Characterization of the potential of building climatization for dynamic management of electricity demand

Mariana Alves Vieira

Master's Dissertation

Supervisor from FEUP: Prof. Vítor Manuel da Silva Leal

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Master's In mechanical engineering

July 2022

"Success consists of going from failure to failure without loss of enthusiasm"

Winston Churchill

Abstract

Population growth and technological development have led to an increase in primary energy consumption. As we know, much of the energy used still comes from fossil fuels, which causes climate change that, not only affects ecosystems but also the economy and human health. To respond to environmental adversities and the availability of resources, energy distribution has evolved to use as many renewable resources as possible to produce electricity. However, a problem related to the use of renewable energy sources is their intermittent nature, so economically harnessing the power grids will require the use of load flexibility. Buildings are one of the largest contributors to global primary energy consumption, therefore, these can be part of the answer to the future of energy networks. Particularly HVAC systems, which represent a large part of the energy demand in buildings and may allow flexible management, i.e., enabling their temporary interruption without significantly harming the comfort of the occupants.

So, this works aims to characterize the potential of buildings for shedding electrical loads for heating a building, without harming the comfort of its users, based on their level of useful thermal mass and the time during which the HVAC systems are turned off.

The first step was to develop two reference models with 14 m² and different building constructions, one with high thermal inertia and other with low thermal inertia. For each of these models, two different cases were simulated, one with windows and other without windows. In addition to these changes, the values of the internal gains were also modified. The interest of these simulations was to study the evolution of the indoor thermal conditions, in particular the interior temperature of the room, for the coldest day of the year and for the coldest month during the morning and evening periods. The models were built in OpenStudio software using EnergyPlus as a calculation technique.

During the development of the models mentioned in the previous paragraph it was found that the results were not as expected. So, to understand the results, another model was developed, where the building solution of the room with low thermal inertia was kept and thermal mass was added to the interior of the building, throughout furniture, to achieve a value equal to that obtained for the building with high thermal inertia of the previous model.

The results obtained with this second approach kept being unusual. It was found that during the coldest day, the time it took for the indoor temperature to decrease during the morning period was about 30 to 45 minutes, which is not in accordance with what would be expected. In addition, it was observed that, in some cases, the temperature decreased faster for the room with high thermal inertia. This abnormality was reported to the expert's community that use and develop OpenStudio and EnergyPlus, for further assessment of the software.

To complement the study, a comparison was made between the case without windows and the case with windows. As expected, it was concluded that for the second one, the indoor temperature fell more quickly. The effect of the building's internal loads was also studied, and it was noticed that an increase in the internal loads increased the time it took for the temperature to decrease, as expected.

Although the results were inconclusive, with this work it was possible to understand that modifying the thermal mass of the buildings it is possible to find a solution that allows turning off the air conditioning system during a period where it is not possible to use renewable energy sources, getting the indoor thermal conditions to decrease at a gentle pace so as not to significantly harm the comfort of the occupants.

Key Words: Demand-side management; Load shedding; OpenSudio

Resumo

O aumento da população e o desenvolvimento tecnológico têm levado a um maior consumo de energia primária. Como se sabe, grande parte da energia utilizada provém ainda de combustíveis fósseis, o que origina alterações climáticas que afetam não só os ecossistemas como também a economia e a saúde humana. Com vista a responder às adversidades ambientais e à disponibilidade de recursos, a distribuição de energia tem evoluído no sentido de utilizar o máximo de recursos renováveis para produzir eletricidade. No entanto, um problema que se prende com a utilização das fontes de energia renováveis deve-se à sua natureza intermitente, assim, o aproveitamento económico das redes elétricas implicará o recurso à flexibilidade de cargas. Os edifícios são um dos maiores contribuidores para o consumo de energia primária a nível global, portanto, estes podem ser vistos como a resposta para o futuro das redes de energia. Nomeadamente os sistemas de climatização, que representam uma grande parte da procura de energia num edifício e podem permitir uma gestão flexível, isto é, possibilitam a sua interrupção temporariamente sem prejudicar significativamente o conforto dos ocupantes.

Assim, com este trabalho pretende-se caracterizar o potencial dos edifícios para deslastre de cargas elétricas para aquecimento de um edifício, sem prejudicar significativamente o conforto dos seus utilizadores, com base no seu nível de massa térmica útil e no tempo durante o qual os sistemas de climatização serão desligados.

O primeiro passo, consistiu no desenvolvimento de dois modelos de referência com 14 m² e diferentes soluções construtivas, um com inércia térmica elevada e outro com inércia térmica baixa. Para cada um destes modelos simularam-se dois casos distintos, um com janelas e outro sem janelas. Adicionalmente a estas alterações, também se alteraram os valores dos ganhos internos interiores. O interesse destas simulações foi estudar a evolução das condições térmicas interiores, nomeadamente a temperatura interior do compartimento, para o dia mais frio do ano e para o mês mais frio durante o período da manhã e de noite. Os modelos foram construídos no software OpenStudio utilizando o EnergyPlus como técnica de cálculo.

Durante o desenvolvimento dos modelos referidos no parágrafo anterior verificou-se que os resultados não estavam de acordo com o esperado. Assim, com vista a perceber os resultados construiu-se um outro modelo, onde se manteve a solução construtiva do compartimento com baixa inércia térmica e adicionou-se massa térmica ao interior do edifício, recorrendo-se à adição de mobília, para alcançar um valor igual ao obtido para o edifício com inércia térmica elevada do modelo anterior.

Os resultados obtidos com recurso a esta segunda abordagem também não estiveram de acordo com o esperado. Verificou-se que para o dia mais frio, o tempo que a temperatura interior demorava a decair durante o período da manhã era cerca de 30 a 45 minutos, o que não está de acordo com a normalidade. Para além disto, observou-se que, em alguns casos, a temperatura decrescia mais rapidamente para o compartimento com elevada inércia térmica. Esta anormalidade foi comunicada à comunidade de peritos que utilizam e desenvolvem o OpenStudio e EnergyPlus, para uma avaliação mais aprofundada do software.

De forma complementar o estudo, efetuou-se uma comparação entre o caso sem janelas e o caso com janelas e conclui-se que para este último, como era de esperar a temperatura interior caiu mais rapidamente. Estudou-se ainda o efeito das cargas internas no edifício e percebeu-se que um aumento das cargas internas aumentava o tempo que a temperatura demorava a decair.

Apesar dos resultados se terem verificado inconclusivos, o desenvolvimento deste trabalho possibilitou compreender que modificando a massa térmica dos edifícios é possível encontrar uma solução que permite desligar o sistema de climatização durante um período onde não seja possível utilizar fontes de energia renováveis, conseguindo com que as condições térmicas interiores decresçam a um ritmo suave de forma a não prejudicar significativamente o conforto dos ocupantes.

Palavras-chave: Gestão dinâmica da procura; Limitação de carga; OpenStudio

Acknowledgement

The process of writing this dissertation was challenging, enabling for both professional and personal development. This would not have been possible without the ongoing help and guidance of the following people. To them, I owe my genuine appreciation for it.

First, I would like to thank to my supervisor, Professor Vítor Leal, for his guidance, availability, and support in the development of this dissertation.

Additionally, my warm and heartfelt thanks go to my family who have always supported me in all my decisions and situations throughout my journey. Especially to my sister who always stood by me and taught me to grow, making me the person I am today. All my accomplishments and success are because they believed in me. To my family, I give everything.

Finally, I would just like to say thank you to my friends, who have continuously accompanied me throughout these five years, with them I lived unforgettable moments. A special thanks to Rafaela Castro for constantly listening to me and talk things out, for proofreading over and over, and for the constant motivation.

Mariana Vieira

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Project background and motivation

Energy is required to run our basic day-to-day services and companies, such as lighting, heating and/or cooling, transportation, and industry. The use of energy has increased exponentially following the growth in both population and technology. However, most of the energy comes from fossil fuels rather than renewable energies, which, among other questions, leads to a serious problem of global warming.

Climatic change is defined as a shift in climate patterns caused by human activity that exceeds natural climate variability, due to the emissions of greenhouse gases into our atmosphere. The combustion of fossil fuels, industrial activities, animal rearing and waste treatment are the most contributors to these emissions. The effects of these emissions directly affect ecosystems, economy, society, and human health, causing substantial damages in global temperatures and sea levels.

As a consequence of lowering prices, legislation encouraging renewable energy and concerns about greenhouse gas emissions from fossil fuels generators, renewable energy has expanded substantially across the world. However, renewable energy generation presents a major issue their intermittent nature. For example, the availability of wind energy depends on whether there is wind or not.

To achieve carbon neutrality in 2050 and in line with the EU targets, the National Integrated Energy and Climate Plan (PNEC) in Portugal set some goals and objectives for 2030. These goals are [1]:

- Decreasing greenhouse gas emissions: -45 % to -55 %;
- Energy efficiency: 35 %;
- Renewable energy sources: 47 %;
- Renewable in transports: 20 % ;
- Electricity interconnections: 15 %.

Buildings are a major contributor to global energy consumption, greenhouse gases emissions and global warming. According to Eurostat, energy consumed in residential, commercial, and administrative buildings, accounted for more than 40 % of world energy consumption, with domestic buildings accounting 27 % of total final energy utilization. Estimates show that, without proper action, global warming detrimental influence will increase by 1,8 percent each year until 2050, implying that future consumption and emissions would be worse than they are now [2]. Heating, cooling, and ventilation systems influence cannot be ignored, as they account for more than 20 % of the energy consumed in buildings. Energy consumption in the domestic sector, represents around 18 % of the total final energy consumption in Portugal[3] [4] .

Buildings can be friendly to future energy grids. For example, many buildings will be both consumers and producers of energy (heat or electricity), named as “prosumers”. Buildings storage potential can be either in the structure itself (thermal storage) or in specific units, such as hot water tanks or batteries. Both buildings and occupants can manage their energy consumption to meet a flexible energy demand [5].

To implement systems that increase the efficiency of buildings and reduce their ecological footprint, the concept of Zero-energy buildings (ZEBs) emerged, these types of structures are becoming more prevalent in energy grids. As discussed earlier, the renewable energy supply is fluctuating. So, the focus on ZEBs plays an important role, since when it comes to responding to energy supply, this solution has a lot of options. Low-energy buildings, such as ZEBs are gaining popularity as a way of reducing carbon emissions. ZEBs are described as structures that create as least as much energy as they consume each year, which is often accomplished through energy saving measures and integration with the local renewable energy sources system. On a shorter time, scale, however, ZEBs are zero-balanced because to the intermittency and unpredictability of n-site renewable energy output, resulting in a mismatch between building energy demand and on-site energy supply [6].

Portugal stablished measures to help buildings decarbonize, including laws, certifications, and financial incentives for upgrades. All new buildings owned or occupied by a public entity must meet virtually zero-energy building (NZEB) regulations as of January 2019. Beginning in January 2021, any newly constructed or extensively remodeled private buildings with a floor area of more than 1000 square meters must meet NZEB regulations [7].

1.2 Objectives and structure of the thesis

The main objective of this dissertation is to study the potential of buildings to switch off electrical loads for heating, without significantly impairing the comfort of all occupants, as a function of their useful thermal mass level, both in the amount and in the time duration in which the systems can be switched off.

In the first chapter, the theme is contextualized in the current world and Portuguese energy situation, as far as buildings are concerned, presenting the motivations that led to this dissertation. The next chapter presents the literature review of demand-side management, which defines important strategies for energy management in buildings. This chapter also presents and discusses some of the thermal simulation models used to model buildings.

Chapter three starts with the development of two models that allowed to simulate the evolution of the indoor temperature of a compartment with 14 m² with and without windows. For each model, two building construction solutions were defined, with different thermal characteristics, to allow the evaluation of the decrease of indoor temperature in two scenarios with different thermal inertias: low and high. Given the unusualness of the results obtained, another model was elaborated, where the thermal inertia of the low thermal inertia building was increased by increasing the thermal mass inside the space, through the addition of furniture. In this section, the steps taken in the software used to model both reference rooms are also described.

