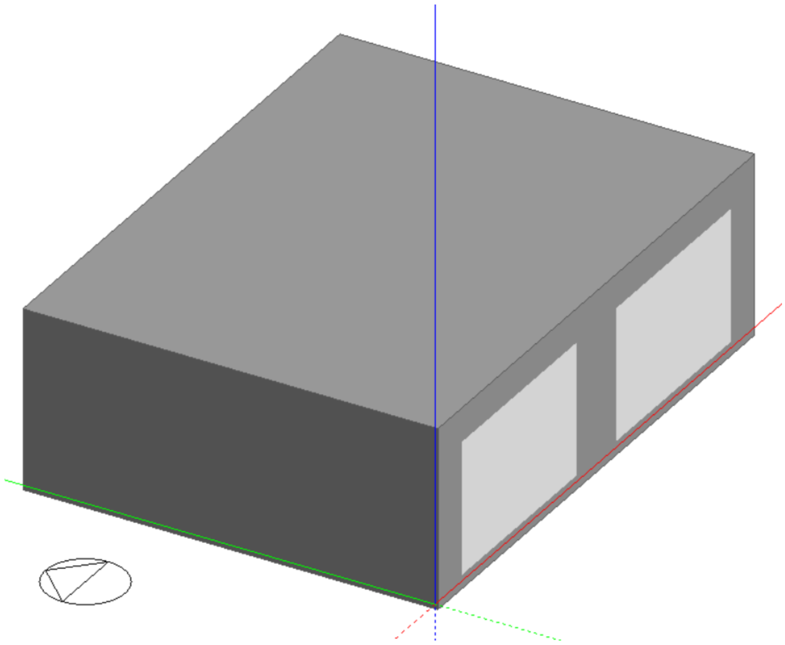


Fig. 16 – Building model, both for the Low Mass Basic Test Case 600 and High Mass Basic Test Case 900.

The construction elements (walls, floor and roof) for the low mass test case (Case 600) are detailed in Table 2, Table 3 and Table 4, while Table 5 to Table 7 describe the properties of the building components for the high mass test case (Case 900) [69]:

Table 2 - Wall construction form inside to outside, Low Mass Basic Test Case 600 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m^2.K))	R (m^2.K/W)	Density (kg/m^3)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Plasterboard	0,160	0,012		0,075	950	840
Fibreglass Quilt	0,040	0,066		1,650	12	840
Wood Siding	0,140	0,009		0,064	530	900
Ext. Surface Coeff.				0,034		
Total air-air			0,514			

Table 3 - Floor construction from inside to outside, Low Mass Basic Test Case 600 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m².K))	R (m².K/W)	Density (kg/m³)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Timber Flooring	0,140	0,025		0,179	650	1200
Insulation	0,040	0,100		25,075	12	840
Total air-air			0,039			

Table 4 - Roof construction from inside to outside, Low Mass Basic Test Case 600 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m².K))	R (m².K/W)	Density (kg/m³)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Plasterboard	0,160	0,010		0,063	950	840
Fibreglass Quilt	0,040	0,112		2,794	12	840
Roof Deck	0,140	0,019		0,136	530	900
Ext. Surface Coeff.				0,034		
Total air-air			0,318			

Table 5 - Wall construction from inside to outside, High Mass Basic Test Case 900 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m².K))	R (m².K/W)	Density (kg/m³)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Concrete block	0,510	0,1		0,196	1400	1000
Foam insulation	0,040	0,062		1,537	10	1400
Wood Siding	0,140	0,009		0,064	530	900
Ext. Surface Coeff.				0,034		
Total air-air			0,512			

Table 6 - Floor construction from inside to outside, High Mass Basic Test Case 900 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m^2.K))	R (m^2.K/W)	Density (kg/m^3)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Concrete Slab	1,130	0,080		0,071	1400	1000
Insulation	0,040	1,007		25,175		
Total air-air			0,039			

Table 7 - Roof construction from inside to outside, High Mass Basic Test Case 900 [69].

Element	λ (W/(m.K))	Thickness (m)	U (W/(m^2.K))	R (m^2.K/W)	Density (kg/m^3)	Cp (J/(kg.K))
Int. Surface Coeff.				0,121		
Plasterboard	0,160	0,010		0,063	950	840
Fibreglass Quilt	0,040	0,112		2,794	12	840
Roof Deck	0,140	0,019		0,136	530	900
Ext. Surface Coeff.				0,034		
Total air-air			0,318			

In this dissertation, three U-values for the wall system were used. It was, then, necessary to change the thickness of the insulation layer in order to obtain the desired thermal transmittance. The U-values used were 0,35 W/(m^2.ºC), which is the most stringent maximum value permitted in the Portuguese regulation for the state of insulation [70], 0,6 W/(m^2.ºC) and 1,0 W/(m^2.ºC), which are values that are not acceptable for the heating season in Portuguese regulation but that are used to assess the thermal response of the wall system in the state of conduction (Table 8). The U-value of 0,6 W/(m^2.ºC) was experimentally obtained in the laboratory when the prototype was in a conductive state [71]. In addition, was used an U-value equal to 1,0 W/(m^2.ºC) to gauge the potential impact of it on internal thermal comfort if the prototype could be optimised for a higher value.

Table 8 - Thickness of the insulation layer to the correspondent U-value for the low mass and high mass building.

U-value (W/(m^2.ºC))	**0,35**	**0,6**	**1**
Fiberglass quilt thickness for the Low Mass Building (m)	0,103	0,055	0,028
Fiberglass quilt thickness for the High Mass Building (m)	0,098	0,050	0,024

4.2.2 WEATHER DATA

The simulations ran for three different exterior climates, one for each Portuguese city (Porto, Faro and Bragança). In Fig. 17, is possible to see the monthly average and maximum exterior temperature, for each city. The values were collected from the climate file from SCE (Sistema de Certificação Energética dos Edifícios) [72].

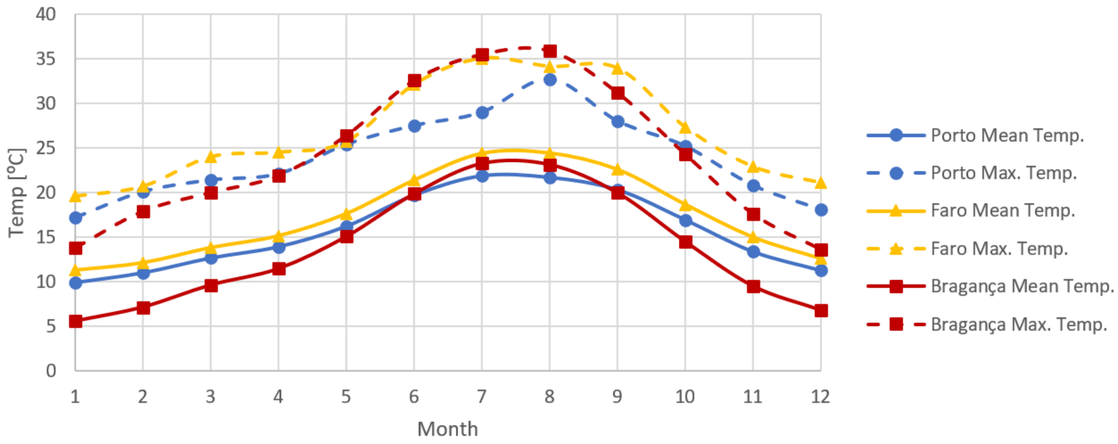


Fig. 17 - Monthly average and maximum exterior temperatures for Porto, Faro and Bragança.

Fig. 17 shows that Faro climate has the highest values of average temperatures over the year, but Bragança during spring and summer has higher maximum temperatures. Bragança presents lower average and maximum temperatures than other climates during autumn and winter. On average, Porto has the climate with the lowest seasonal variation.

Regardless the existence, by default, of climate files in *DB* database for the locations under study, the files download from SCE were used, in order to achieve more accurate values. In fact, these files have the advantage of providing the Portuguese Reference Meteorological Years for each city, mathematically treated by the Direção Geral de Energia e Geologia. This way, in an Excel file, Fig. 18, provided by SCE and called "Climas SCE", it is possible to choose the location and to prepare an EPW file (EnergyPlus Weather) [72]. This file is then introduced as a new location in *DB* software.

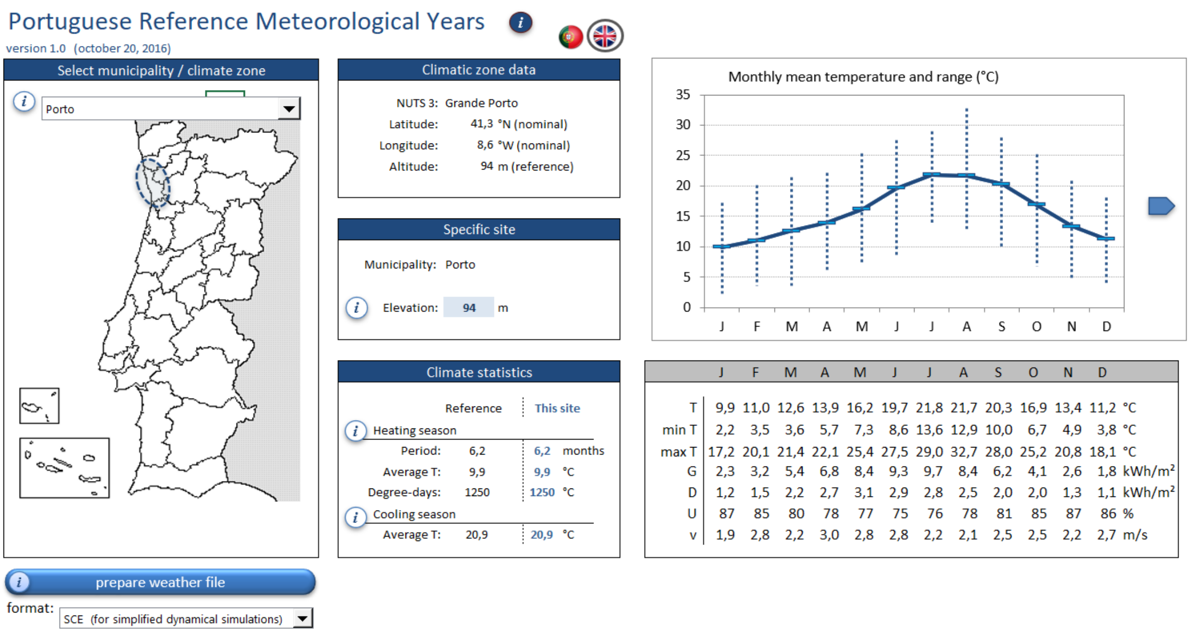


Fig. 18 - Spreadsheet to generate the climate location file (Example of Porto) [72].

4.2.3 COOLING AND SHADING SYSTEMS

The cooling system was used to guarantee thermal comfort inside the building. The energy requirements for cooling were established as the useful energy to maintain a maximum indoor temperature of 25ºC throughout the cooling season. The cooling system was, then, scheduled to operate when the operative temperature was equal or higher than 25ºC, between April and September.

As the simulated building has a considerable glazed area facing south, the effect of different shading systems, to moderate the interior temperature, was assessed. The external shading used was a "Blind with high reflectivity slats" and it was activated when the internal air temperature is equal to or higher than 25ºC. This system was scheduled to activate every month of the year. An inside shading system was also used in one scenario, in order to understand the impact of this device, compared with the exterior one, helping with the choice of the system that has the most impact on moderating the internal temperature.

4.3. SCENARIOS

The 74 simulation scenarios that are considered to be the most relevant to the evaluation of the thermal response and energy consumption of a building with a dynamic thermal insulation system are presented in Table 9, which also defines the code for the variation of each parameter. This way, all the simulations obeyed to the same coding classification format by following Case_Climate_U-value_Cooling_Shading_Period. As an example, LM_P_0,35_ON_EXT_A refers to the simulation of a low mass building in Porto with a U-value of 0,35 W/(m^2.ºC), with cooling system activated and using an exterior shading device, simulated for twelve months.

Table 9 – Parameters that compose the simulation scenarios.

Period	Case	Climate	U-value	Cooling	Shading
A	LM	P	0,35	ON	NO
M	HM	F	0,6	OFF	INT
		B	1,0		EXT

4.4. DATA TREATMENT

The outputs of the performed simulations are the hourly values of operative temperatures and energy consumptions, when air-conditioning systems are used.

In the first phase, for each scenario, the annual variation of the operative and exterior ambient temperature was represented. The objective of this analysis is to evaluate the influence of the outside temperature in each location with the thermal performance of the building.

Then, in order to analyse the discomfort felt inside the building, the output data from *DesignBuilder* was treated. The discomfort is analysed based on EN 16798 [7] adaptive model that recommended the use of four categories to describe the yearly indoor environmental performance. This norm defines the upper and lower limit of comfort depending on the category and is defined by equations that relate the indoor operative temperature and the outdoor running temperature, giving a graphical output.

Then, in order to analyse thermal discomfort, the adaptive model defined by EN 16798 [7] was used, considering category II. Two discomfort performance indicators were used. Indicator 1 represents the severity of discomfort by assessing the difference between the uncomfortable temperature by overheating and the corresponding comfort limit temperature defined by EN 16798 [7], already described in Section 2.2. Indicator 1 is calculated by using equation (8). Indicator 2 shows the percentage of time with discomfort by overheating and can be calculated by equation (9).

$$I1 = \frac{\sum_{i=1}^{n}(\theta_o - \theta_{ul})_i}{N} \wedge \theta_o > \theta_{ul} \quad (^{\circ}C) \tag{8}$$

$$I2 = \frac{N}{n} * 100 \quad (\%) \tag{9}$$

Where:

N – number of hours with discomfort

n – number of hours simulated

θ_{ul} – temperature of the upper limit of comfort (ºC)

θ_o – operative temperature (ºC)

5

ANALYSIS OF RESULTS

5.1. PORTO SCENARIOS

5.1.1. ANNUAL RESULTS

5.1.1.1. Air temperature

The first modelling scenario is for Porto. In Fig. 19 and Fig. 20, it is possible to observe the variation of temperatures outside and inside the low mass and the high mass buildings, respectively, considering a U-value for the walls of 0,35 W/(m^2.ºC). Results are shown for the scenarios where the glazed windows have no shading devices and where they have exterior shading devices.