Chapter four contains the results obtained and its analysis for the different simulations performed for each of the models.

Finally, the last chapter presents the main conclusions drawn from this work and some proposals for future work.

2 Literature Review

2.1 Demand-Side Management and Flexible Loads

The increasing use of renewable energies has led to the appearance of new challenges in the power grid including demand changes, intermittent energy supply, price instability, and new peak/valley hours. The mismatch between renewable energy supplies and electricity demand, might result in reduced revenues and increase curtailment risks, preventing further growth in the renewable energy sector [8].

For any electrical company, maintaining a balance between supply and demand is a big challenge. Intermittent patterns in energy usage can result in peak loads, which can originate power outages and raise generating and distribution costs. The term "peak energy demand" describes the time of the day when loads or the electricity distribution system is at the highest. During the summer, this tends to happen between 04:00 and 08:00 p.m., when high outside temperatures coincide with people coming home from work, and during the winter this is seen around 5:00 and 9:00 a.m. and after 05:00 p.m., resulting in both scenarios in a high domestic climatization [9].

Peak load management solutions are an attempt to minimize or shift end-user energy consumption during peak load periods, avoiding these additional costs. Thereby, peak load management may be used to reduce energy demand-supply imbalances and improve the power system flexibility and reliability by making better use of the existing generation and distribution resources. Peak load control solutions have the potential to assist grid operators, end users, and the environment by decreasing the total demand on the energy system, so end users can reduce their electricity bills while enhancing power supply reliability by shifting loads from peak to off-peak hours or shedding loads during peak periods. Furthermore, peak load strategies can reduce carbon emissions by avoiding the increased fuel consumption. As a result, employing a peak load control plan also contributes to the long-term sustainability of energy supplies [10].

Demand-side management (DSM) defines the design and execution of techniques that adjust energy consumption patterns to minimize energy usage, peak loads, and energy costs. According to differing durations, DSM can be categorized into short-term (0,5 - 2h) and intermediate-term (2h or more) and is a procedure that combines the following three key domains to develop a successful demand response strategy [10]:

1- Demand response (DR), which consists in DR programs that help promoting the benefits of energy reduction, DR strategies such as load shifting, load shedding and onsite generation, and DR techniques that focus on the different building systems like heating, ventilation, and air conditioning (HVAC) or lighting and plug loads;
2- Load forecasting, which uses physical, regression or machine learning models to anticipate building electrical needs based on old data;
3- The influence of DR methods on occupants' thermal and visual comfort, as well as indoor air quality, is assessed in the indoor environment.

As we can see in the following illustration, end-users must establish a DR strategy that takes use of the DR programs available. Peak loads may be forecasted using a load forecasting model that enable end-users to forecast peak loads in terms of time and magnitude. Thus, end-users can choose an appropriate set of DR approaches to lower their peak loads based on the model projections and see the impact on the occupant comfort.

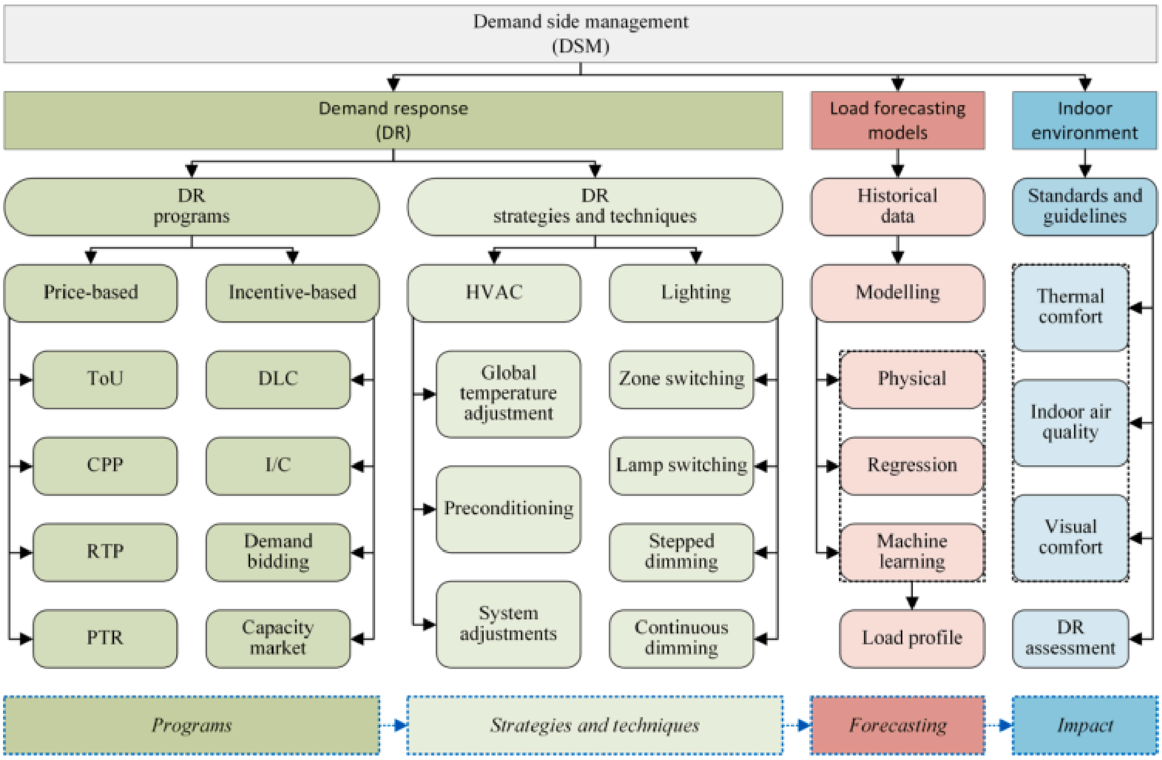

Figure 1: Relationship between the three key domains: demand response, load forecasting models and indoor environment with demand-side management [10].

According to "United States Department of Energy" DR definition as the "change in the electric use by demand side resources from their normal consumption patterns in response to changes in the electricity prices". Hence, the principal purpose of a DR program is to increase energy efficiency and grid security by moving certain on-peak demands to off-peak.

Commonly, DR strategies are classified as load shifting techniques that aim to shift power demand from peak periods to off-peak periods by utilizing energy storage, load shedding strategies which intent is to limit power demand during peak load periods and onsite generation procedures which typically use renewable generation during peak load hours. The HVAC systems, lights and plug loads can all benefit from load shedding and load shifting solutions [11].

Building DR measures are crucial for improving energy flexibility. By that, the concept of demand flexibility (DF) appears and is defined by the U.S Department of Energy as the "capability of distributed energy resources to adjust a building's load profile across different timescales" [12].

Thereby, DSM, DR, or flexible control of flexible resources are common approaches to obtaining energy flexibility. So, building energy flexibility is known as the building capacity to control its demand and generation while considering local weather conditions, user demands, and energy network requirements, as defined by International Energy Agency. Buildings with on-site renewable energy generation may not only participate in demand response, but also manage energy demand and generation flexibility according on their own requirements, such as expanding on-site energy generation self-consumption [6].

Many quantification approaches for energy flexibility have been developed based on distinct management applications, control objectives, and flexibility resources. These approaches assess energy flexibility from a few perspectives, including power generation, energy consumption, energy storage efficiency, CO_2 emissions, electric costs, load matching and grid interaction.

In some articles, the methodology proposed to quantify the demand flexibility can be divided into direct and indirect. Direct techniques try to estimate the demand flexibility potential of a building in a bottom-up way for specified flexibility event, moreover, indirect methods try to estimate the demand flexibility potential to shift energy usage from high to low price periods. Hence, some authors offered a straightforward technique based on set-point modulation for quantifying the flexibility potentials and efficiency of various architectural archetypes, emerging the concept of downward flexibility events for heating or cooling devices, which decrease or increase, respectively, the setpoint, and contrariwise upward flexibility events which increase or decrease. Thus, the demand flexibility potentials and flexibility supply efficiencies can be calculated by comparing the power curve achieved for the base scenario and those obtained for the downward and upward flexibility events [12].

Residential buildings have a variety of energy demands, including space cooling and/or heating and hot water, which are mostly met by different household electric equipment including air conditioners and electric water heaters. Other domestic electric equipment also leads to electricity demands. Building load profiles may be modified to give flexibility through demand-side management measures. To reduce or increase power consumption the temperature set-points of thermostatically controlled loads can be adapted, i.e., can be shed, shifted, and modulated. In the same way the operation time of domestic electric equipment can be shifted to off-peak periods. To increase the demand flexibility in buildings some measures were discussed, including renewable energy generation, heating, ventilation, and air conditioning (HVAC) systems, energy storage, building thermal mass, moveable electrical appliances, and occupant behaviors [13].

2.1.1 *Thermal Comfort*

Thermal comfort plays an essential role when it comes to the potential of structural storage, since imposes acceptable limits to temperature fluctuations when a building is occupied. The expression *thermal comfort* is defined as “that condition of mind which expresses satisfaction with the thermal environment” [14].

With global development, emerged the need to introduce and accept the use of mechanical means to provide desired comfortable temperature for building user, leading to a massive energy consumption. It is estimated that about a third of the fossil fuels are consumed in buildings. Along these lines, thermal comfort boundaries are restrictions that is assist building physicist to determine how much a structure should be heated or cooled. Predicting this temperature range is difficult since it is influenced by environmental and personal factors as well as cultural influences [15].

Thermal comfort is important, since it aims to provide satisfactory conditions for users, while controlling the energy consumption and offer and set standards. Hence, the main objectives are control over the internal environment by people, improve indoor air quality, save energy, and reduce negative environmental impacts, reducing the production of CO_2 [16].

When determining the requirements for thermal comfort, there are six key considerations that must be made [17]:

- Metabolic rate;
- Clothing insulation;
- Air temperature;
- Radiant temperature;
- Air speed;
- Humidity.

The thermal comfort temperature is not constant. In Portugal, as in several countries, energy regulations indicate constant temperature values for obtaining reference comfort conditions.

According to the REH, during the cooling season the minimum comfort temperature is equal to 18º and during the cooling season the maximum is equal to 25 ºC [18].

As an alternative to this static and defensive approach, an adaptive approach can also be used, in which indoor temperature ranges are admitted as a function of external conditions, to reduce the energy spent on air conditioning without compromising the thermal comfort of the occupants. The ASHRAE 55-2010 standard describes an adaptive comfort model, applied to naturally conditioned buildings, where the occupants can adapt their clothing according to indoor or outdoor conditions. Thus, as we can see in the graph in figure 2, this model, represented by a linear relationship, indicates a comfort range of the operative comfort temperature as a function of the average monthly outside temperature for two comfort classes that correspond to 80% and 90% occupant satisfaction. The comfort zone corresponding to 80% acceptability, has a bandwidth of ± 3.5 °C around the operative comfort temperature and applies to existing and rehabilitated buildings. The comfort zone corresponding to 90% acceptability has a bandwidth of ± 2.5 °C around the operative comfort temperature and applies to new buildings where high levels of comfort are required [19].

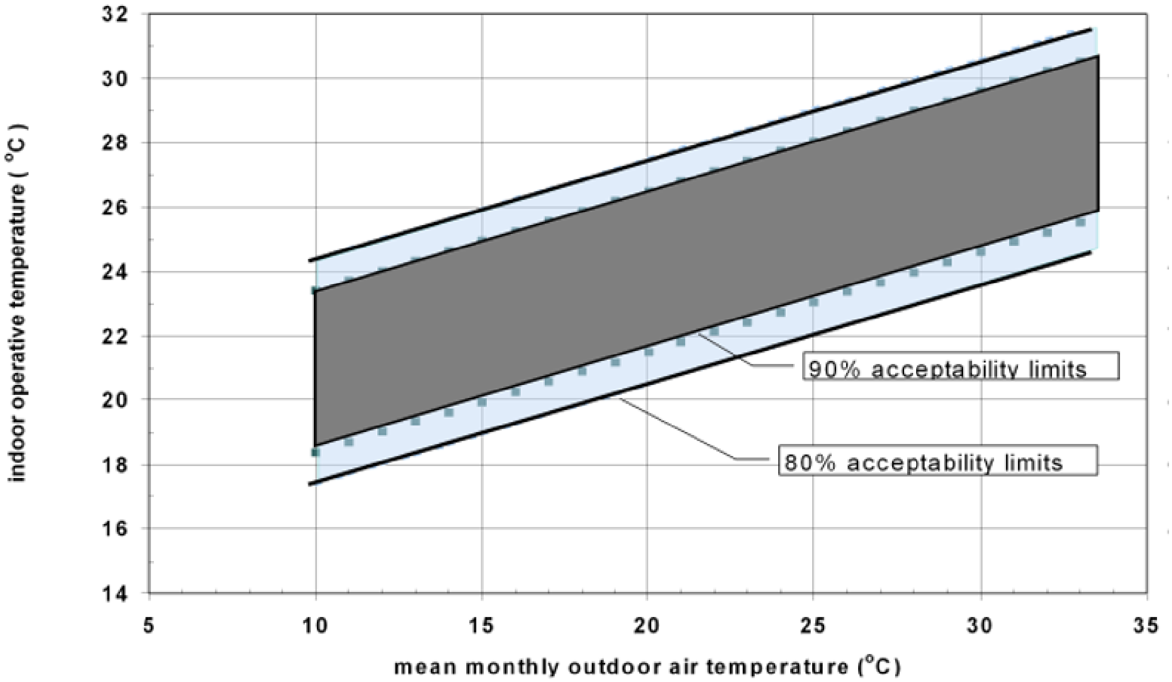

Figure 2: Acceptable operative temperature ranges for naturally conditioned spaces [19]

This adaptive method is only valid for cases where the average monthly outside temperature varies between 10 ºC and 33.5 ºC, the buildings have natural ventilation and the thermal environment of the rooms is regulated by the occupants, i.e. by opening or closing the glass windows, the buildings may have a heating system, but the model is not valid when the system is working, they cannot have any mechanical cooling system, and the users must have an activity level between 1.0 and 1.3 meters and freely adapt their clothing to the indoor and outdoor environmental conditions [19].

There are two techniques to incorporating thermal comfort limitations into DSM control strategies. The first one includes thermal comfort into the cost function used to compute temperature setpoints, so the cost of deviations from the comfort temperature should be determined and compared to the cost of heating energy. The second approach imposes boundary restrictions to the optimization issue using thermal comfort criteria, which are then used to determine the amount of temperature change that may be tolerated [20].

2.1.2 HVAC systems

Load shifting, load shedding and load modulation, can help utility systems meet demand flexibility. The adaptability of central air conditioners, electric water heater, wet appliances, refrigerators, and lights has been the focus on some research. As we can see in the following illustration, HVAC systems, due to their high consumption and automation level present a high demand response capability in buildings [13].

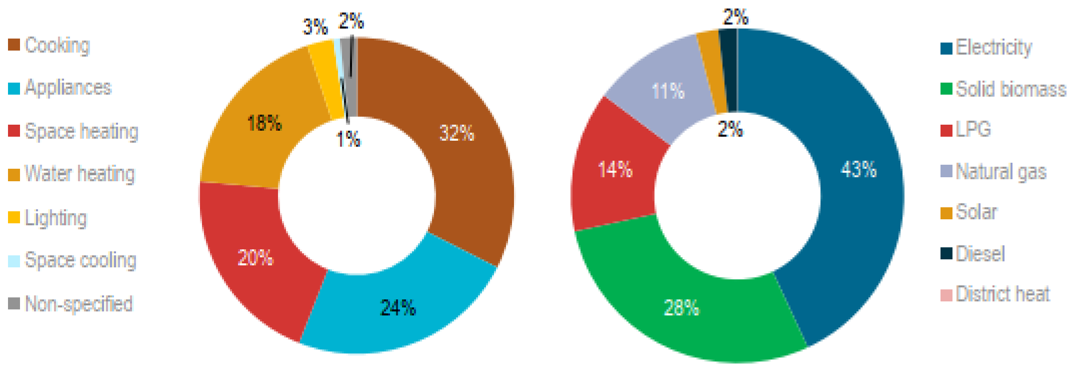

Figure 3: Energy demand in residential buildings in Portugal by use (2018) and by fuel (2019) [7]

HVAC related DR solutions should be able to achieve the load reduction requirement while ensuring an adequate interior environment. These strategies can target buildings zones or HVAC equipment, depending on the equipment utilized and the degree of automation in the control network. There are some techniques that target the HVAC system by adjusting operation setpoints, restricting or lowering the speed of fans or pumps, limiting modulating valve positions, or reducing equipment capacity [10].

Generally, the HVAC systems represent around 40% of the total building energy consumption and they contribute considerably to peak demand in the summer and winter. In order to ensure that the occupants have the best comfort conditions, productivity, and health, they normally function intermittently during both seasons, so that, they keep the indoor temperature, humidity, and CO_2 concentration within the appropriate limits. Temperature set-point resetting, and pre-cooling or pre-heating are common ways to provide demand flexibility using the HVAC system. Also, HVAC systems can store cooling/heating capacity in the thermal mass of the building and then release it during peak demand periods to provide load shifting and shedding services for utility grids [13].

As we can see, heating, ventilation and air-conditioning systems are the perfect application for demand side management schemes due to their ability of improve energy demand flexibility. When compared to other electrical loads, such as lights, HVAC systems offer more flexibility without jeopardizing equipment performances, therefore, time shifts in operation or modulation can be accomplished with minimum discomfort loss. The power demand of HVAC systems is very adjustable, it can be managed either by variable setpoints or directly modulating the absorbed power of the system to follow a specified limit or curve [4].

2.1.3 Thermal mass of a building

It is evident that reducing the amount of energy necessary to heat and cold every building is a crucial goal. For that, engineers and architects are including energy efficiency measures at various stages of the design process, whether for a new or a renovation project.

Beyond thermal comfort, is expected that the thermal performance of the building envelope influences the structural storage capacity. The ability of a building's thermal mass to retain energy as either sensible or latent heat impacts its ability to control internal temperatures, power consumption, and occupant comfort. Thermal mass is important when it comes to transient cooling or heating [21].

To use this demand-side management potential, the inherent thermal mass of a building may be actively employed as structural thermal storage capacity. So, there are some intelligent management techniques that can be employed to maximize the usage of thermal storage in buildings by takin into account the building's thermal properties as well as time of use and energy costs. The utilization of structural storage may result in higher transmission and ventilation losses due to the activation of the thermal mass demands for temperature changes. As a result, it's reasonable to assume that well-insulated structures have a better structural storage efficiency [20].

Demand side management potential is determined by the availability of thermal mass, by that this availability is not only function of the material properties but is also influenced by the shape of the building, the disposal of the thermal mass, the interaction between the heating and cooling systems and the thermal mass. Hence, building thermal mass as a potential and a cost-effective way to achieve energy flexibility among the different flexibility resources, since it is naturally incorporated in structures [20].

There are three main factors that contribute to a structure's overall thermal mass: thermal zone envelope, like the exterior walls and ceiling, the indoor air volume, and finally the interior thermal mass, for example furniture and interior walls. The thermal inertia of heavy materials like the envelop and interior mass is significant. The amount of building insulation influences the modulation of heating power, for example, for a low insulated building, the impact is restricted in duration and intensity, on the contrary, well insulated structures have a long-lasting impact [11].

Therefore, building thermal mass has been identified as a valuable buffer for zone temperature management when combined with other measures. For instance, building thermal inertia was presented as a demand restriction of HVAC loads. Buildings have the natural capacity to give short-term energy flexibility due to the thermal inertia of interior thermal mass, without needing major adjustments or additional investment [22].

2.2 Building simulation

There are models for describing the behavior of heat transfer systems based on solving physical equations and models for deducing this behavior based on statistical functions. Causes and effects are not included in strictly statistical models; only inputs and outputs are considered. Models based on physical equations, on the other hand, grow in agility. Physical equations, on the other hand, are developed using conservation principles to replicate the true behavior of systems.

There are a few techniques for establishing models of flexible loads in domestic buildings, depending on the detail that is required the models can be organized into three groups [13]:

- White-box: Are mainly physical models, which explain physical processes in detail. For that they utilize multiple mathematical equations based on basic principles, such as Newton's laws, equations of heat transfer, and others, allowing the investigation of a variety of situations with different boundary conditions that are difficult to replicate in real buildings. Usually, they are widely used to model thermostatically controlled loads such as HVAC, electric water heaters and refrigerators. Normally, these models take time to develop and calibrate, and in most cases, users utilize commercial tools such as TRNYS, EnergyPlus and Modelica. In short, white box models are those that represent the thermal behavior of structures when it comes to building thermal performance modeling, expressing, with detail, the dynamic physical processes of flexible loads. Heat and moisture transport equations are utilized at various scales to implement this strategy.

- Black-box: When the internal structure of a model is unknown, it is referred to as a black-box model. This type of modeling starts by measuring the system's inputs and outputs, establishing a mathematical relationship between them, without knowing the internal physical processes in detail. To create these models, it can be used machine learning techniques, such as artificial neuro networks and support vector machines;

- Grey-box: This kind of models come as a combination of the two models explained above. In this case, some components can be modeled starting with first principles, while others must be fitted empirically applying the observed data. Thus, they are easier to scale up and simplify physical processes and increase computing efficiency without sacrificing accuracy. An example of a grey-box model is the resistance-capacitance (RC) models.

When dealing with individual flexible loads, white-box models are the best to evaluate building demand flexibility and optimize schedules. For flexibility quantification at aggregation levels and optimizing scheduling with multiple flexible loads, grey-box models are the most used. Finally, for assessing the flexibility potential at aggregated levels, black-box models are considered [23].

Design tools have been built by reducing the complexity of the underlying system equations to reduce the computational load and the resulting input burden placed on the user. To represent each conceivable energy flow path and their interactions, a mathematical model is created. Simulation, in this sense, is an attempt to replicate reality [24].

Building energy simulation software can provide the user with energy usage and energy demand data when given a complete set of building characteristics. This complete set of building characteristics includes building geometry, HVAC systems, internal loads, wall construction, and weather conditions. The figure 4 represents the generic workflow of a building energy simulation software.

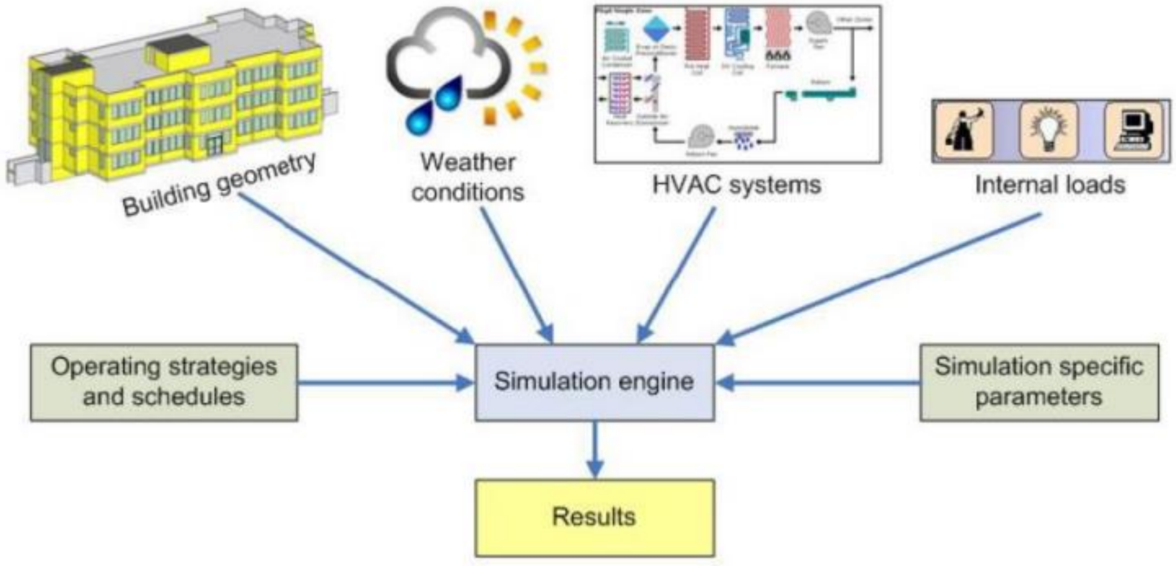

Figure 4: Energy Simulation Parameters [25]

Building energy modeling uses a range of software combinations to create a comprehensive energy model, since it usually necessitates a simple modeling software and a supporting calculation software. OpenStudio® is a cross-platform software suite that includes a set of tools for modeling whole buildings in EnergyPlus employing radiance in an advanced daylight analysis. It also operates on a variety of systems that make community development, extension, and commercial sector adoption easier. OpenStudio SketchUp Plug-in, OpenStudio

Application, ResultsViewer, and the Parametric Analysis Tool are among the graphical apps. The main features of OpenStudio include: building modeling using a SketchUp plug-in to construct custom geometry; the possibility of assigning space types, thermal zones, building loads, and HVAC systems; capability to assign construction types to walls, floors, and ceilings; importing geometry from other sources via gbXML, SSD, IDF, or IFC file formats; running simulations using multiple opensource measures that give access to different custom-made outputs such as HVAC sizing and heating/cooling load outputs; parametric analysis for energy performance and lifecycle costing analyses [26–28].