In Fig. 19 and Fig. 20, it is visible that indoor temperatures reach very high values in the scenario without shading, with the winter peaks being higher than the ones in summer. This can be explained by the fact that about 83% of the southern façade is glazed openings and that during winter the incident radiation angle is lower, providing more internal gains. This phenomenon is less relevant in the HM building, due to its higher heat storage capacity that acts as a buffer.

When shading is used, Fig. 19 and Fig. 20 show its effectiveness, by reducing considerably the peaks of indoor temperature. Results also prove that interior shading is less effective than exterior shading, because, although indoor temperatures in this scenario are lower than when no shading is applied, they are higher and suffer greater fluctuations than when exterior shading exists.

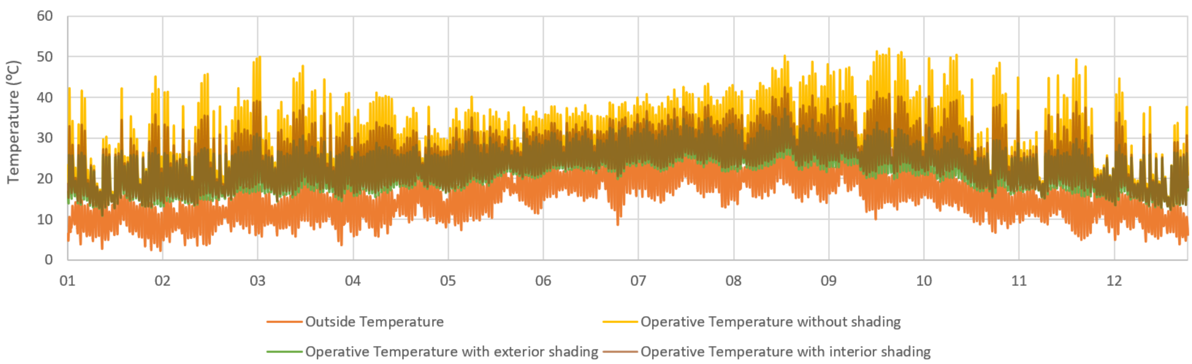


Fig. 19 - Temperatures for Porto, for a LM building, and walls with a U-value equal to 0,35 W/(m^2.ºC).

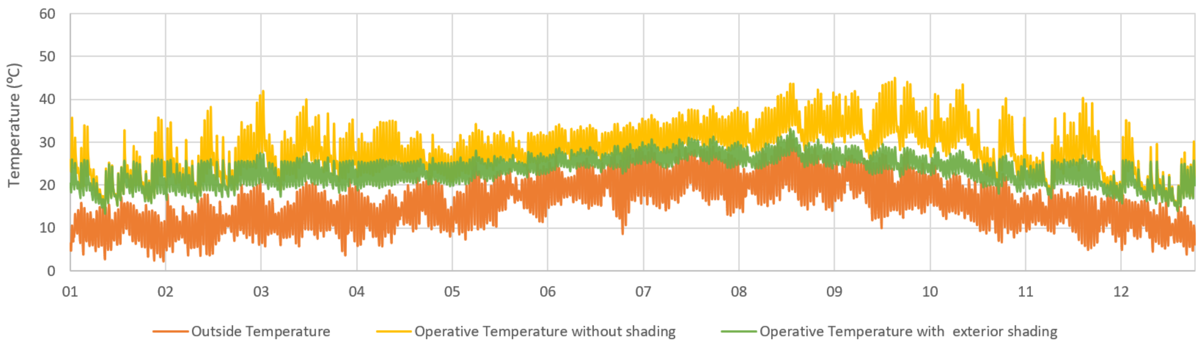


Fig. 20 - Temperatures for Porto, for a HM building, and walls with a U-value equal to 0,35 W/(m^2.ºC).

Table 10 and Table 11 show the range of temperatures for the Porto scenarios to complement the information given by the graphs. By observing the values presented in Table 10 and Table 11, it is possible to understand that the exterior shading system reduces the interior temperatures more than the interior shading system, especially the maximum value. The high mass building, by comparation with the low mass building, has a more stable interior temperature with lower maximum temperatures and higher minimum temperatures, providing more comfort.

Table 10 – Annual maximum, average and minimum temperatures for the LM case in Porto (U = 0,35 W/(m^2.ºC)).

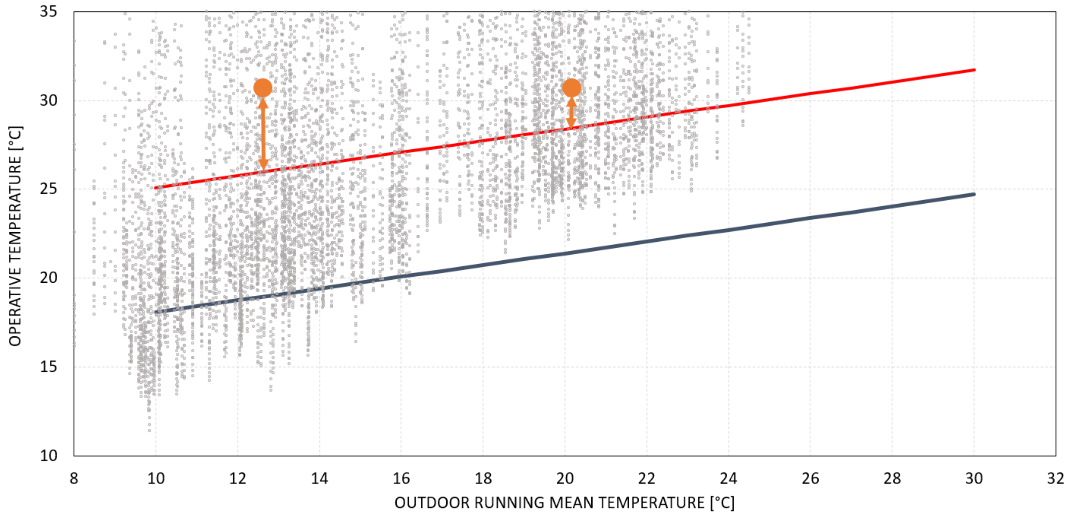
LM	Exterior	Interior without shading	Interior with exterior shading	Interior with interior shading
Max Temp (ºC)	32,7	52,0	37,2	42,5
Mean Temp (ºC)	15,7	28,0	23,0	24,8
Min Temp (ºC)	2,2	11,4	10,9	11,0

Table 11 – Annual maximum, average and minimum temperatures for the HM case in Porto (U = 0,35 W/(m^2.ºC)).

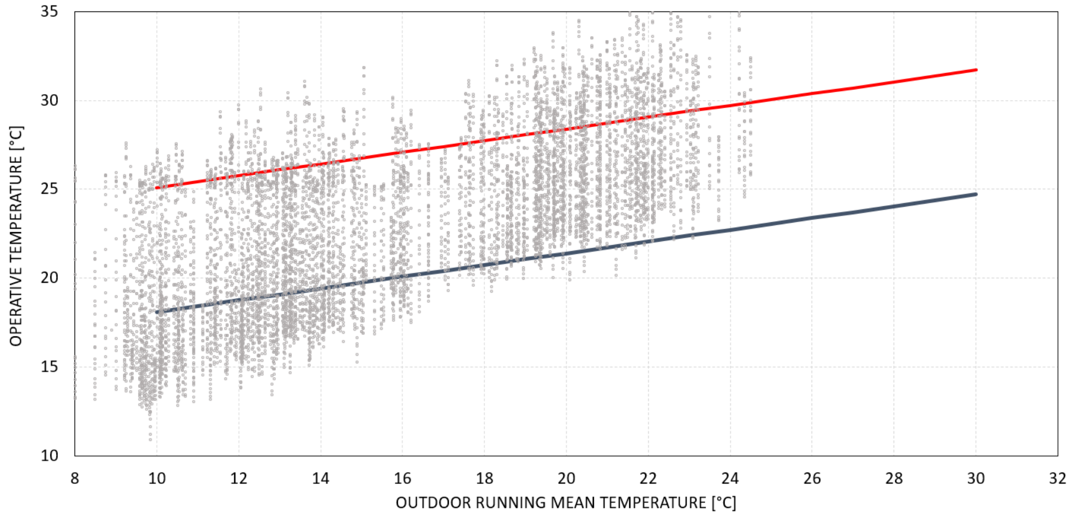
HM	Exterior	Interior without shading	Interior with exterior shading
Max Temp (ºC)	32,7	45,0	33,1
Mean Temp (ºC)	15,7	28,0	23,6
Min Temp (ºC)	2,2	14,0	13,3

5.1.1.2. Evaluation of the thermal comfort based on the EN 16798 adaptive model

In Fig. 21, it is showed the upper and lower limits of comfort, defined in the EN 16798, for category II, and the dispersion of hourly points (outdoor running mean temperature, operative temperature) for one year simulation, considering the scenario for a LM building in Porto with a U-value of 0,35 W/(m2.ºC), without shading device (Fig. 21 a)) and with an exterior shading system (Fig. 21 b)). It is possible to observe that without shading there are a higher number of points above the maximum limit of comfortable temperature than in the case with the use of an exterior shading system. This way, it is possible to conclude that the use of shading is an effective measure for the mitigation of overheating.



a)



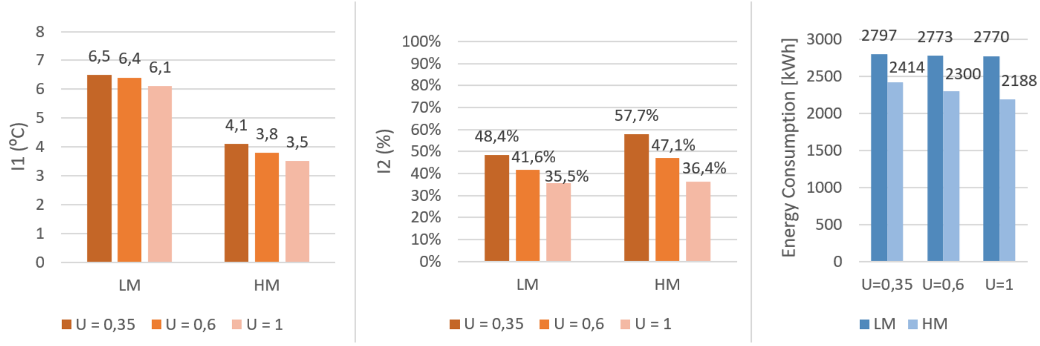
b)

Fig. 21 – Thermal comfort evaluation for the LM building, U-value equal to 0,35 W/(m^2.ºC) and for Porto climate: (a) without shading device; (b) with an exterior shading system.

It is also important to state that only the right-side region of the graphs, in Fig. 21, has interest for this study, because it is the region with high outdoor temperatures (summer season). Another aspect that is important to focus on is the fact that in winter the severity of the discomfort felt is higher because the comfort limit is lower, as shown in Fig. 21 a) by the orange arrows. The results are highly influenced by this fact and, also, by the geometry that was selected for the building, small volume with a high percentage of glazed windows at the south façade, which increases the impact of the discomfort. This way, the interpretation of the results obtained in this work focused not only on the twelve month period, but also in one single month, being selected July, because it is one of the months with higher and more constant temperatures, presenting higher discomfort levels.

5.1.1.3. Evaluation of thermal comfort based on discomfort performance indicators

Fig. 22 shows the annual evaluation of thermal comfort based on discomfort performance indicators for a low mass and a high mass building located in Porto without the use of a shading system. Indicator 1 represents the severity of discomfort by overheating (Fig. 22a)) and Indicator 2 shows the percentage of time with discomfort by overheating (Fig. 22 b)). Fig. 22 c) presents the energy consumption to achieve thermal comfort using a cooling system that activates when the operative temperature is higher than 25ºC between April and September. The bar chart displays the variation of the DPIs and of the energy consumption with the U-value.



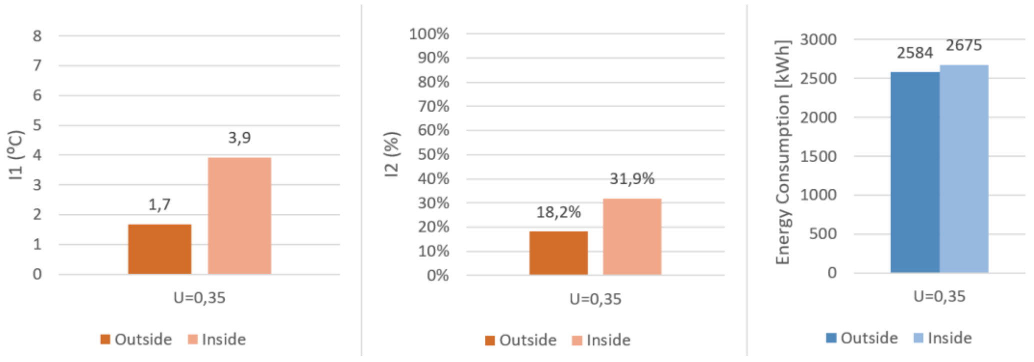
a) b) c)

Fig. 22 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and a high mass (HM) building in Porto without shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

Fig. 22 shows that Indicators 1 and 2 decrease with the increase of the U-value, around 6% for LM and 15% for HM, for Indicator 1, and about 27% for LM and 37% for HM, for Indicator 2. That happens because more energy can be released through the envelope, in situations of overheating, when the building is less insulated. Indicator 1 have higher values for the case of a low mass building on average 2,5ºC, and Indicator 2 have higher values for the case of a hight mass building about 5,2% on average. This means that despite of having lower percentage of hours with discomfort, the discomfort felt by the occupants is more severe in the case of a low mass building. When the thermal resistance is lower the heat transfer through the façade increases and the thermal mass effect is not dominant. In fact, Indicator 2 when the U-value is equal to 1,0 W/(m^2.ºC), the difference between the LM and HM is low.