3 Thermal Model

Throughout this chapter, the thermal model used to evaluate the evolution of the interior thermal conditions of the room under study is described. To introduce this chapter a brief description of heat transfer processes in a building is given. Then, the models that will be implemented in the OpenStudio software are described, as well as the steps used in the program to build the models.

3.1 Fundamentals - Heat Transfer in Buildings

Heat transfer is the process of transferring thermal energy due to a difference in temperatures between two substances. The heat transfer mechanisms existing in a building can be of three types, illustrated in the figure 1: conduction, convection, and thermal radiation.

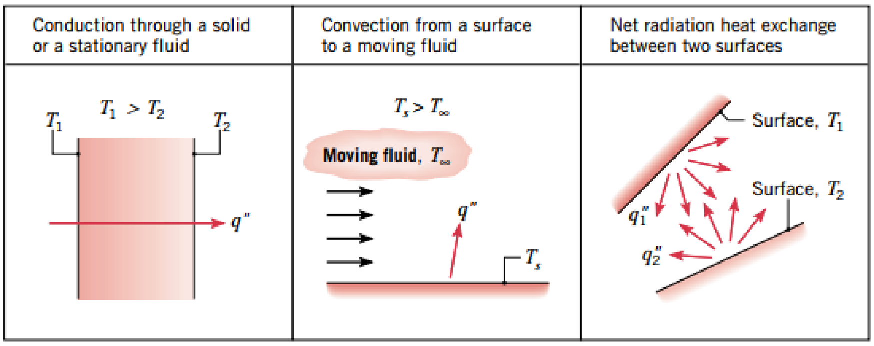

Figure 5: Heat transfer processes [29]

In buildings, the main factors that give rise to the heat transfer mechanisms are related to the conditions of the external environment, mainly weather conditions, ambient temperature, and incidence of solar radiation. The difference between indoor and outdoor temperatures causes heat exchanges by conduction in the elements of the building envelope and convection due to the renewal of interior air that can occur intentionally, through the windows or ventilation systems of the building, or in an unwanted way, named infiltrations, due to imperfections in the construction. In addition to the two mechanisms discussed, there is also heat exchange by radiation that corresponds to the incidence of solar radiation. This mechanism can occur directly, when the radiation is transmitted to the interior through the glazing elements, or indirectly, where part of the incident solar radiation is absorbed by the opaque elements of the envelope. The internal gains of a domestic building are related to lighting, occupants (depending on their activity), and appliances. They are divided into sensible and latent heat exchange gains. Therefore, it is possible to define that the main processes present in the thermal balance of the interior conditions of a building are heat exchanges by the building envelope, interior air renewals, gains due to solar radiation, internal gains, and heat exchanges due to the air conditioning system [30].

From a thermal point of view a building should be seen as a modifier of the climate. Typically, the construction of a building serves as a filter and/or buffer, in addition to this the ability to impose a bias on ambient temperature by providing heating or cooling. The heating or cooling load is determined by several factors, including the choice of ambient temperature, measures of severity of ambient as it affects the comfort conditions, and exchange of heat by conduction and ventilation between the indoor and outdoor environments.

Commonly, a building is seen has a group of sub-systems or thermal zones, each one composed of elements with different conductivities and thermal inertia. By that, the heat load entry rate and the activated thermal efficiency are the most important factors in a building's transient thermal behavior. In practice, the ability of a building to store energy is determined by its effective thermal capacitance, which describes the total of the specific heat capacity of the building parts, which might chance significantly [31].

3.1 Test Room and Study Scenarios

Since the objective of this dissertation is to characterize the potential of buildings when electrical loads are deactivated for heating, according to their level of useful thermal mass, it has been chosen to simulate a small space, initially without windows or internal loads and then with two windows and a door, whose arrangement can be seen in figure 6, and without internal loads. This perspective considers an ideal scenario where it is possible to see the influence of the parameters set for heating in an HVAC system on the evolution of the indoor temperature of the space considered over a given time.

For both spaces (with and without windows), two variants with internal gains (occupancy, lighting, electric equipment) equal to 4 and 8 W/m², were also simulated.

The reference space considered designates a room with 14 m² (4 m x 3,5 m) of floor area and 3 m of height, with two exterior walls facing south and west, where the two windows, considered afterwards, were located, each with 2 m², a horizontal roof, two interior walls and an interior floor. In one of the interior walls was placed a door with 2 m². The interior walls were considered adiabatic, which in “OpenStudio” means that the heat is allowed to be stored in the wall but cannot transfer through the outer of the construction.

In the next figure we can see a schematic representation of both reference rooms (with and without windows, figure 6 and 7, respectively), used to simulate the load shedding episodes and the evolution of the indoor temperature. In table 1 it’s possible to see the main characteristics of both rooms and table 2 shows the size of the enveloping surfaces.

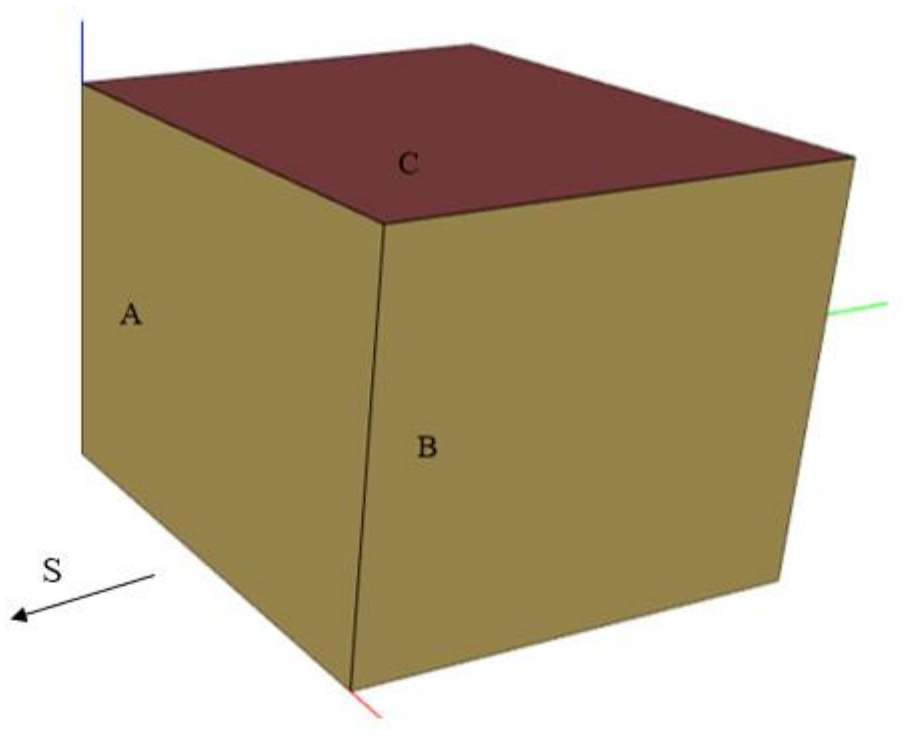

Figure 6: Schematic representation of the reference room without windows

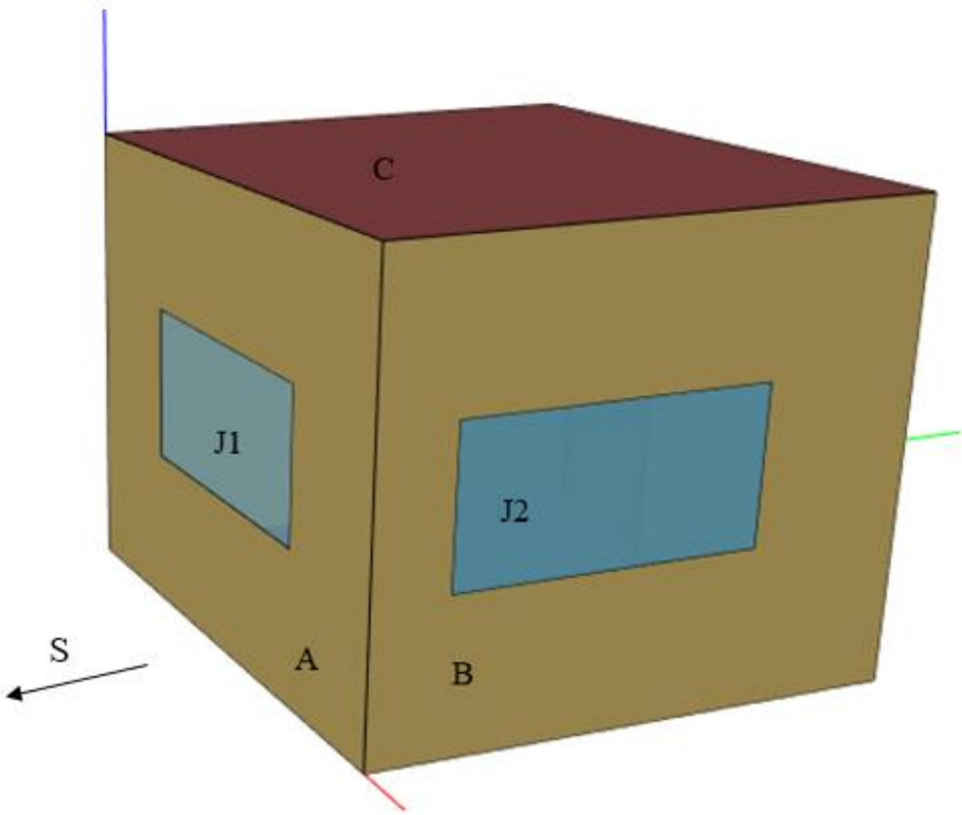

Figure 7: Schematic representation of the reference room with windows

Table 1: Main characteristics of the model

Parameter	*Value*	*Units*
Volume	42	m³
Floor Area	14	m²
Windows Size	2	m²
Internal Loads	0, 4 and 8	W/m²
Heating Set Point	18	˚C

Table 2: Description of the indoor and outdoor enclosure elements of the reference room

Elements Sizes		
Element	**Description**	**Total Area [m²]**
Exterior Walls	A	12
	B	10,5
Roof	C	14
Interior Walls	D	12
	E	10,5
Floor	F	14
Windows	J1	2
	J2	2
Door	P	2

3.1.1 Building Construction Solutions

The level of insulation of the building is expected to have a significant impact on energy flexibility, so in order to study the influence of the typology of the building on the interior temperature, two buildings with different thermal properties were modelled for each scenario (with and without windows): one with high density materials such as bricks and concrete to simulate a high thermal inertia building and another using low density material, such as plasterboard for a low thermal inertia building.

The high thermal inertia space was built with ceramic bricks and expanded polystyrene EPS insulation on the exterior, and this construction was based on a typical Portuguese building. For the exterior walls was considered a masonry cloth of 15 cm drilled ceramic brick with a 3 cm layer of expanded polystyrene EPS insulation on the outside and 2 cm of plaster cement on both sides. The interior walls were considered adiabatic, and they were made of a 11 cm masonry panel of ceramic brick and 2 cm plaster on both sides. The roof was made up of a 5 cm exterior protection inert, 3 cm of expanded polystyrene EPS insulation, a layer of cavernous concrete formwork with expanded clay with 5 cm, 15 cm of lightweight slab and finally 2 cm of plaster in the interior. The floor was built with 1 cm of oak wood, 4 cm of screed, 15 cm of lightweight slab, 3 cm of EPS insulation and 2 cm of plaster on the exterior.

For the low thermal inertia building solution, the configuration of the walls was like the one used in the high thermal inertia scenario. The main difference lies in the interior walls, where were used 1,8 cm of plasterboard on both exterior and interior sides and a 12 cm air gap in between. Also, the EPS insulation was placed on the inside of the structuring elements.

In both scenarios it was considered that the windows were built with colorless double glazing with 6 cm in the interior and 8 cm in the exterior and 18 cm of air in the middle space. The 2 m² door was made of wood with 3 cm of thickness.

The table 3 show the properties of the selected materials, and the table 4 the constructive solutions that were adopted in the high and low thermal inertia rooms.

Table 3: Material thermal and physical properties used in the room construction

Material	*Thermal Conductivity, k [W/(m.k)]*	*Volumetric Density, ρ [kg/m³]*	*Specific Heat, cp [J/(kg.K)]*
Plaster Cement	1.3	1900	837
Holed Ceramic Brick 15	0.38	800	936
Holed Ceramic Brick 11	0.41	900	936
Lightweight Slab (with form layer)	0.85	1320	965
Cavernous Concrete	0.25	700	1000
Inert	2	2000	500
Screed	1.3	1800	880
Plasterboard	0.25	750	1000
Wood Floor	0.27	750	2400
Expanded Polystyrene EPS Insulation	0,036	15	1210

Table 4: Building solutions for high thermal inertia and low thermal inertia variants

	High thermal inertia		***Low thermal inertia***	
Element	**Material**	**Thickness [m]**	**Material**	**Thickness [m]**
Exterior Wall (A, B)	Interior Plaster	0,02	Interior Plaster	0,02
	Ceramic Brick	0,15	EPS Insulation	0,03
	EPS Insulation	0,03	Ceramic Brick	0,15
	Exterior Plaster	0,02	Exterior Plaster	0,02
Interior Wall (D, E)	Plaster	0,02	Plasterboard	0,018
	Ceramic Brick	0,11	Air Gap	0,12
	Plaster	0,02	Plasterboard	0,018
Roof (C)	Exterior Protection (Inert)	0,05	Exterior Protection (Inert)	0,03
	EPS Insulation	0,03	Shape Layer	0,05
	Shape Layer	0,05	Light Slab	0,15
	Light Slab	0,15	EPS Insulation	0,03
	Interior Plaster	0,02	Interior Plaster	0,02
Floor (F)	Wood Floor	0,01	Wood Floor	0,01
	Screed	0,04	EPS Insulation	0,03
	Light Slab	0,15	Screed	0,04
	EPS Insulation	0,03	Light Slab	0,15
	Plaster	0,02	Plaster	0,02

3.1.2 Thermal Inertia

The interior thermal inertia (I_t) of a room, determinates the ability of a room to retain heat, due to the storage capacity and heat conduction of each of the building elements, and it can be calculated using the following expression:

$$I_t = \sum_i \frac{M_{si} \times r_i \times S_i}{A_p} \quad kg/m^2 \tag{1}$$

Where M_{si} is the useful surface mass of the building element i (kg/m^2), the r_i describe the M_{si} reduction factor and depends on the thermal resistance of the cladding element $((m^2.{}^\circ C)/W)$, the S_i represents the inner surface area of the element i (m^2), and finally the A_p that is the useful floor area (m^2).

The M_{si} results from the sum of the masses of each of the elements that compose the envelope, considering, for this purpose, only the elements that are located from the thermal insulation to the interior of the room. For each element, this parameter can only take a value up to 150 kg/m^2. The r_i was considered equal to 0,5 in the interior walls and 1 in the other elements.

Given the limits presented in the following table, the buildings were classified according to their thermal inertia value. The thermal inertia is divided into three categories, as shown in table 5.

The tables 6 and 7 show the thermal inertia classification (high and low) of the windowed room and tables 8 and 9 for the space without windows. As the tables also show, this classification was obtained based on the results of the thermal inertia calculation and the respective indicator for each building solution (I_t).

Table 5: Classification of the thermal inertia

Class of thermal inertia	I_t **[kg/m^2]**
Low	$I_t < 150$
Medium	$150 \leq I_t \leq 400$
High	$I_t < 400$

Table 6: Calculation of the thermal inertia for the high thermal inertia building solution with windows

Element	***S_i [m²]***	***M [kg/m²]***	***M_{si} [kg/m²]***	r_i	$M_{si} \times r_i \times S_i$
Exterior Wall, A	*10*	*158*	*150*	*1*	*1500*
Exterior Wall, B	*8,50*	*158*	*150*	*1*	*1275*
Roof, C	*14*	*271*	*150*	*1*	*2100*
Interior Wall, D	*10*	*87,5*	*87,5*	*0,50*	*437,5*
Interior Wall, E	*10,5*	*87,5*	*87,5*	*0,50*	*459,375*
Floor, F	*14*	*277,5*	*150*	*1*	*2100*
				Total [Kg]	*7871,88*
				I_t [kg/m²]	*562,277*
				Classification	*High*

$A_p = 14\ m^2$

Table 7: Calculation of the thermal inertia for the low thermal inertia building solution with windows

Element	S_i [m²]	M [kg/m²]	M_{si} [kg/m²]	r_i	$M_{si} \times r_i \times S_i$
Exterior Wall, A	10	38	38	1	380
Exterior Wall, B	8,50	46,94	46,94	1	399
Roof, C	14	38	38	1	532
Interior Wall, D	10	13,50	13,50	0,50	67,50
Interior Wall, E	10,5	13,50	13,50	0,50	70,88
Floor, F	14	7,50	7,50	1	105
				Total [Kg]	1625,25
$A_p = 14\ m^2$				**I_t [kg/m²]**	111,03
				Classification	Low

Table 8: Calculation of the thermal inertia for the high thermal inertia building solution without windows

Element	S_i [m²]	M [kg/m²]	M_{si} [kg/m²]	r_i	$M_{si} \times r_i \times S_i$
Exterior Wall, A	10	189,60	150	1	1500
Exterior Wall, B	8,5	195,18	150	1	1275
Roof, C	14	271	150	1	2100
Interior Wall, D	10	105	105	0,50	525
Interior Wall, E	10,50	87,5	87,5	0,50	459,38
Floor, F	14	277,5	150	1	2100
				Total [Kg]	7959,38
$A_p = 14\ m^2$				**I_t [kg/m²]**	568,53
				Classification	High

Table 9: Calculation of the thermal inertia for the low thermal inertia building solution without windows

Element	S_i [m²]	M [kg/m²]	M_{si} [kg/m²]	r_i	$M_{si} \times r_i \times S_i$
Exterior Wall, A	10	45,6	45,6	1	456
Exterior Wall, B	8,50	46,94	46,94	1	399
Roof, C	14	38	38	1	532
Interior Wall, D	10	16,20	16,20	0,50	81
Interior Wall, E	10,5	13,50	13,50	0,50	70,88
Floor, F	14	7,50	7,50	1	105
				Total [Kg]	1643,88
$A_p = 14\ m^2$				**I_t [kg/m²]**	117,42
				Classification	Low

3.1.3 Alternative modeling of the thermal mass

After analyzing the results obtained with the model presented so far, it was found that these values did not confirm what was expected, as shown in chapter 4. So, to understand the results, it was decided to assess an alternative approach, where the thermal mass was added as furniture instead of through the construction solution.

For this, to the low thermal inertia model, thermal mass was added to the interior of the space to increase the thermal inertia of the building in the same way achieved by changing the constructive solution. This way, a material was created, with the designation of "thermal mass", whose properties were: density equal to 1000 kg/m³, thickness of 1 m and area equal to 1 m², as shown in figure 8. Next, the total mass of this material was calculated and divided by the total floor area, obtaining the useful surface mass added through the internal thermal mass load. The difference between the useful superficial mass of the building with high thermal inertia and the one with low thermal inertia was calculated and divided by the value described above, as we can see in the following table. It was concluded that for increase the thermal inertia of the low thermal inertia room to match the one in the building with high thermal inertia, a multiplicative factor equal to 7 should be used.

Table 10: Calculation of the multiplicative factor

	Without Windows	*With Windows*	*Units*
Difference between HTI and LTI	490,6	497,0	kg/m²
Added useful surface mass	71,4		kg/m²
Multiplier	7,0	7,0	-

The following figures show the process used in OpenStudio to increase the thermal inertia of the low thermal inertia building, though furniture.