When a cooling system is used, the energy consumption decreases when the U-value increases, especially in the building with high thermal mass. It is showed that a building with higher thermal mass needs less energy to have a comfortable environment than a low mass building. It can be concluded that although the thermal mass limits the amplitude of indoor temperature (Fig. 19 and Fig. 20), this effect is not reflected in the percentage of hours with discomfort.

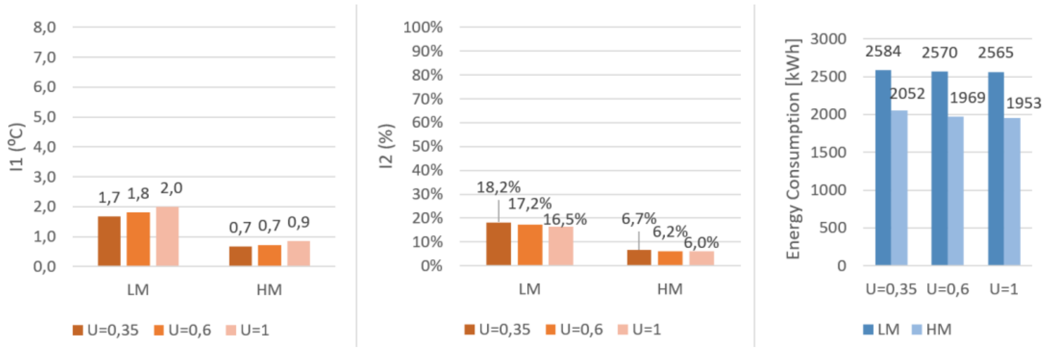
Comparing the effect of the interior and exterior shading systems, on annual basis, for the low mass building in Porto, with a U-value of the walls of 0,35 W/(m^2.ºC) it is visible that an exterior shading system is better to mitigate the impacts of overheating, reducing the interior discomfort felt by the occupants (Fig. 23), as the severity of discomfort decreases almost 56% and the percentage of time with discomfort reduces about 43%. In terms of energy consumption, the impact of the type of shading is not relevant because the effect of the thermal mass of the building is predominant.



a) b) c)

Fig. 23 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) building in Porto with the use of an interior and exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

In contrast to Fig. 22, looking at Fig. 24 that shows the results of the simulations ran with exterior shading devices, it is possible to see that the indicators have substantially lower values, about 3,8ºC on average for Indicator 1 and 33% for Indicator 2, showing that those devices are effective to restrain situations of overheating, especially in buildings with high thermal mass. Comparing the results, one can also point that the tendency of Indicator 1 changed. Indicators 1 increases with the increase of the U-value around 15% for LM and 20% for HM, and Indicator 2 decrease about 9% for LM and 10% for HM. The percentage values for Indicator 1 are higher (6% for LM and 15% for HM), and for Indicator 2 are lower (27% for LM and 37% for HM), than the case without shading. In fact, the range of discomfort is greater when the U-value increases, because the heat flux is not always in the same direction over the day, mainly due to incident solar radiation. Indeed, when indoor temperatures are very high, as in the case of no shading, they are the trigger for heat flux through walls, which mainly occurs from inside to outside, reducing the impact of incident solar radiation. When indoor temperatures decrease due to shading, the impact of incident solar radiation in the heat flux direction over the day increases, impacting the Indicator 1. It is, then, necessary to do more detailed and dynamic simulations in order to get more reliable results.



a) b) c)

Fig. 24 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and a high mass (HM) building in Porto with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.1.2. Results for July

5.1.2.1. Air temperature

The results interpretation focused, not only on the twelve month period, but also in one single month, being selected July. This way, it was possible to get a more reliable assessement of the effect of a higher U-value in mitigating overheating in summer, as it is one of the months with higher and more constant temperatures, presenting higher discomfort levels, and preventing the impact of winter peaks of operative temperatures.

Fig. 25 and Table 12 present the results for a low mass building and a high mass building in Porto, considering a U-value for the walls of 0,35 W/(m2.ºC). Simulations were performed for the scenarios where the glazed windows have no shading and where they have exterior shading. Comparing the values for July with the annual ones, it is possible to see that in July the temperatures gradient is lower. Although the maximum values are similar, the minimum values are much higher. Also, the effect of shading is less relevant in July, due to the higher position of the sun in the horizon.

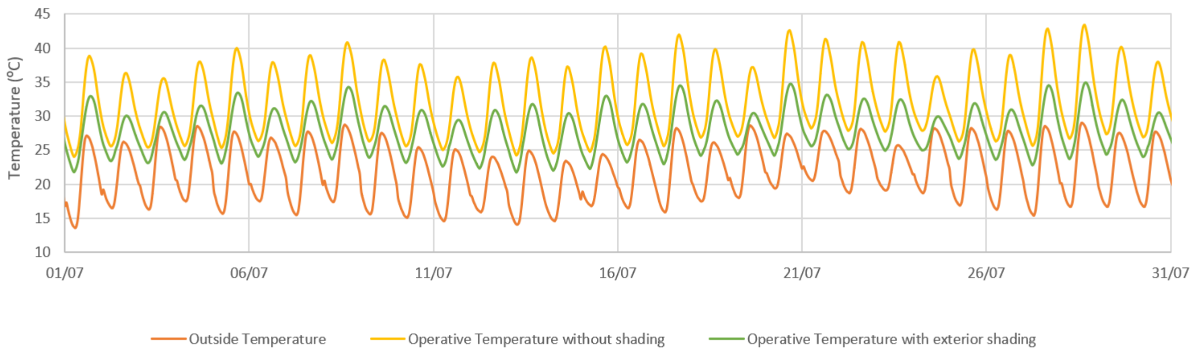


Fig. 25 – July temperatures for Porto climate, for a LM building, and walls with a U-value equal to 0,35 W/(m^2.ºC).

Table 12 - July maximum, average and minimum temperatures for the LM and HM case in Porto (U = 0,35 W/(m^2.ºC)).

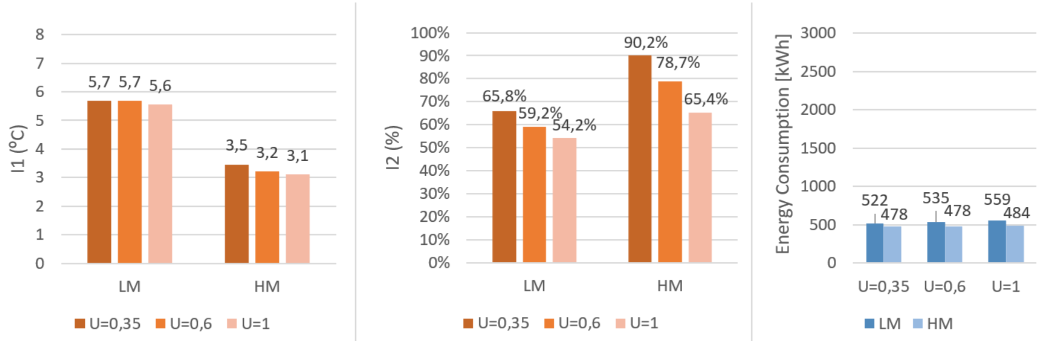
		LM		HM	
	Exterior	Interior without shading	Interior with exterior shading	Interior without shading	Interior with exterior shading
Max Temp (ºC)	29	43,4	34,9	38,4	31,3
Mean Temp (ºC)	21,8	24,0	27,7	27,0	27,5
Min Temp (ºC)	13,6	32,0	21,7	32,0	24,0

5.1.2.2. Evaluation of thermal comfort based on discomfort performance indicators

For July, in the scenarios of a low mass building and a high mass building, located in Porto, without shading, the discomfort performance indicators follow the same tendency of the annual case, with the indicators decreasing with the increase of the U-value (Fig. 22 and Fig. 26). Indicator 1 for July has lower values than in the annual analysis, about 0,6ºC on average, because it doesn't include the contribution of the winter peaks. But the percentage of hours with discomfort (Indicator 2) is higher, 25% on average, because indoor minimum temperatures in July are higher than when all year is considered, causing discomfort for longer periods. It must be noted that the percentage of time with discomfort by overheating in calculated based on the number of hours simulated (equation 9).

Fig. 26 shows that Indicator 1 decrease with the increase of the U-value around 2% for LM and 11% for HM, and Indicator 2 decrease about 18% for LM and 27% for HM. Then, the indicators decrease with the U-value at a lower rate than in an annual simulation, decreasing more for a high mass building.

In terms of energy consumption, in July, the values are very similar regardless the thermal mass and the U-value, unlike in the annual evaluation. The values remain higher for the low mass building, because it allows more internal gains through the façade. But the energy consumption slightly increases with the U-value, in July, unlike the annual simulations. This difference between the annual and the July simulation can be explained by the fact that, in walls with higher U-value, heat transfer by conduction from the outer surface to the inner one will increase when there is incident solar radiation. This will negatively affect the indoor temperature, increasing the cooling demands and the energy consumption of the system. These results confirm that the type of simulation used is not the most adequate, being necessary to simulate considering a dynamic U-value.

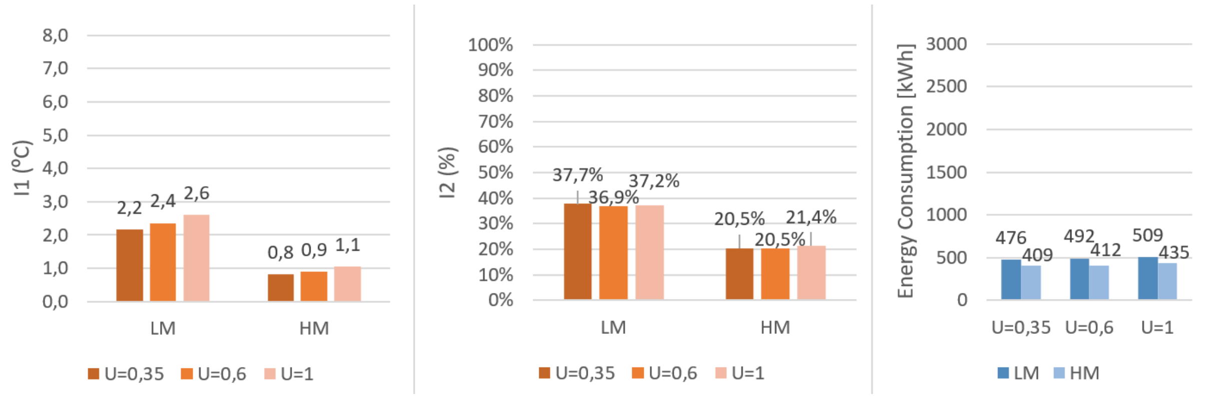


a) b) c)

Fig. 26 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and a high mass (HM) building in Porto without shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

When exterior shading is added to the simulation, as in the annual analysis, the indicators have lower values, showing the effectiveness of this system in maintaining indoor comfort, especially in building with high mass. Indicators 1 and 2 are about 2,8ºC on average and 40% lower, respectively. Indicator 1 increases with the U-value of around 15% for LM and higher variation of around 27% for HM. This happens because the heat flux is not always in the same direction over the day, mainly due to incident solar radiation. Regarding energy consumption, the limitations previously highlighted remain, so this parameter will not be considered for assessing Faro and Bragança simulations. To do a more detailed and dynamic simulation is essential in order to get more reliable results. Also, in Fig. 27 and looking at Indicator 2, it is noted that it suffers less variation than in the annual analysis (Fig. 24), with the discomfort performance indicator for the U-value equal to 0,6 W/(m^2.ºC) lower than for 1 W/(m^2.ºC).

Comparing to annual results, Indicators 1 and 2 have higher values, on average 0,4ºC and 17% respectively, because July is a month with high temperatures.



a) b) c)

Fig. 27 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Porto with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.2. Faro Scenarios

5.2.1. Annual Results

5.2.1.1. Air Temperature

The second location that was simulated was for Faro. Fig. 28, Fig. 29 and Table 13, show the variation of the temperatures for the low mass and high mass cases, considering the U-value for the walls equal to 0,35 W/(m^2.ºC) and the existence or not of exterior shading. The results are similar to the ones obtained in Porto, although the indoor temperatures reached in Porto are lower than the ones in Faro, due to the climatic differences of both locations.

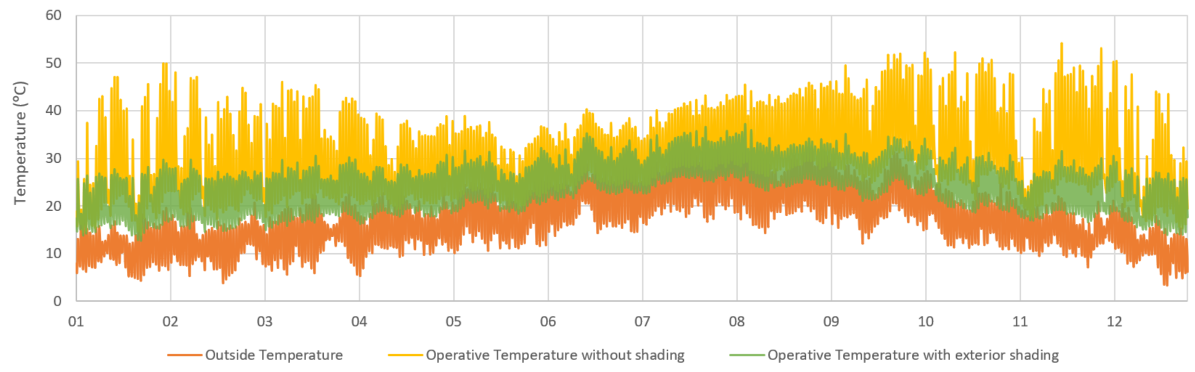


Fig. 28 - Temperatures for Faro climate, for a LM building, and walls with a U-value equal to 0,35 W/(m^2.ºC).

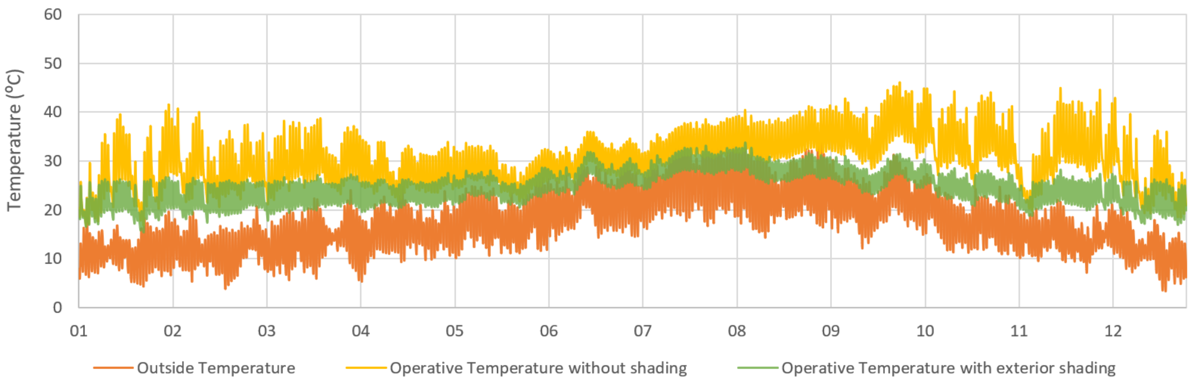


Fig. 29 - Temperatures for Faro climate, for a HM building, and walls with a U-value equal to 0,35 W/(m².ºC).

Table 13 – Annual maximum, average and minimum temperatures for the LM and HM case in Faro (U = 0,35 W/(m².ºC)).

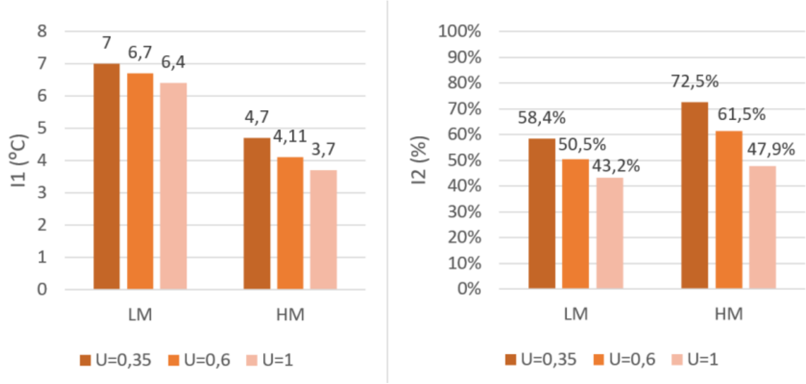
		LM		HM	
	Exterior	Interior without shading	Interior with exterior shading	Interior without shading	Interior with exterior shading
Max Temp (ºC)	35,0	54,1	37,2	46,1	33,8
Mean Temp (ºC)	17,4	30,3	24,4	30,3	24,8
Min Temp (ºC)	3,3	13,9	12,7	16,8	15,4

5.2.1.2. Evaluation of thermal comfort based on discomfort performance indicators

In Fig. 30 and Fig. 31 are shown the discomfort performance indicators for Faro scenarios, without and with exterior shading, respectively. Without shading (Fig. 30), Indicators 1 and 2 decrease with the increase of the U-value, similar to what happens in Porto. Indicator 1 decrease around 9% for LM and 21% for HM, and Indicator 2 decrease about 26% for LM and 35% for HM. The rate of indicators decrease is similar to the values obtained for Porto. Indicator 1 has higher values for the low mass buildings and Indicator 2 has higher values for the high mass buildings. This indicates that, although having a smaller percentage of discomfortable hours, the severity is greater in the case of a low thermal mass.

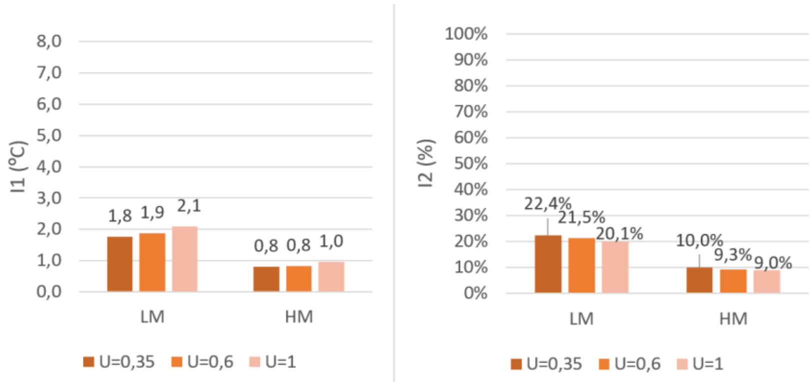
With shading (Fig. 31), the values of the indicators decreased, confirming that the use of a shading system provides more interior comfort. In addition, Indicator 1 increases with the U-value, showing the need for a more detailed and dynamic simulation to better understand when increasing the walls U-value results in a real benefit. Indicator 1 increase around 14% for LM and 20% for HM, and Indicator 2 decrease about 10% for LM and HM.

Comparing the following figures with Fig. 22 and Fig. 24 for Porto, the indicators for Faro present higher values, which is related to the higher exterior temperatures reached in Faro over the year. Then, it is possible to see that the indicators have higher values for Indicators 1 and 2, about 0,3ºC on average for Indicator 1 and 11% for Indicator 2, without shading, and about 0,1ºC on average for Indicator 1 and 4% for Indicator 2, with exterior shading.



a) b)

Fig. 30 – Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Faro without shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.



a) b)

Fig. 31 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Faro with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.2.2. Results for July

5.2.2.1. Air Temperature

Fig. 32 and Table 14 show the results, simulated hourly for July, for a low mass building and a high mass building in Porto, considering a U-value for the walls of 0,35 W/(m^2.ºC). The temperatures in July are very high, with the maximum exterior temperature of the year occurring during this month and with a higher minimum temperature for this month, when comparing with the annual value.

In a building with higher thermal mass, the maximum temperature peaks are attenuated, having less overheating potential problems. The same occurs when using an exterior shading device.

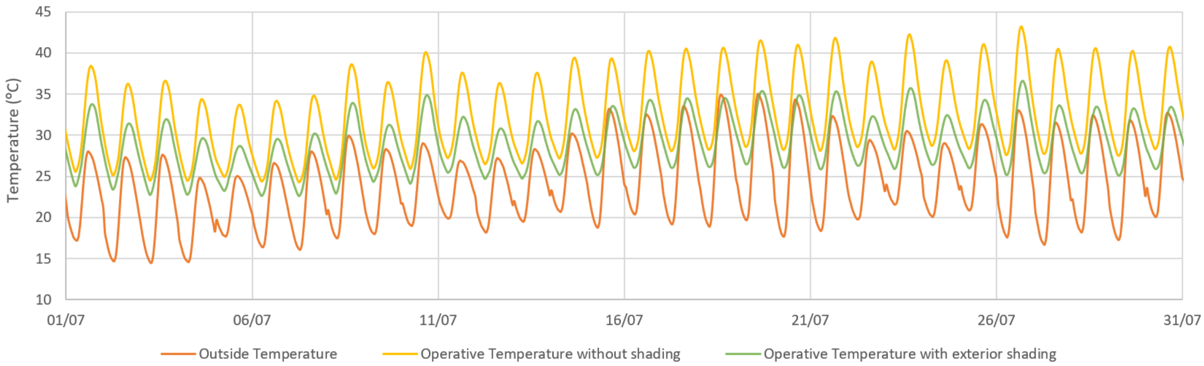


Fig. 32 - July temperatures for Faro climate, for a LM building, and walls with a U-value equal to 0,35 W/(m^2.ºC).

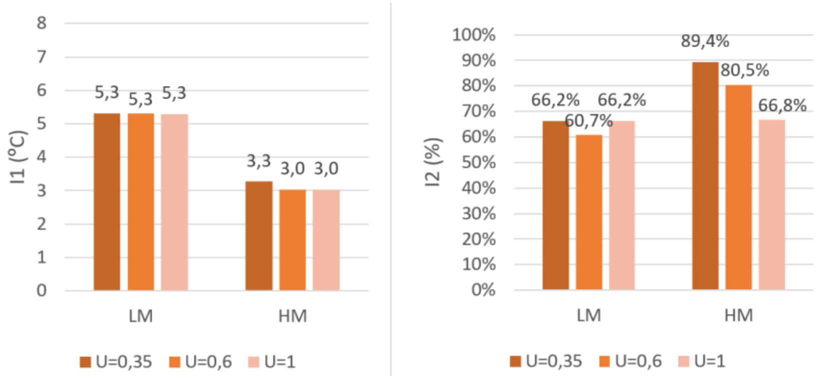
Table 14 - July maximum, average and minimum temperatures for the LM and HM case in Faro (U = 0,35 W/(m^2.ºC)).

		LM		HM	
	Exterior	Interior without shading	Interior with exterior shading	Interior without shading	Interior with exterior shading
Max Temp (ºC)	35,0	43,2	36,6	38,6	33,1
Mean Temp (ºC)	24,3	32,5	28,9	32,4	28,8
Min Temp (ºC)	14,5	24,3	22,6	26,7	24,2

5.2.2.2. Evaluation of thermal comfort based on discomfort performance indicators

For July, when comparing LM and HM buildings without shading, it is visible that Indicators 1 and 2 are more constant when varying the U-value, decreasing at a slower rate (Fig. 33). Indicators 1 and 2 decreases about 10% and 25% for HM, respectively. For a LM building, indicator 1 has lower values for the intermediate U-value. In this case, and for a lower U-value, the low mass building has less hours with discomfort, although it presents higher severity of discomfort. When the thermal resistance is lower, the heat transfer through the façade increases and the thermal mass effect is not so dominant. This phenomenon can be observed as the differences between LM and HM are smaller when the U-value is equal to 1 W/(m^2.ºC), for Indicator 2.

Comparing with Porto (Fig. 26) the indicators have lower values of about 0,3ºC on average for Indicators 1 and higher values, generally of 3%, for Indicator 2. It can be concluded that the severity is slightly lower, but that the number of hours with discomfort by overheating is slightly higher. That was expected as exterior temperatures in Faro are higher than in Porto, contributing to more uncomfortable time.

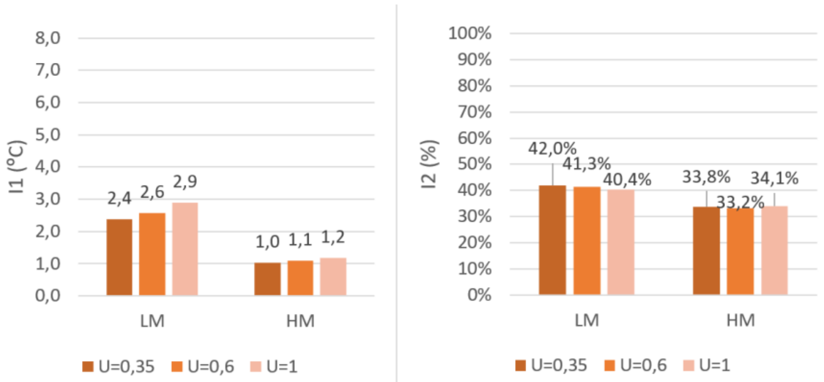


a) b)

Fig. 33 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Faro without the use of a shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

Indicator 1 increases with the increase of the U-value of about 17% for LM and HM. Indicator 2 decreases with the U-value about 4% for LM and increases 1% for HM. The increase in the values of Indicators 1 and 2 is due to the already explained phenomenon.

In Fig. 34 both indicators are higher than in Porto, Fig. 27. In fact, Indicators 1 and 2 are around 0,2ºC and 8% higher than in Porto, respectively. These values are slightly higher than in Porto because the climate in Faro has higher temperatures in this month.



a) b)

Fig. 34 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Faro with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.3. BRAGANÇA SCENARIOS

5.3.1. ANNUAL RESULTS

5.3.1.1. Air Temperature

The third location that was simulated is Bragança. Fig. 35, Fig. 36 and Table 15 show the variation of temperatures annualy in Bragança for LM and HM buildings, with and without the use of shading devices. It is clear that the high mass building has a more uniform interior temperature, with lower maximums and higher minimums, both without and with shading. The maximum temperatures in Porto, Table 15, are lower than the ones in Bragança, however, the minimum temperatures in Porto are higher.

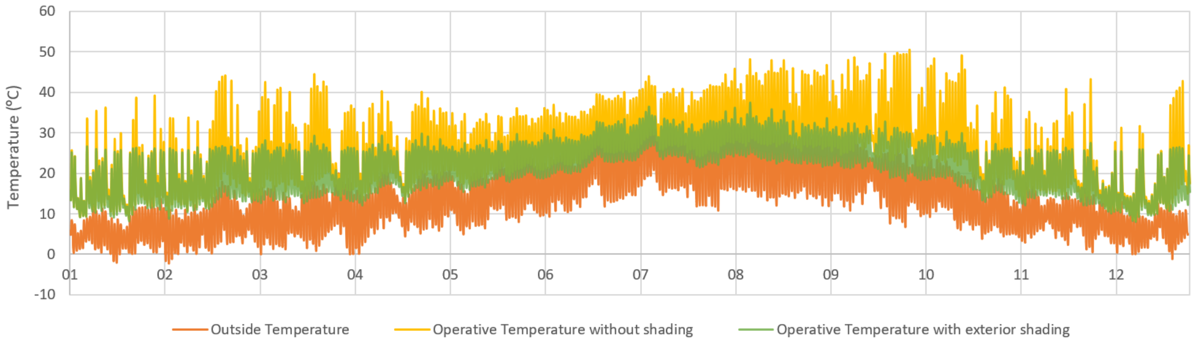


Fig. 35 - Temperatures for Bragança climate, for a LM building, and walls with a U-value equal to 0,35 W/(m²ºC).