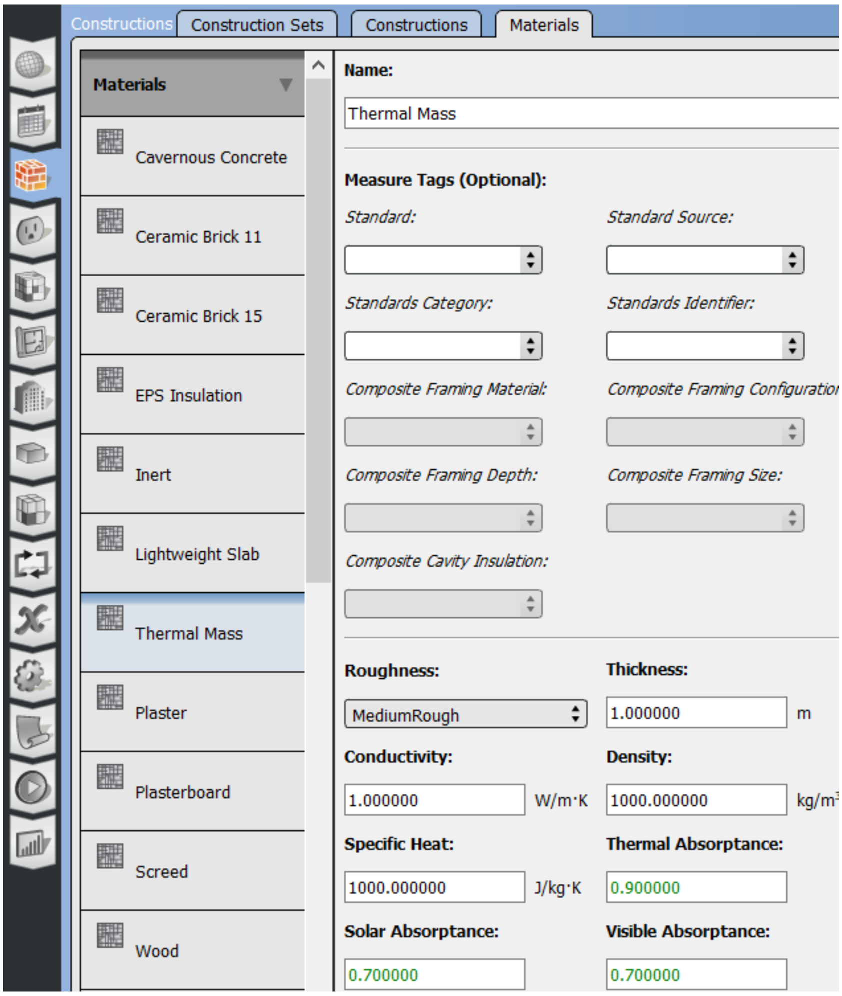

Figure 8: Creation of the "thermal mass" material

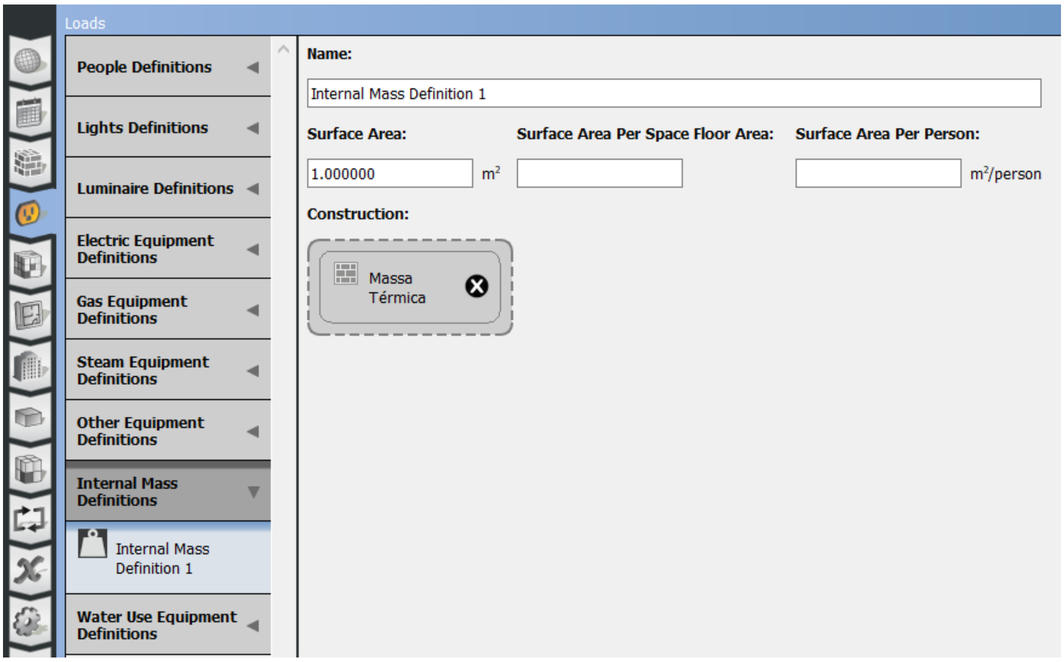

Figure 9: Creation of the internal mass load

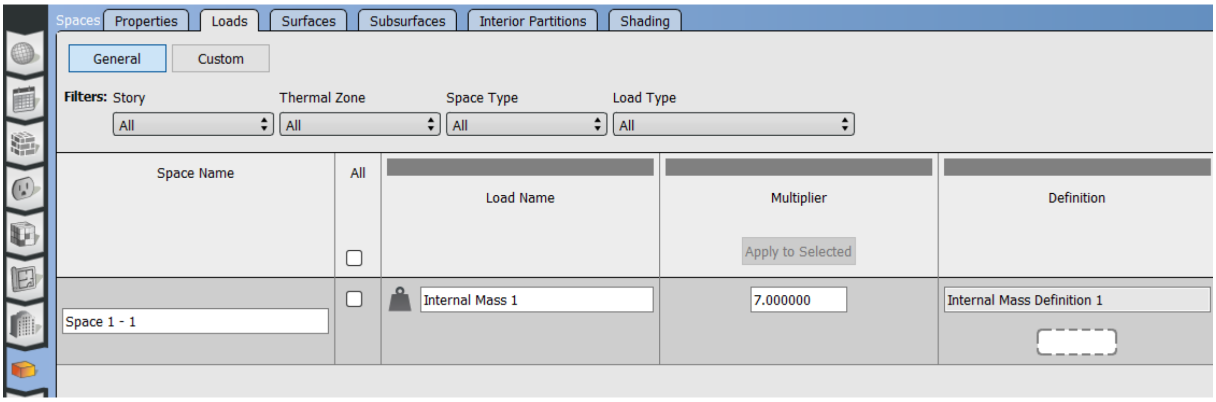

Figure 10: Addition of thermal mass to space through furniture

3.2 Software Inputs

This section describes the methodology used to model the reference rooms in EnergyPlus using the OpenStudio platform. Furthermore, the buildings were modeled using different construction solutions and internal loads.

3.2.1 Climate Data

Initially, data referring to environmental conditions outside the compartment under study were introduced. For this, climatic data referring to the city of Porto, obtained from the EnergyPlus Weather Data website, was used, which allowed exporting the data in the format recognized by the program.

Considering the objective of the work, the study focused on the months of January and February, with the purpose of evaluating the behavior of the proposed space in situations where outside temperatures were lower. For the monthly evaluation, the focus was on the period between January 17th and February 17th. These dates were chosen foreseeing some initialization problem.

Additionally, a study for the standard day, was also performed. For this, January 25th was considered, whose minimum outdoor air temperature has a value of 0 ºC, and the maximum is equal to 12.3 ºC.

The following figures show the profile of outdoor temperature and solar radiation for the standard day (figure 11) and for the focused month (figure 12).

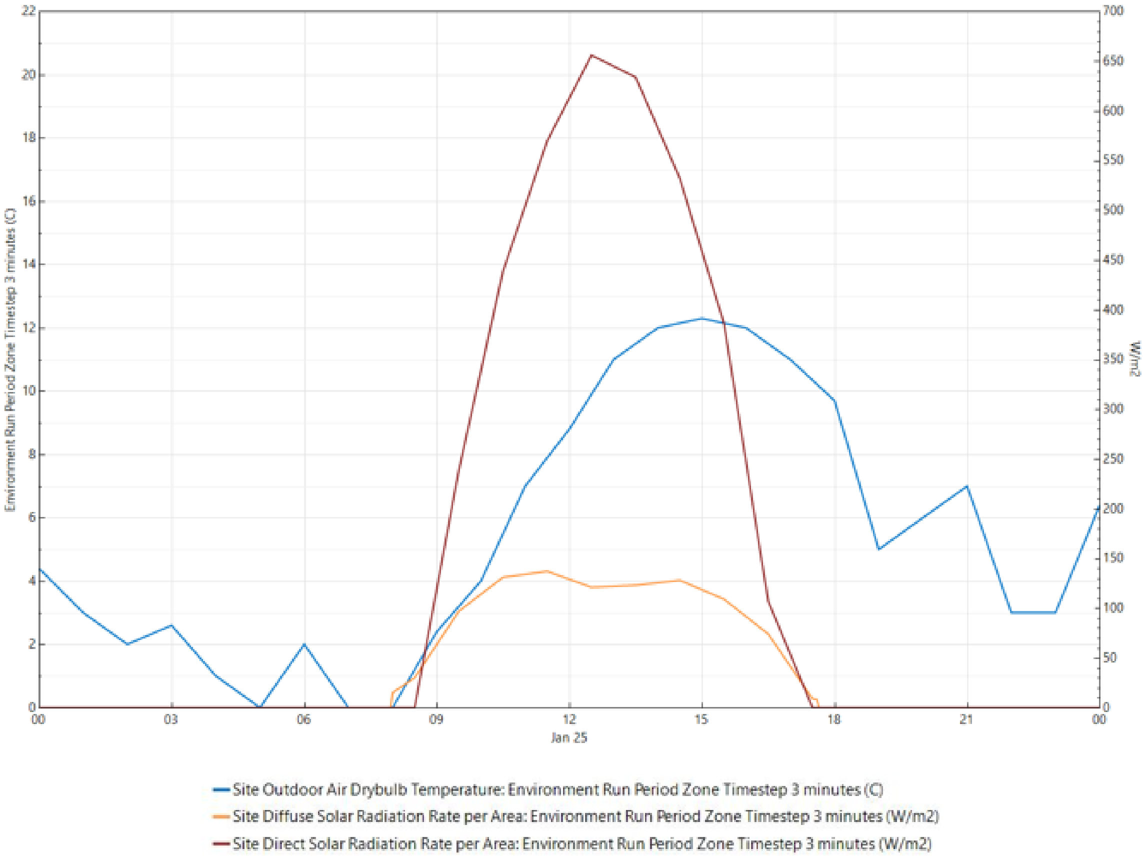

Figure 11: Outdoor temperature profile and global solar radiation for the focused heating season day

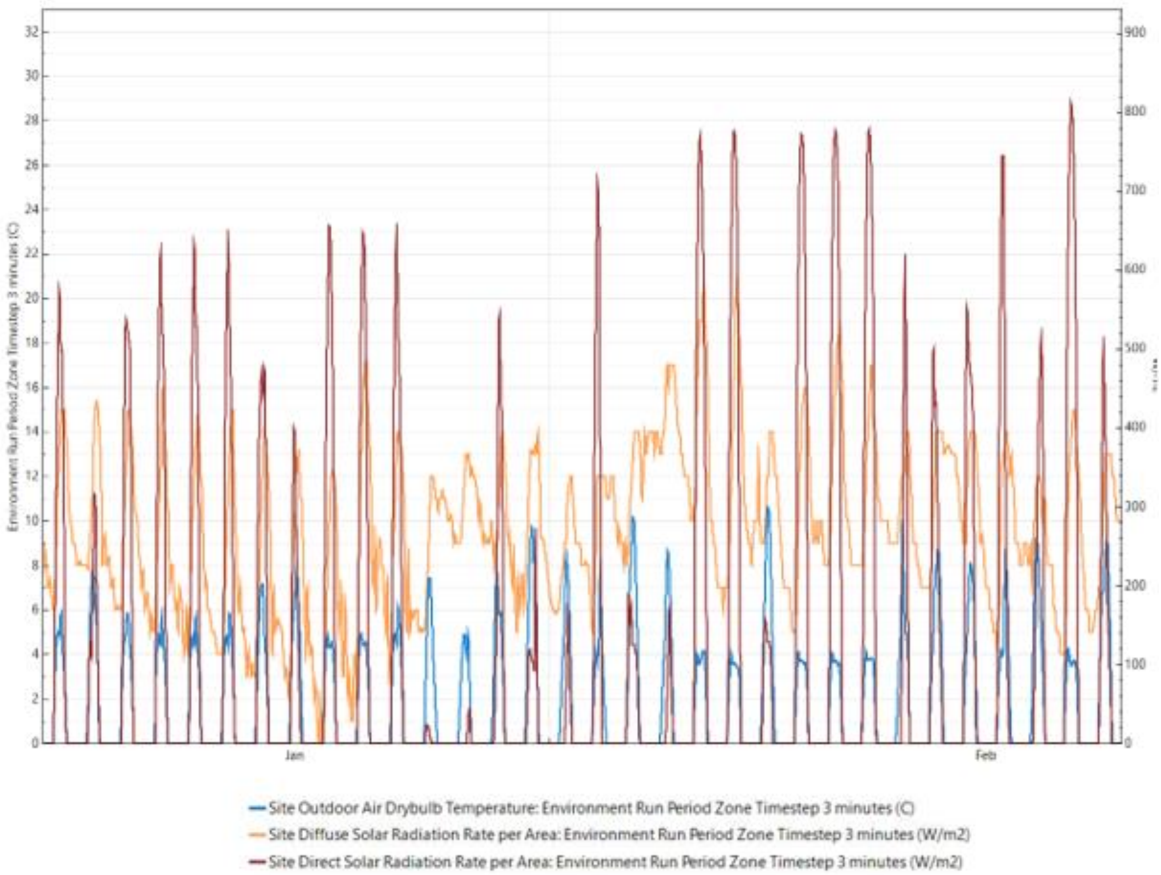

Figure 12: Outdoor temperature profile and global solar radiation for the focused heating month

3.2.2 Geometry and Materials

The construction of the external structure of the model was developed in the geometry interface. Here, the parameters of each surface, described in table 2, were determined, as well as the thermal zone corresponding to the room. Each surface was characterized according to its name, type (whether the surface is a ceiling or floor), constructive solution adopted, associated thermal zone and outside boundary conditions. At this point, was also defined the exposure to sunlight and air from external surfaces, as seen in the appendix A, figure A 1.