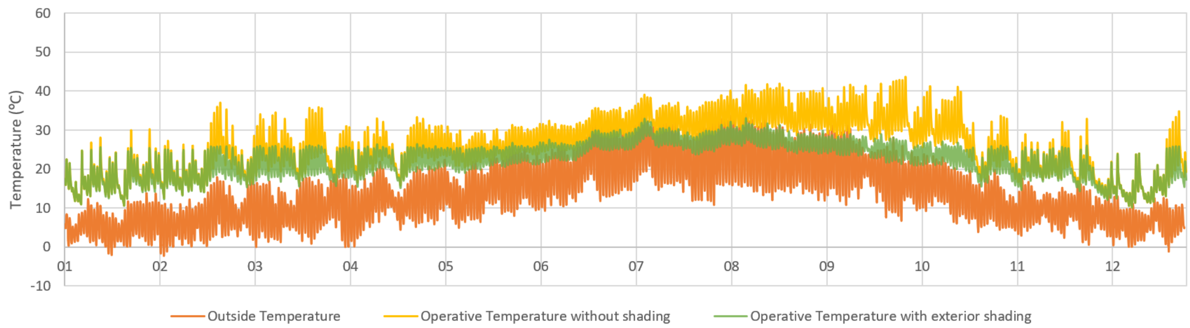


Fig. 36 - Temperatures for Bragança climate, for a HM building, and walls with a U-value equal to 0,35 W/(m²ºC).

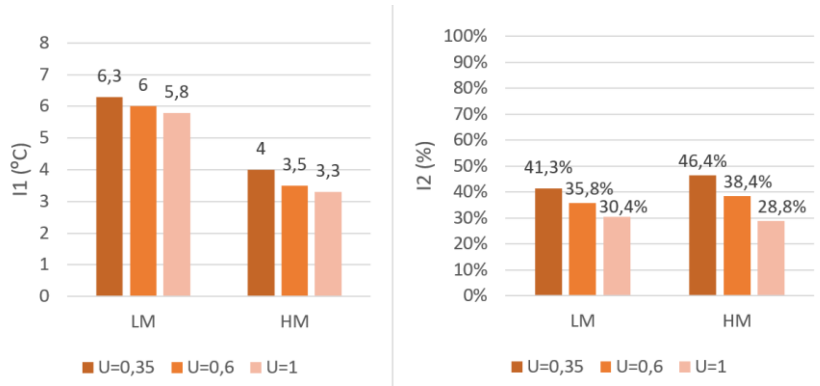
Table 15 – Annual maximum, average and minimum temperatures for the LM and HM case in Bragança (U = 0,35 W/(m^2.ºC)).

	LM			HM	
	Exterior	Interior without shading	Interior with exterior shading	Interior without shading	Interior with exterior shading
Max Temp (ºC)	35,9	50,5	37,5	43,7	33,1
Mean Temp (ºC)	13,8	25,8	21,7	25,8	22,3
Min Temp (ºC)	-2,3	8,2	8,0	10,1	10,1

5.3.1.2. Evaluation of thermal comfort based on discomfort performance indicators

Fig. 37 shows the variation of the discomfort performance indicators, for buildings with low and high mass located in Bragança, with no shading devices. For both indictors, the values decrease with the increase of the U-value, as happens in Porto and Faro. This way, the decrease of the discomfort is higher for the HM building. Indicator 1 decrease around 8% for LM and 18% for HM, and Indicator 2 decrease about 26% for LM and 38% for HM. Indicator 1 has greater values for low mass structure, whereas Indicator 2 has higher values for a high mass building. This suggests that, while a low mass structure has a lower percentage of uncomfortable hours, the severity is greater, being better to adopt a high mass building with a high U-value.

In comparation with Fig. 22, obtained for Porto climate, simulations for Bragança deliver smaller values for Indicator 1 and Indicator 2, about 0,3ºC on average for Indicator 1 and 8% for Indicator 2, without shading. It is understandable that the indicators have lower values than in Porto, because, in these simulations, most of the annual discomfort by overheating is during winter and Bragança presents lower exterior temperatures during that period.

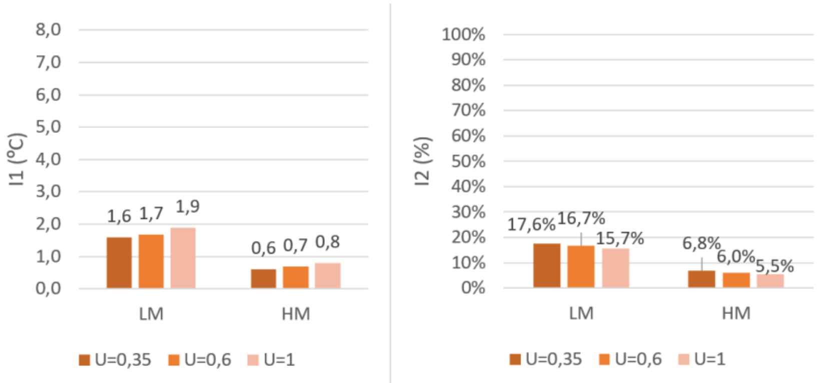


a) b)

Fig. 37 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Bragança without shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

When running simulations for buildings with low and high mass located in Bragança, with exterior shading devices on, Indicator 1 increases around 16% for LM and 25% for HM, and Indicator 2 decrease about 11% for LM and 26% for HM, with the U-value, as shown in Fig. 38. The values of the indicators vary at a higher rate than in Porto.

Comparing with Fig. 24 it is shown that the values in Porto and Bragança are similar, being slightly lower in Bragança. In fact, Indicator 1 is about 0,1ºC lower on average and Indicator 2 is 0,4% lower, with exterior shading.



a) b)

Fig. 38 - Annual evaluation of thermal comfort based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Bragança with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.3.2. RESULTS FOR JULY

5.3.2.1. Air Temperature

Fig. 39 and Table 16 show the results for a low mass and a high mass building in Bragança, considering a U-value for the walls of 0,35 W/(m^2.ºC), only for July, analysing a hot summer month and preventing the impact of winter peaks. Comparing the values for July with the annual ones, it is possible to see that in July the temperatures gradient is lower. Although the maximum values are similar, the minimum values are much higher. In a building with higher thermal mass, the maximum temperature peaks are attenuated, having less overheating potential problems. The same occurs when using an exterior shading device.

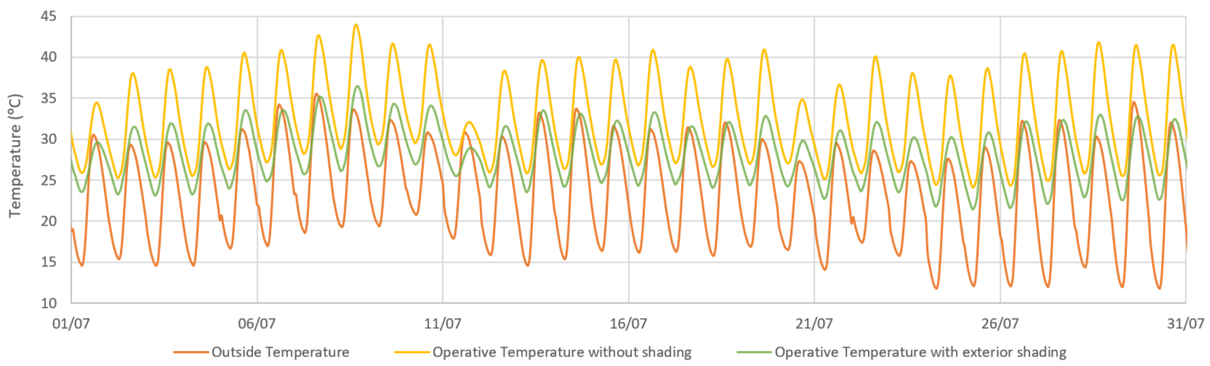


Fig. 39 – July temperatures for Bragança climate, for a LM building, and walls with a U-value equal to 0,35 W/(m²ºC).

Table 16 - July maximum, average and minimum temperatures for the LM and HM case in Bragança (U = 0,35 W/(m².ºC)).

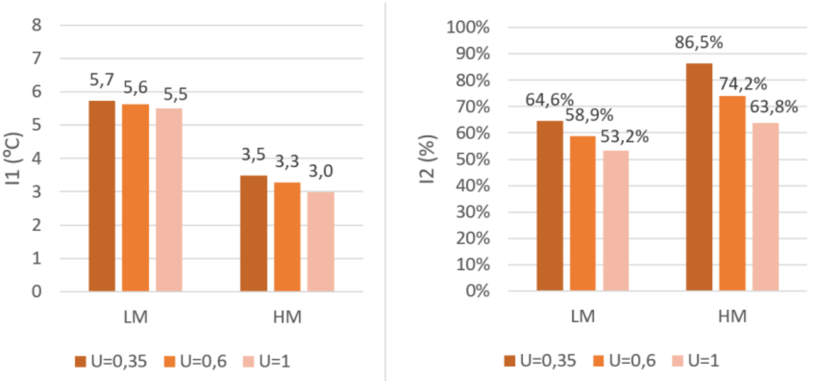
		LM		HM	
	Exterior	Interior without shading	Interior with exterior shading	Interior without shading	Interior with exterior shading
Max Temp (ºC)	35,5	44,0	36,5	39,1	32,9
Mean Temp (ºC)	10,8	24,2	21,4	27,5	23,7
Min Temp (ºC)	23,2	32,4	28,1	32,4	27,9

5.3.2.2. Evaluation of thermal comfort based on discomfort performance indicators

In July, for the scenarios LM and HM without shading, it is possible to visualise the variation of the discomfort indicators in Fig. 40 and with shading in Fig. 41. Without shading, Indicators 1 and 2 decrease with the increase of the U-value. Indicator 1 decreases about 4% for LM and 14% for HM, and Indicator 2 decreases about 18% for LM and 26% for HM. These values are similar to the ones registered in Porto, being slightly higher for Indicator 1 but slightly lower for Indicator 2.

Comparing with annual results, Fig. 37, for the scenario without shading, Indicator 1 has lower values but indicator 2 has higher values. Indicator 1 is 0,4ºC lower and Indicator 2 is 30% higher than the annual results. This way, in July the occupants feel more discomfort but with less severity.

By comparing with, Fig. 26, Porto results, it is observed that Indicator 1 has similar values without any difference between values on average and Indicator 2 has lower values of about 2%, without shading. It can be concluded that the severity and the number of hours with discomfort by overheating are very similar in both locations.

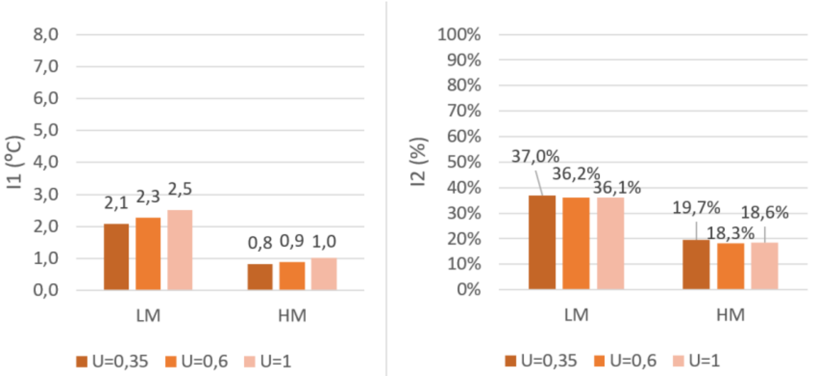


a) b)

Fig. 40 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and a high mass (HM) building in Bragança without shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

With shading, Indicator 1 increases about 16% for LM and 20% for HM, and Indicator 2 decreases about 2% for LM. For the HM building, Indicator 2 has a lower value for the intermediate U-value. These values are similar to the ones registered in Porto, being slightly higher for Indicator 2 but slightly lower for Indicator 1. Comparing with annual results, Indicators 1 and 2 have higher values of around 0,4ºC and 16%, respectively. July is, then, a more problematic month in terms of discomfort by overheating, because of the high exterior temperatures.

By comparing with Porto, Fig. 27, Indicators 1 and 2 are 0,1ºC and 1% lower respectively, for July. In terms of discomfort by overheating, it can be concluded that Porto and Bragança are very similar.



a) b)

Fig. 41 - Evaluation of thermal comfort, for July, based on discomfort performance indicators for a low mass (LM) and high mass (HM) building in Bragança with the use of an exterior shading system: (a) Indicator 1 – severity of discomfort by overheating; (b) Indicator 2 – percentage of time with discomfort by overheating; (c) Energy consumption to achieve thermal comfort.

5.4. Results Discussion

After the analysis of the values obtained, the present sub-chapter focuses on summarizing the results already presented. In Fig. 42, the results for Indicator 1 and Indicator 2, for each region, for a low mass and a high mass building are showed. Only the simulated values for July are shown because those are the most reliable results, not having the contribution of the winter peaks. The results of the simulations without shading are considered, as they correspond to the worst-case scenario, but compared with the case with the use of exterior shading devices. Also, simulations with U-values of 0,35 W/(m^2.ºC) and of 1,0 W/(m^2.ºC) were found relevant, because they correspond the limit values under analysis.