Initially, the materials that would be used in the construction set must been defined. For that the several materials were created for every structure, such as floor, roof, walls, windows, and doors. Therefore, the materials described in the table 3 have been added to the materials library. For each material was defined its thickness, conductivity, density, and specific heat, and for the thermal absorptance, solar absorptance and visible absorptance values were set automatically, as shown in the next figure.

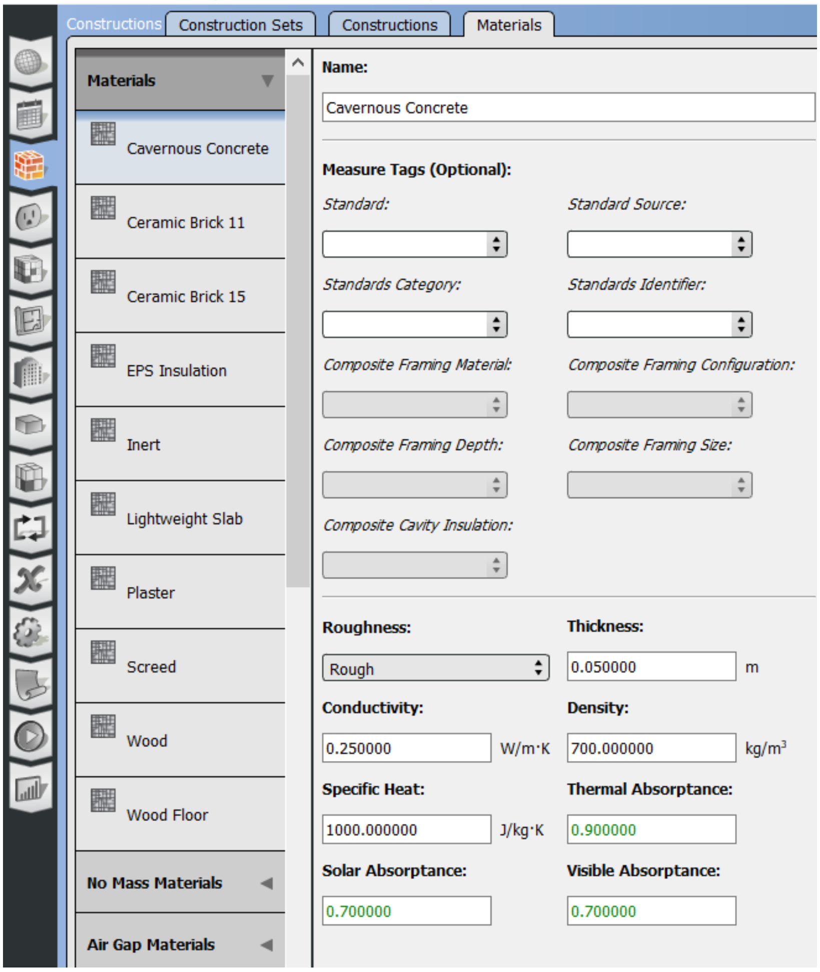

Figure 13: Creation of the surrounding materials

After all the materials were defined, they were placed in the order represented in the table 4, and the positions of each one in each surface was defined from the outside to the inside, as noted in the appendix A, figure A 2. Finally, the constructions were matched with the construction sets defined in the geometry.

3.2.3 Thermal loads and Schedules

Sub-hourly simulation of energy behavior of a building is one of the features of EnergyPlus programs, as been said in the introduction to the software. The software enables the design so a.m.-called Schedules that specify the building's purpose.

The heating schedule is a part of the control thermostat settings for the day. The main thermostat settings for heating mode were divided into four periods, as seen in figure 14:

- 00:00 – 08:00 a.m. at 22 ºC
- 08:00 a.m. – 02:00 p.m. at 18 ºC
- 02:00 p.m. – 07:00 p.m. at 22 ºC
- 07:00 p.m. – 00:00 at 18 ºC

A temperature equal to 22º was defined as the limit, to establish a comfortable range that would make it possible to turn off the air conditioning for a significant period of time, without the decay of the temperatures harming the comfort of the occupants.

The idea of the sudden drops in thermostat temperature at 08:00 a.m. and 07:00 p.m. was to allow the building to enter in a free temperature fluctuation mode ("free float"), without heating. This enables to observe the evolution of the temperature in the subsequent hours, as if a load interruption order had been received.

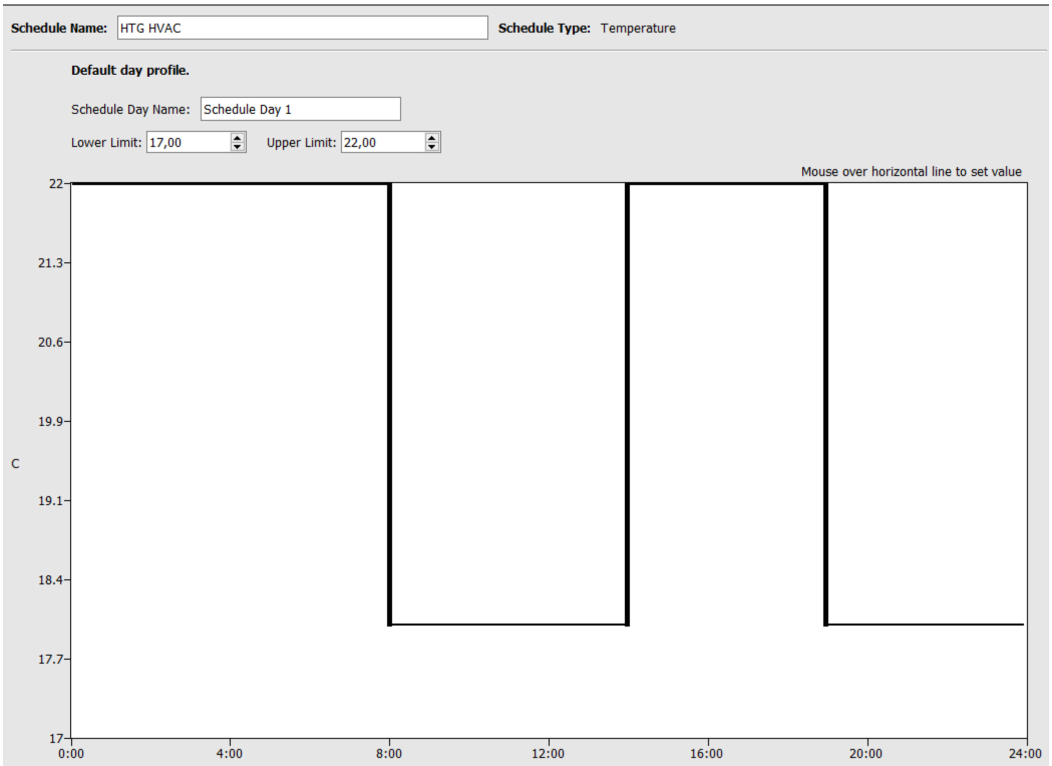

Figure 14: Heating HVAC schedule

Considering that the objective of this work was to study the way in which the temperature decreases during heating season, a temperature of 60º was defined in the cooling schedule, so that the HVAC system would never reach that value, and consequently did not cool down in that period. This enabled some slight overheating (e.g., due to solar gains) which could be beneficial.

All thermal gains that aren't produced from solar radiation or a heating system are referred to as internal gains. Occupancy, lighting, and electrical equipment all contribute to such thermal increases. In this case, were considered two scenarios: one with 4 W/m², and other one with 8 W/m², both always on.

3.2.4 HVAC system

To control the behavior of the thermal zone in the simulated room, a packaged rooftop heat pump was used. Each heat pump has a single speed direct expansion (DX) cooling coil, a single speed (DX) heating coil, an electric heating coil, a constant volume fan and a single duct constant volume air terminal, as shown in the next figure.

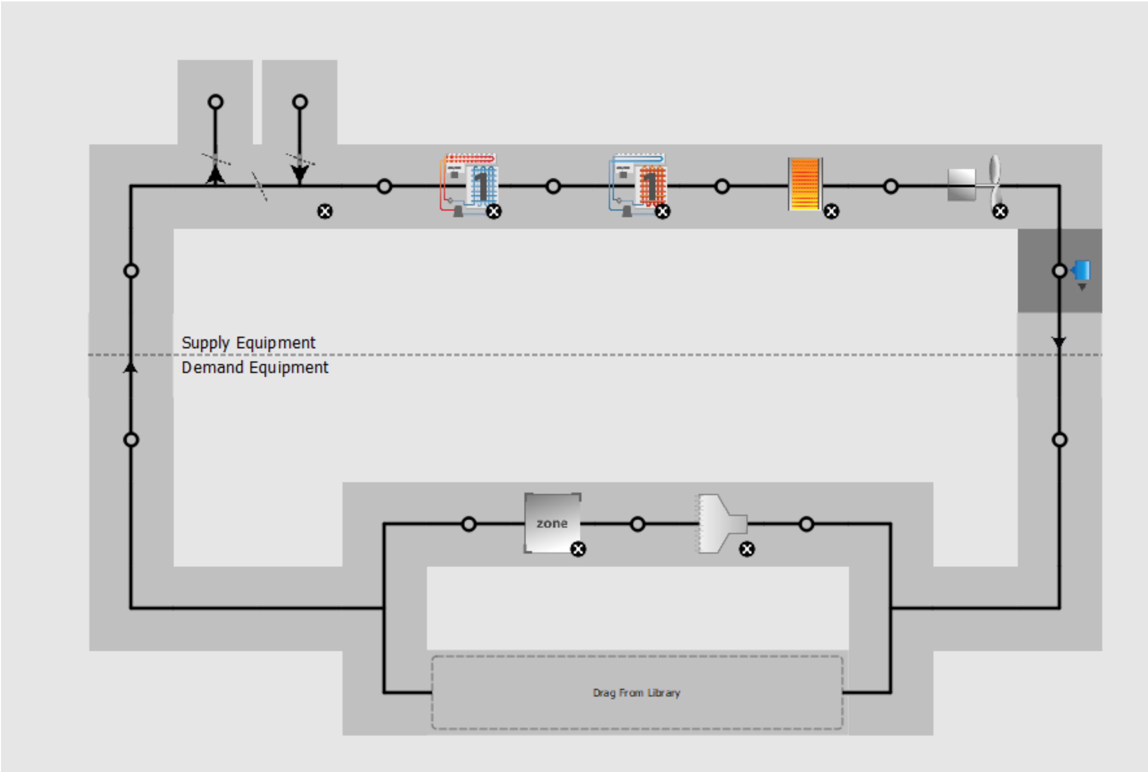

Figure 15: HVAC system design

The operation of the HVAC system was based on temperature set points described previously. Each element was sized according to the cooling and heating demand of the room. The minimum and maximum supply air temperature were set at 14 and 40 degrees, respectively.

For the rated total cooling capacity 1 W was set. This value was stablished considering what was explained in the chapter 3.2.3, that is, to take advantage of overheating that could be positive. The rated COP for the cooling coil was set at 3. The rated total heating capacity was set by the program according to the space heating requirements and the COP for the heating coil was equal to 5. The minimum and maximum outdoor air flow rate was set in 0,0035 m³/s.

4 Results and parametric analysis

This chapter presents the evolution of the thermal conditions inside the rooms for each scenario under study, with a focus on how the building responds to turning off the heating at 08:00 a.m. and 07:00 p.m.

Initially, the temperature was evaluated for the room without windows and then for the space with windows. In each of these sub-chapters, was made an evaluation for the coldest day of the year, then was taken an average for the period under study (Jan 17 to Feb 17) and the results obtained were analyzed. Finally, the cases where internal gains were introduced: 4 W/m² and 8 W/m², were also analyzed for the coldest day.

All the simulations were performed using 24 timesteps per hour, to allow more accuracy and better representation of the control system.

4.1 Results - Model Without Windows

This section presents the results obtained in the simulations performed for each case.

4.1.1 Results for the coldest day

The graph in the following figure represents the evolution of the indoor temperature for the three scenarios under study throughout January 25th, considered to be the coldest day of the year. The figure 17 shows the results obtained for the system's sensible heating rate evolution during the same period.