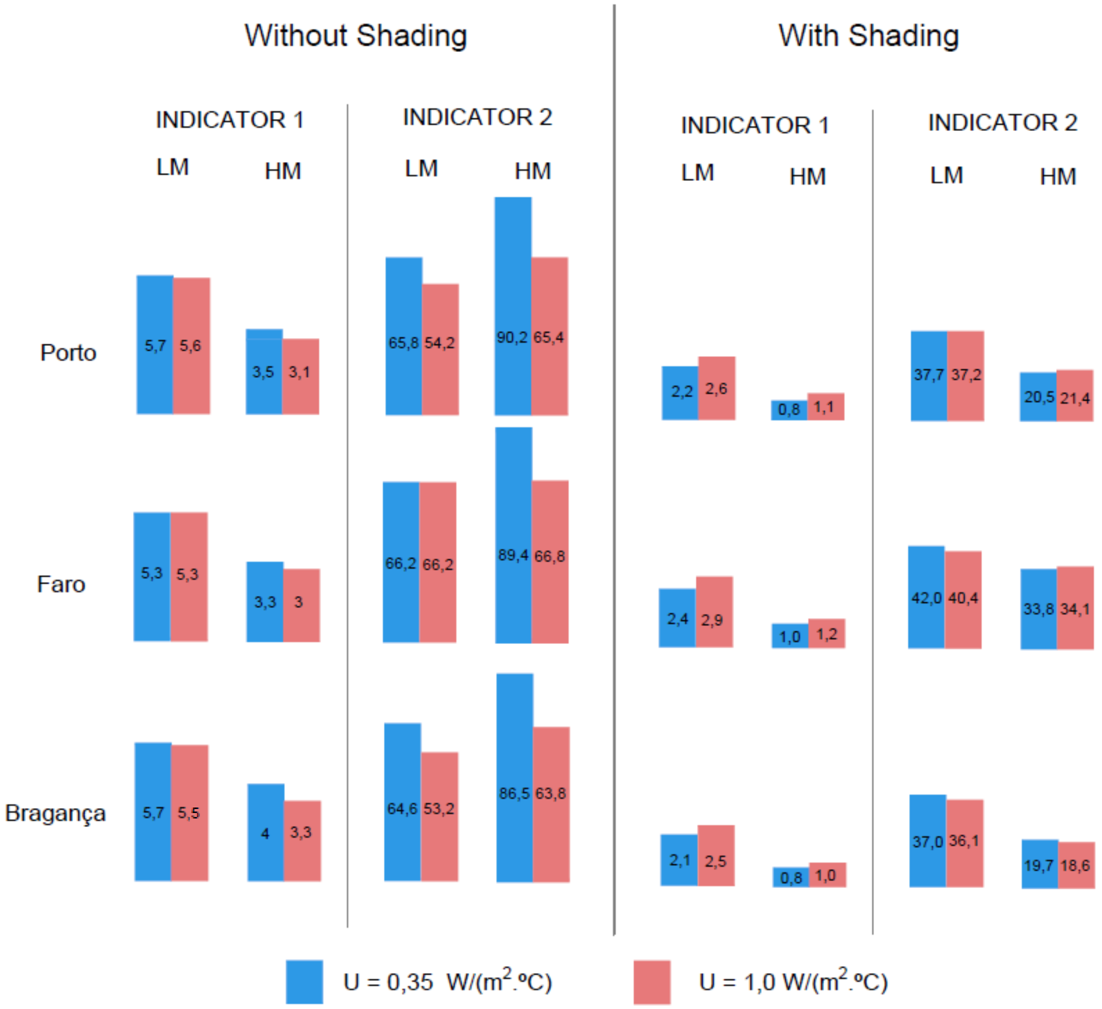


Fig. 42 - Results for low and high mass buildings, located in Porto, Faro and Bragança, for July, without and with shading.

Generically, in Fig. 42 it is possible to see that, without the use of a shading system, the discomfort, analysed by both discomfort performance indicators, decreases with the increase of the U-value. The same is not true when an exterior shading system is applied. The change in the tendency of Indicator 1 and in some cases of Indicator 2 is due to the fact that, with shading, the overheating phenomenon is lower, reducing the number of hours when it is beneficial to have a higher U-value. These results confirm that a dynamic U-value will be more effective in the situations of more pronounced overheating. It is however important to note that more accurate simulations are required, imposing a real dynamic U-value in the inputs. This way, in this sub-chapter, it is only analysed the values obtained without shading, i.e. when overheating is more pronounced.

Without shading, the highest reduction of Indicator 1 is for Bragança, decreasing about 18% for HM, when the U-value goes from 0,35 W/(m^2.ºC) to 1,0 W/(m^2.ºC). For Indicator 2 is around 27% for a HM building located in Porto. This way, Porto has more interest in utilizing a DTIS to reduce the percentage of hours with discomfort, and Bragança is the location where it is more relevant to have a DTIS to reduce the discomfort severity, increasing the occupants thermal comfort. In Faro, this system has less impact, because it is the climate with less thermal amplitude during the day, in July.

Bragança is the location with higher discomfort severity, because it is the location with higher temperatures during the day, but that presents lower values of severity, because it is the location with lower exterior night temperatures, improving the building response to overheating by releasing heat through the façade. Faro is the region with higher percentage of hours with discomfort for a LM and a HM building, with a U-value equal to 1 W/(m^2.ºC) because is a climate with high temperatures both during day and night.

Another aspect that is interesting to note is that this system implemented in a HM building has greater impact than in a LM building. These results were obtained by simulating all hours of July with a constant U-value. For this reason, this conclusion should be further discussed with the simulation for a dynamic U-value.

Without shading, a U-value of 1 W/(m^2.ºC) is always beneficial to decrease the percentage of hours with discomfort by overheating, reaching a maximum reduction of 27% in HM in Porto, and a maximum reduction of severity of 18% in HM in Bragança. This way, it can be concluded that a dynamic thermal insulation system can be a good strategy for the mitigation of overheating.

6

OPTIMIZATION OF THE WALL PERFORMANCE

6.1. FRAMEWORK

This chapter aims to optimize the operational performance of the dynamic thermal insulation system (DTIS) by determining when it is interesting to have a high U-value to minimize overheating problems. To that end, two questions will be discussed:

- Is it beneficial to the performance of the building to have a high U-value, for each exterior climate?
- Which are the periods in which the high U-value is beneficial to the performance of the building?

In order to analyse deeply this phenomenon, different scenarios were simulated for a building located in Porto, Faro and Bragança with walls with a U-value of 0,35 W/(m^2.ºC). This value was selected because it is the maximum prescribed by the Portuguese law for the opaque vertical envelope. The simulations were conducted for a low mass building as it is the situation with higher values of overheating. The simulations were performed for the first week of July, obtaining as an extra output the interior and exterior surface temperatures.

Once the simulations have been carried out, hourly indoor and outdoor surface temperatures were obtained and analysed over time. Then, in order to analyse the discomfort numerically, four discomfort performance indicators were defined and evaluated. Indicator I (0ºC) represents de period of time when the system with high U-value would be useful, i.e., when the operative temperature is higher than 25ºC and when the difference of the exterior and interior surface temperatures is negative (equation 10). Indicator I (5ºC) is similar to the previous one, but the interior surface temperature has to be at least 5ºC higher than the exterior one (equation 11). The value of 5ºC was selected in order to reduce the period of time to when the heat flux is more intense. Indicator I (ΔT) shows the sum of the superficial temperatures differences for the cases defined by I (0ºC), as described in equation 12. Indicator I (T disc.) reflects the number of hours with discomfort by overheating (with the operative temperature higher than 25ºC), as established by equation 13.

$$I\ (0°C) = \sum_{i=1}^{n} 1\ ,\ (\theta_o)_i > 25ºC\ \wedge\ (\theta_{sur.\,ext.} - \theta_{sur.\,int.})_i < 0°C \tag{10}$$

$$I\ (5°C) = \sum_{i=1}^{n} 1\ ,\ (\theta_o)_i > 25ºC\ \wedge\ (\theta_{sur.\,ext.} - \theta_{sur.\,int.})_i < -5°C \tag{11}$$

$$I\ (\Delta T) = \sum_{i=1}^{n} (|\ \theta_{sur.\,ext} - \theta_{sur.\,int.}|)_i\ ,\ (\theta_o)_i > 25ºC\ \wedge\ (\theta_{sur.\,ext} - \theta_{sur.\,int.})_i < 0°C\ \ (ºC) \tag{12}$$

$$I\ (T\ disc.) = \sum_{i=1}^{n} 1\ ,\ (\theta_o)_i > 25°C \tag{13}$$

Where:

n – number of hours simulated

$\theta_{sur.ext.}$ – Exterior surface temperature (ºC)

$\theta_{sur.int.}$ – Interior surface temperature (ºC)

θ_{o} – operative temperature (ºC)

Fig. 43 shows the region when it is interesting to have a higher U-value in order to make the building able to dissipate heat through the façade. This area is highlighted in green and occurs when the internal superficial temperature is higher than the exterior superficial temperature and when the operative temperature is higher than 25ºC. The operative temperature inside the building is similar to the internal surface temperature and in Fig. 43 they are represented overlapping.

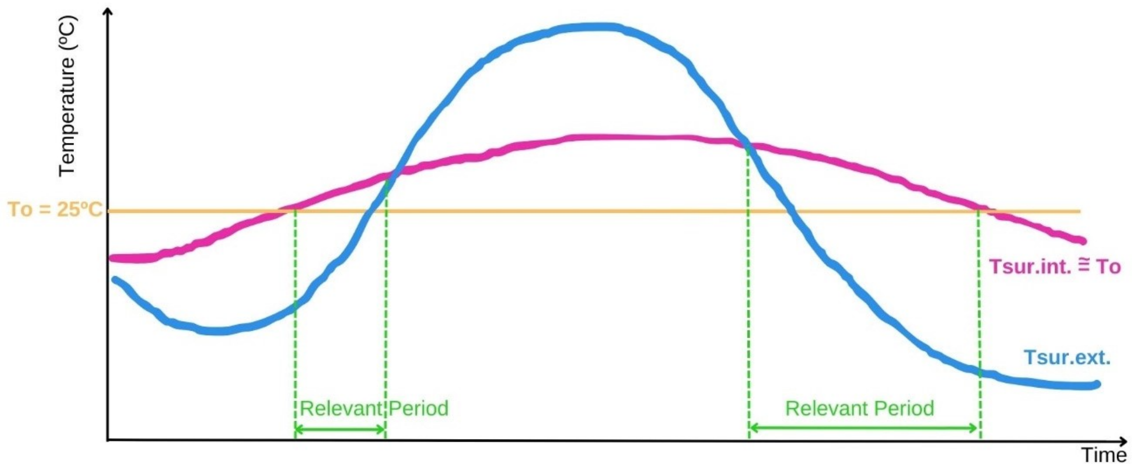


Fig. 43 - Period when it is relevant to have a higher U-value.

6.2. RESULTS - SUPERFICIAL TEMPERATURES

6.2.1. PORTO, WITHOUT SHADING

In Fig. 44 to Fig. 47 it is possible to observe the interior and exterior superficial temperatures, and the difference between them, by orientation for a building located in Porto when no shading device is used. For Faro and Bragança the graphical results are similar, both with and without shading, so only the results obtained for Porto were commented.

When the difference of temperature is positive, the heat flux is from the exterior to the interior. When it is negative, the flux is from the interior to the exterior, and, only in this case, it is useful to have a high U-value. The higher is the negative difference of temperature between the external and the internal surface temperatures, the higher is the heat flux, favouring the use of a high U-value.

It is possible to note that the inside surface temperature is similar in every orientation. However, the external surface temperature has more variation between orientations, as expected due to differences in the incident solar radiation. The following graphs represent 168 hourly results for each orientation. In this case, it is possible to see that the North-oriented façade is the one with more area below zero, and therefore, it is the orientation with higher periods when having a DTIS would be interesting. The North-oriented façade has 156h when the differences of temperatures are negative, so 156h when heat is being released through the façade. This way, it would be interesting to have a DTIS in about 93% of the simulated time. For the façade East-oriented, this percentage decreases to 71%. The percentages for the West-oriented and South-oriented façades are 79% and 80%, respectively.

This way, it is possible to conclude that, in order to decrease overheating and provide thermal comfort to building users, the system under study can be a good strategy, enabling the heat release through the building envelope during around 71%-93% of the time, when no shading system is activated for Porto.

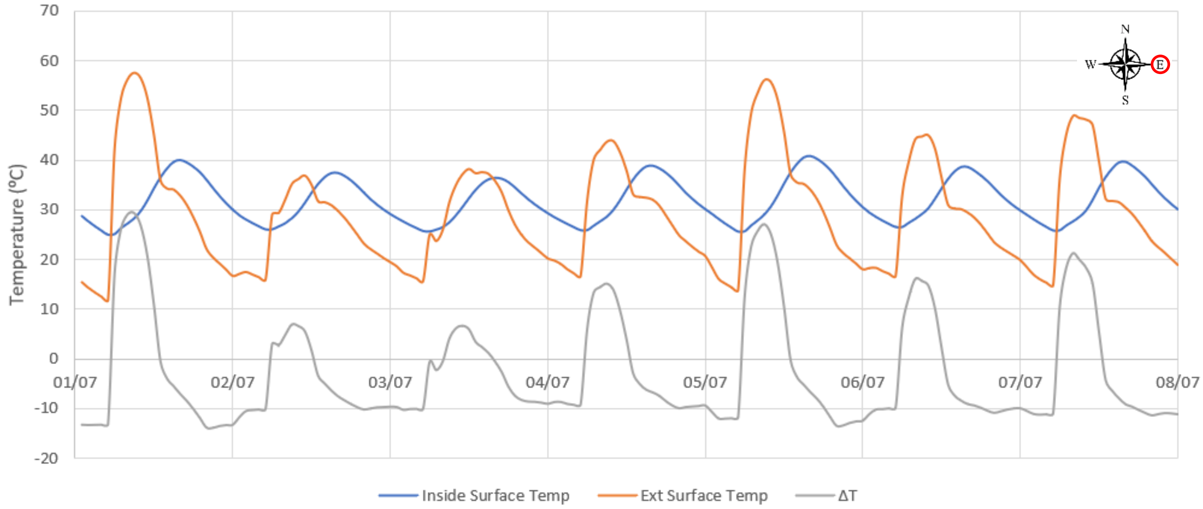


Fig. 44 - External and internal surface temperatures and difference between them, without shading, for Porto and for the wall East-oriented.

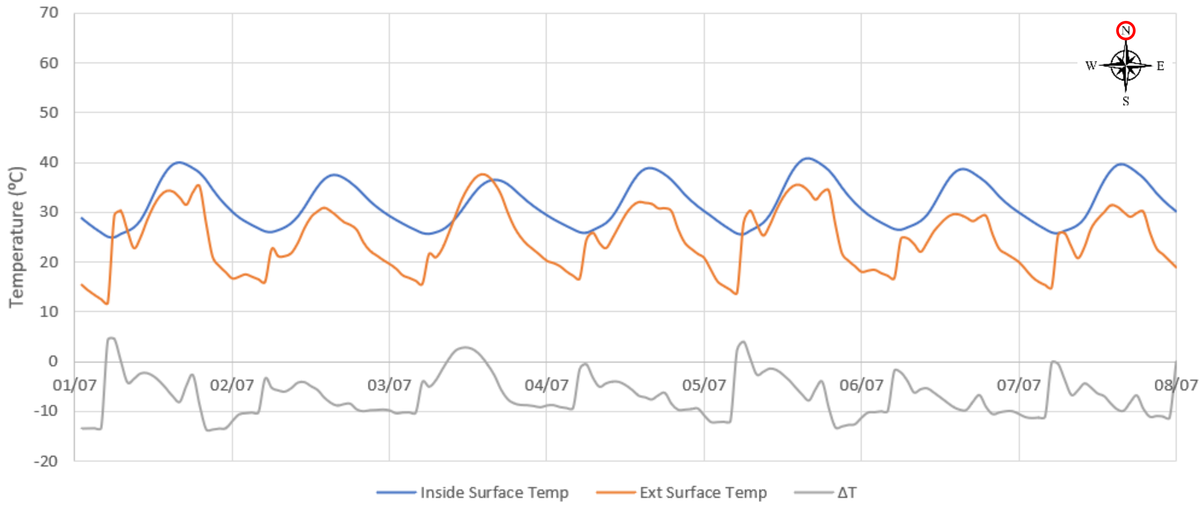


Fig. 45 - External and internal surface temperatures and difference between them, without shading, for Porto and for the wall North-oriented.

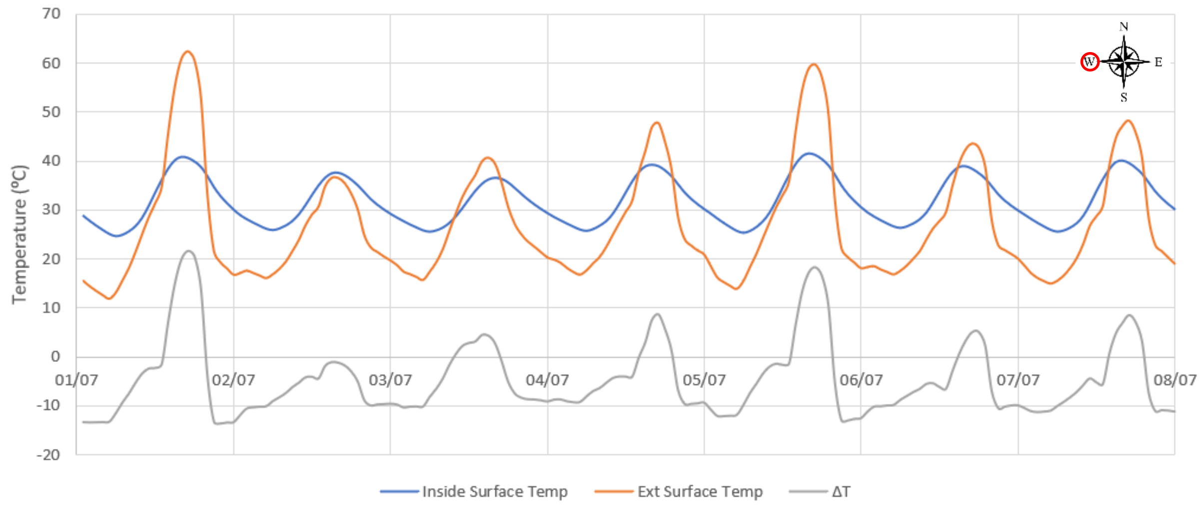


Fig. 46 - External and internal surface temperatures and difference between them, without shading, for Porto and for the wall West-oriented.

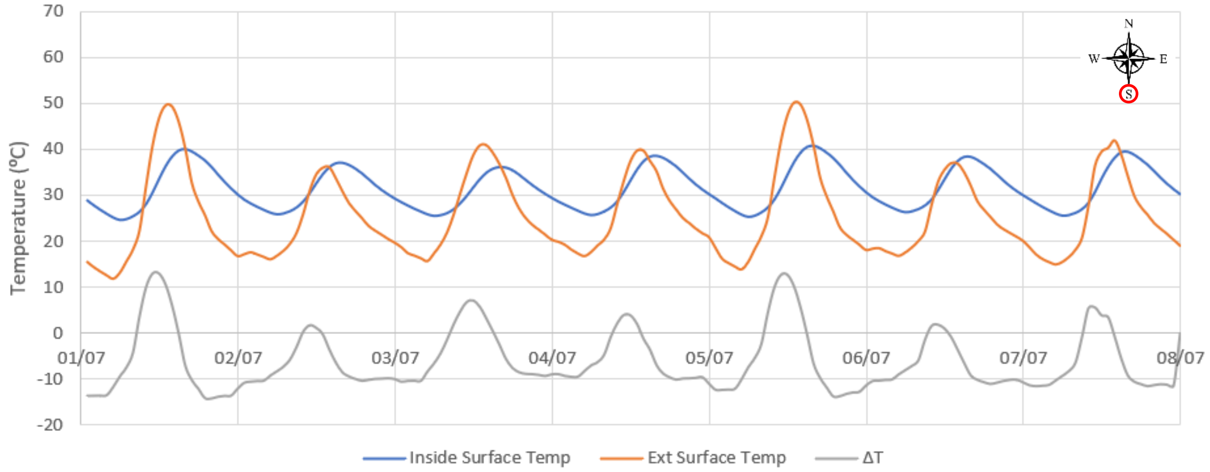


Fig. 47 - External and internal surface temperatures and difference between them, without shading, for Porto and for the wall South-oriented.

6.2.2. Porto, with shading

Fig. 48 to Fig. 51 show external and internal surface temperatures and the difference between them, for a building with external shading on glazed openings, located in Porto and for the walls oriented to the four cardinal points.

Looking at the results with the use of an exterior shading device, it is notable that the South-oriented and North-oriented façades are the ones with higher area with negative values, being the most interesting ones to implement a DTIS. The following graphs represent 168 hourly results for each orientation. The South-oriented façade has 118h when heat is being released through the façade, and the North-oriented façade has 122h. This way, it would be interesting to have a DTIS at the North-oriented façade in about 72% of the simulated time. For the façade South-oriented, this percentage decreases to 70%. The percentages for the East-oriented and West-oriented façades are 58% and 65%, respectively.

Comparing these values to the ones obtained without the shading system it is observable that the percentage of interesting time of the DTIS use is lower, decreasing the heat flux between both environments. In fact, the percentage of the north-oriented façade decreased in about 23%, the East-oriented in 18%, the West-oriented in 18%, and 13% for the South-oriented façade, for Porto. Then, the orientation can have an important impact and the DTIS can be thought differently to each orientation.

This way, it is possible to conclude that, in order to decrease overheating and provide thermal comfort to building users, the system under study can be a good strategy, enabling the heat release through the building envelope during around 13%-23% of the time, when an exterior shading system is activated for Porto.

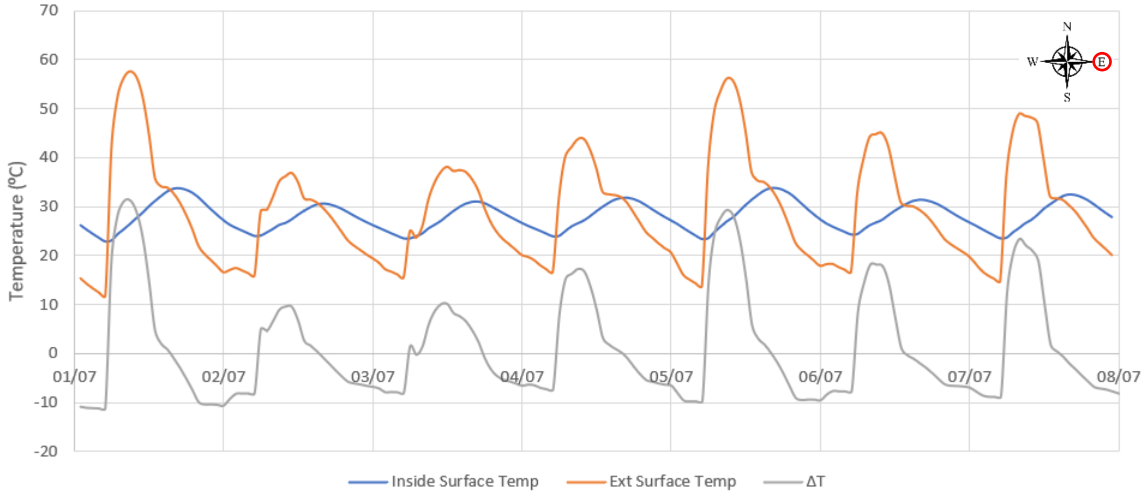


Fig. 48 - External and internal surface temperatures and difference between them, with shading, for Porto and for the wall East-oriented.

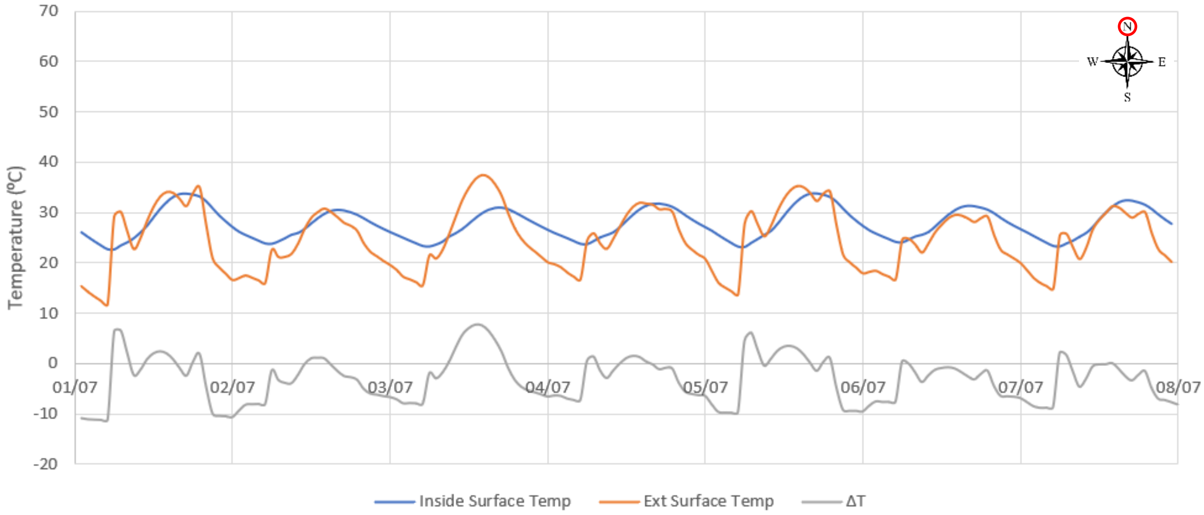


Fig. 49 - External and internal surface temperatures and difference between them, with shading, for Porto and for the wall North-oriented.

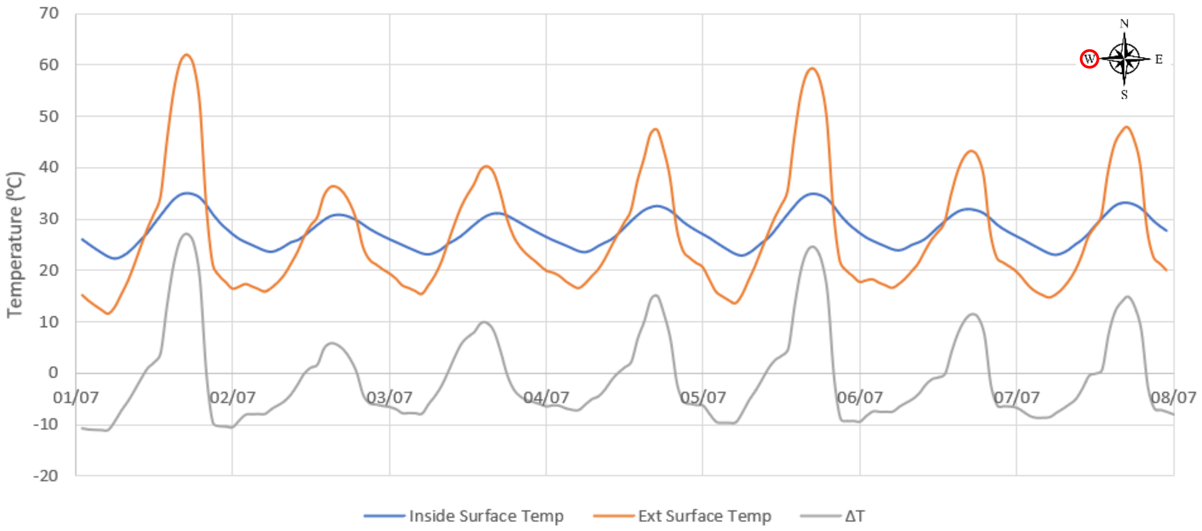


Fig. 50 - External and internal surface temperatures and difference between them, with shading, for Porto and for the wall West-oriented.

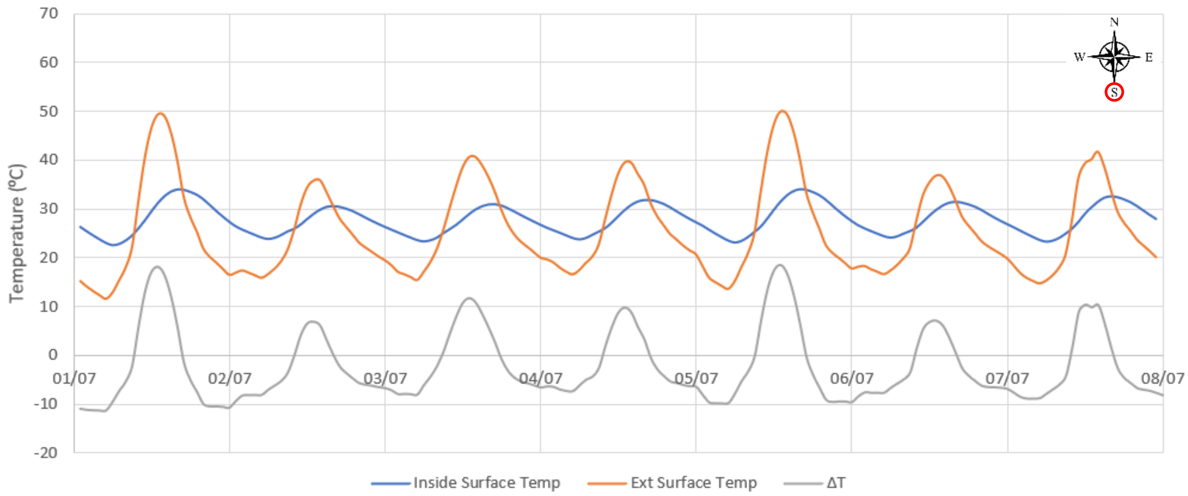


Fig. 51 - External and internal surface temperatures and difference between them, with shading, for Porto and for the wall South-oriented.

6.3. Discussion of the results

Table 17 to Table 19 show the assessment of the simulations' outputs in the form of discomfort performance indicators presented in 6.1. (Equation 10 to 13), by orientation and by location. All indicators were calculated with (Ext) and without (No) the use of a shading system.

Table 17 - Discomfort performance indicators, by wall orientation, for the first week of July (168 hours), in Porto.

	E		N		W		S	
	No	Ext	No	Ext	No	Ext	No	Ext
I (0ºC)	119	79	156	93	132	68	134	77
I (5ºC)	107	56	118	45	104	45	115	56
I (ΔT)	1096	480	1192	447	1049	392	1183	480
I (T disc)	167	126	167	126	167	126	167	126

Table 18 - Discomfort performance indicators, by wall orientation, for the first week of July (168 hours), in Faro.

	E		N		W		S	
	No	Ext	No	Ext	No	Ext	No	Ext
I (0ºC)	116	81	152	102	123	68	127	75
I (5ºC)	101	49	110	43	91	44	105	50
I (ΔT)	978	453	1086	444	925	391	1022	455
I (T disc)	155	120	155	120	155	120	155	120

Table 19 - Discomfort performance indicators, by wall orientation, for the first week of July (168 hours), in Bragança.

	E		N		W		S	
	No	Ext	No	Ext	No	Ext	No	Ext
I (0ºC)	109	71	141	72	111	69	117	77
I (5ºC)	89	42	82	39	79	42	95	43
I (ΔT)	828	343	884	324	781	332	881	371
I (T disc)	150	129	150	129	150	129	150	129

Looking at the Indicator I (T disc), the number of hours with thermal discomfort by overheating (Θ_o > 25ºC) is assessed, being different with and without shading. This indicator doesn't depend on surface temperature as it is based on the operative temperature (Θ_o) inside the building. In Porto, without shading, 99% of the hours simulated are hours with discomfort by overheating, as confirmed in Fig. 52. With shading this number decreases to 75%. In Faro, 92% and 71% of the hours simulated are hours with discomfort by overheating, without and with an exterior shading respectively. For Bragança the percentage of time with discomfort by overheating without a shading system is 89% and with an exterior shading is 77%. Porto, in the first week of July, presents the highest number of hours with discomfort by overheating, followed by Faro and Bragança, when no shading is used. However, when an exterior shading device is used, Bragança is the most discomfortable location, followed by Porto and Faro, Fig. 52.

The graph in Fig. 52 shows the relation between the global number of hours with discomfort by overheating, the sum of the negative superficial differences and the number of hours when having a DTIS would be more useful. The green line shows the simulated period, i.e. 168h.

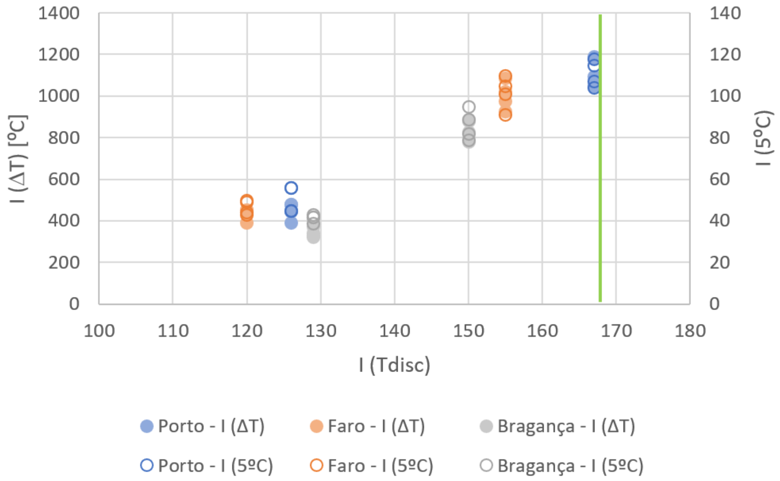


Fig. 52 - Relation between the discomfort performance indicators I (5ºC), I (ΔT) and I (T disc) for Porto Faro and Bragança, and for all façade orientations, with and without shading.

Indicator I (0ºC) and Indicator I (5ºC) both represent the number of hours when it would be beneficial to have a DTIS on the façade. The second indicator is used because it represents the periods when more intense heat flux is mobilized. It is, then, understandable that Indicator I (5ºC) has lower values when comparing with the first indicator. However, the indicators do not follow the same tendency, when compared by orientation, location, and shading systems. For example, without shading, Indicator I (0ºC), for Bragança, presents the highest number of hours when it is interesting to have a DTIS for the North-oriented façade and the lowest for the East-oriented, but Indicator I (5ºC) has the highest values for the South-oriented façade and the lowest for the façade facing West.

For Porto and Faro, Indicator I (5ºC) has the highest value for the North-oriented façade, of 70% and 65%, respectively, and the lowest for West-oriented façade, of 27% and 25%, respectively. In Bragança, Indicator I (5ºC) has the highest value of 56% for the façade facing South and lowest of 23% for the North-oriented façade.

This way, analysing Indicator I (5ºC), without the use of an exterior shading system, the percentages of time when it is interesting to have a DTIS on the envelope goes from 46%, in Bragança, to 70%, in Porto. With shading systems, the percentage of time decreases to from 23%, in Bragança, to 33%, in Porto. The results show that, by using exterior shading devices, there are less hours where the use of a high U-value is interesting. This is because, with the use of an exterior shading system, the temperatures inside the building decreases, having less discomfort by overheating, and less negative differences of superficial temperatures between the exterior and the interior. Then, the use of a shading system decreases the interesting period in around 50%. Porto is the location with higher interest percentages and Bragança with lower interest percentages.

Indicator I (ΔT) translates the potential heat flux between the interior and the exterior environment, when this flux is interesting. The values are higher without a shading system as the temperature differences between indoor and outdoor surfaces are higher in a situation of overheating (as operative temperatures increases) and when the flux is from inside to outside.

Without the use of a shading system, the North-oriented façade have higher values for this indicator, in Porto, Faro and Bragança, with values of 1192ºC, 1086ºC, and 884ºC, respectively. The lowest values are for the wall oriented to West with values of 1049ºC, 925ºC, 781ºC, respectively for Porto, Faro and Bragança.

With the use of an exterior shading system, the South-oriented façade have higher values for Indicator I (ΔT), in Porto, Faro and Bragança, with values of 480ºC, 455ºC, and 371ºC, respectively. For Porto and Faro, the West-oriented façade presents the lowest values of 392ºC and 391ºC, respectively. In Bragança, it happens for the North-oriented façade with 324ºC.

This way, Porto is the location with higher interest for the implementation of a DTIS, because more heat flux from inside to outside when overheating exists can be guaranteed. This shows that this type of systems are also interesting in mild climates. Moreover, the use of a shading device restricts the heat flux and the decreases the usefulness of a DTIS.

6.4. IMPACT OF THE TIME STEP

To evaluate if the time step of the simulation has some impact on the assessment of thermal discomfort, it was done a simulation that provided sub-hourly results (every 15 minutes) for a building located in Porto and, considering the North façade, because it is the orientation that results in higher values of discomfort. In Fig. 53 it is possible to observe the difference between the results simulated using an hourly time step and a sub-hourly of 15 minutes time step, for the first two days of July. It can be seen that the results are similar, showing that changing the simulation to a smaller time interval do not deliver more reliable result.

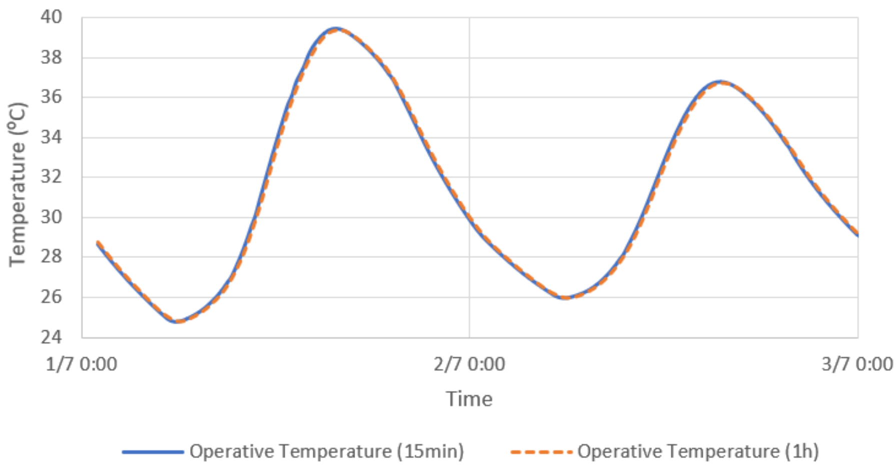


Fig. 53 - Influence of the time step on the results of the simulation.

In Table 20 are shown the results for the four discomfort performance indicators, for the glazed windows with and without the use of shading devices.

Table 20 – Discomfort performance indicators for Porto, by orientation, for a 15min time step of the simulation (672 quarters of hour).

Porto	I (0ºC)	I (5ºC)	I (ΔT)	I (T disc)
No	624	463	4763	665
Ext	376	188	1803	510

By looking to the values in Table 20, in Porto without shading, 99% of the hours simulated are hours with discomfort by overheating and with shading it decreases to 76%. Without shading, 69% of the hours simulated are hours with discomfort by overheating, and with shading this value decreases to 28%. These values are similar to the ones resulting from the hourly simulation. Therefore, it is not necessary to do a simulation with more time steps in order to get reliable results.

7
CONCLUSIONS

7.1. MAIN FINDINGS

Adaptive façades, through the ability of changing the building envelope characteristics, provide numerous benefits, including maintaining indoor temperatures at user comfort levels, economic gains associated with reduced heating and cooling needs of buildings, and lower environmental impacts associated with reduced energy consumption. This capability, however, is difficult to grant on structures due to its complexity and lack of standardised evaluation procedures. Developing and implementing an adaptive façade is challenging, because it includes a system that allows it to adjust to the outer environment conditions based on the interior demands. There are a lot of different categories and typologies of adaptive façades with different purposes. This dissertation focused on the dynamic thermal insulation systems (DTIS), that are an example of adaptive façades. These systems permit the control of the heat transfer through the envelope by varying between a state of insulation and a state of conduction.

This study allowed to broaden the knowledge about an innovative construction system, a dynamic thermal insulation system, by making an assessment and optimization of the impact of a DTIS on indoor thermal comfort.

With this dissertation it was possible to conclude that:

- The use of shading system plays a determinant role in maintaining interior temperatures between the limits of comfort, reducing around 3ºC per discomfort hour and around 35% of the discomfortable simulated hours;
- The use of an external shading system has a higher impact than the use of an internal shading system, reducing the severity of discomfort almost 56% and the percentage of time with discomfort about 43%;
- The use of a dynamic U-value can be effective on mitigating the overheating. Without shading, a U-value of 1,0 W/(m^2.ºC) is always beneficial to decrease the percentage of hours with discomfort by overheating, reaching a maximum reduction of 27%, and a maximum reduction of severity of 18%, when comparing with a U-value of 0,35 W/(m^2.ºC);
- A DTIS implemented in a HM building has greater impact than in a LM building;
- The orientation can have an important impact and the DTIS can be thought differently to each orientation;
- The DTIS can be beneficial to the performance of the building, being a good strategy to mitigate overheating. The high U-value is beneficial during around 46%-70% of the hours, when no shading system exists, and around 23%-33% when there is an exterior shading device;

- With the use of an exterior shading system, the relevance of having a DTIS in the façade decreases around 50%. This occurs because the overall period of discomfort decreases;
- This DTIS are also interesting in mild climates;
- The results simulated hourly and sub-hourly are approximately equal. Then, it is not necessary to do simulations with more time steps in order to get reliable results.

In fact, in general it can be concluded that a dynamic thermal insulation system can be a good strategy for the mitigation of overheating. As a limitation of this research, all the conclusions must be validated by further simulations in which a dynamic U-value is considered.

7.2. Future Developments

More study in this area is required for adaptable façades to be reliably implemented in common structures in the future. This way, it is possible to suggest some future developments, in order to deepen this study and the results obtained, namely:

- Do more detailed and dynamic simulations, with a dynamic U-value under certain restrictions in order to get more reliable results;
- To use a more complex building case study, with higher volume, glazing windows in various orientations and different interior compartments;
- To test a DTIS prototype in a laboratory and then to develop and study a prototype *in situ*, considering not only the thermal requirements but also all the requirements that a building façade have to accomplish.

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