The "LTI" represents low thermal inertia room defined in table 4, the "HTI Constructions" represents the room where high thermal inertia was achieved by changing the constructive solution, also described in table 4. Finally, the "HTI Furniture" represents the space where thermal mass was added as furniture to the building with low thermal inertia to equalize the thermal inertia of the "HTI Constructions".

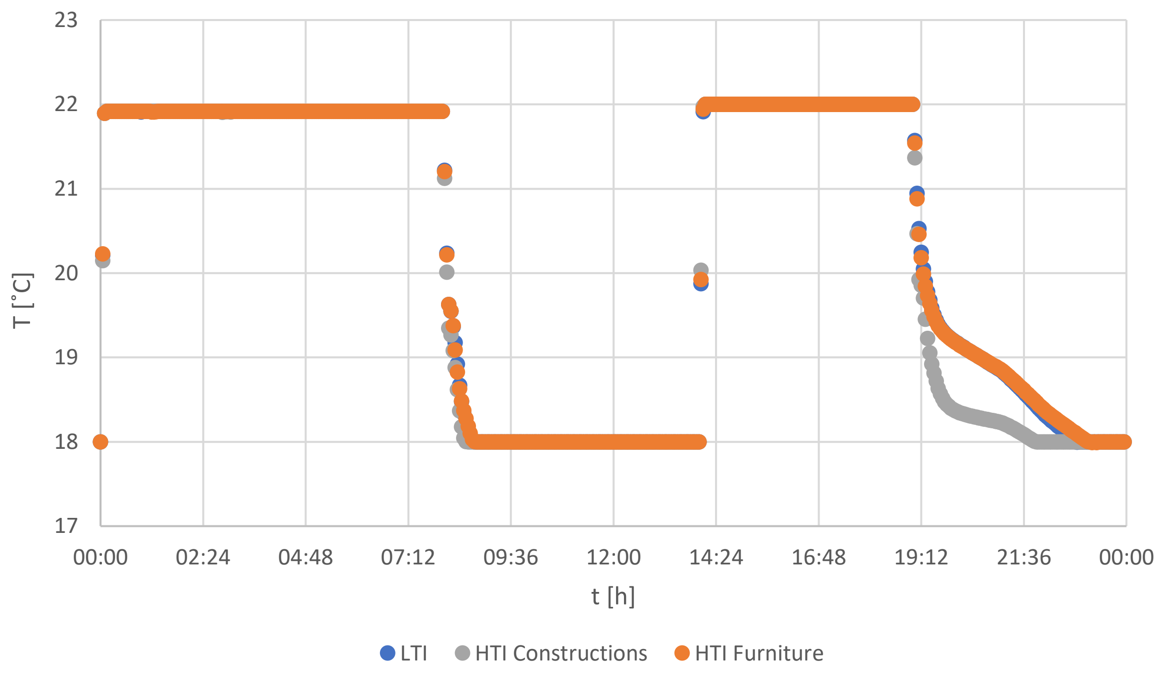

Figure 16: Graphic of indoor temperature evolution of the simulations during the coldest day of the year for the windowless room

As can be seen by analyzing the graph in Figure 16, during the morning the results obtained were very similar for the three cases. During the night period for the “LTI” and “HTI Furniture” cases the results were very close, however for the “HTI Constructions” case it was observed that the temperature decrease was faster than for the previous cases, as not expected.

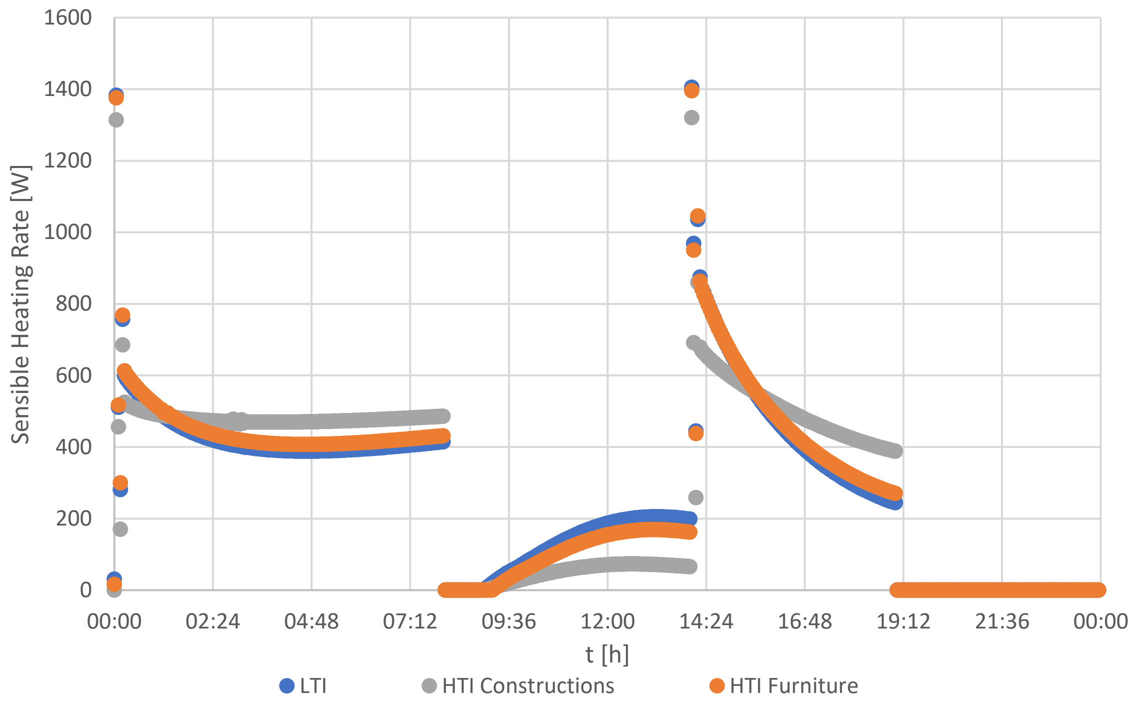

Figure 17: Zone air system sensible heating rate for the windowless room

Analyzing the graphic of figure 17 it is possible to observe that initially (at midnight) the power debited by the heating system was approximately 1400 W, for the three cases, since the indoor temperature of the room should reach to 22 ˚C. However, after reaching this temperature, the power debited by the system stabilizes at lower value, since until 8:00 a.m. the temperature should remain at 22 ˚C. At this time the heating system turns off so that the temperature decreases to 18 ˚C. The system remains off until 9:00 a.m. At 2:00 p.m. the system reaches its maximum power output, to reach 22 ˚C, and from then on it decreases again until 7:00 pm, the time at which the system shuts down. The heat demands are greater for the LTI case, as expected.

To better assess and understand the period during which the temperature took to decrease, the day was divided into two periods. The first period considered was the morning, which based on the observation of the results was defined as being from 8:00 a.m. to 9:00 a.m., the other period considered was the evening from 7:00 pm to midnight.

For each situation was tried to adjust a curve that best fitted the results, as can be seen in the following graphs.

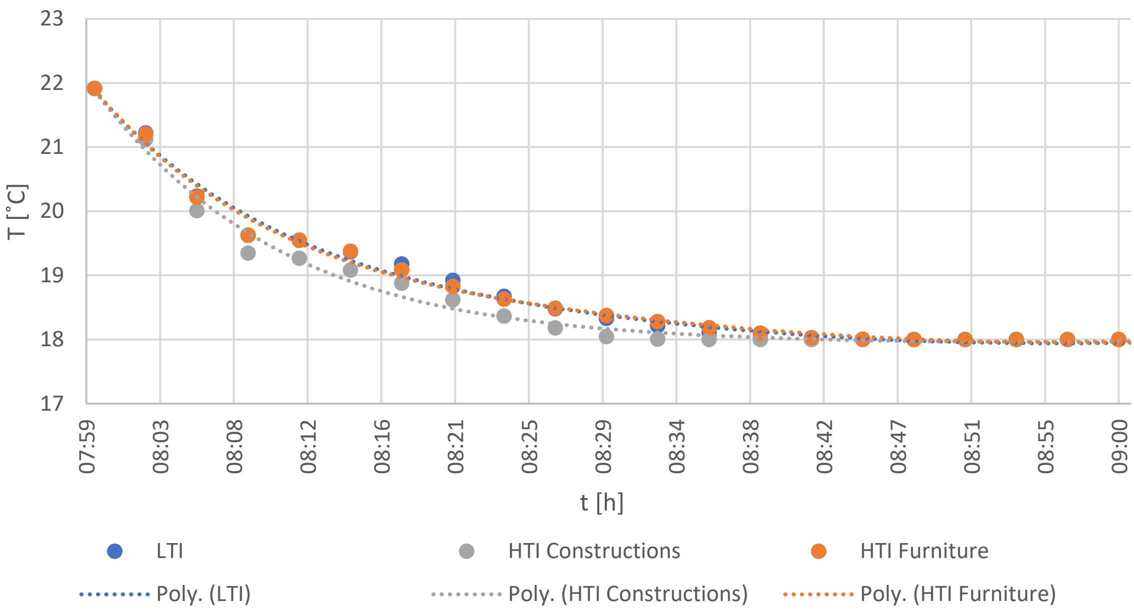

Figure 18: Results for the coldest day for the windowless room **(Morning)**

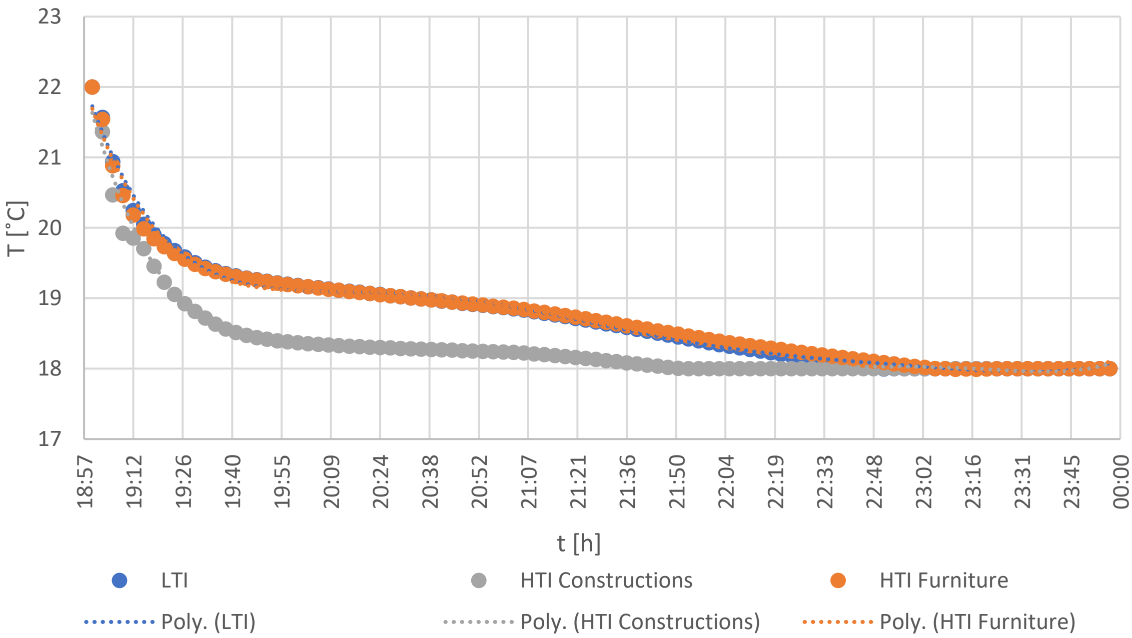

Figure 19: Results for the coldest day for the windowless room **(Evening)**

As can be noticed by reading the graphic in figure 19, the results are not in line with what was expected. The graphic shows that for the "HTI Constructions" scenario the curve has a much steeper decrease than for the "LTI" scenario.

Based on the curves obtained, new values were estimated for the room's interior temperature and these values were compared with those accomplished in the simulation, in appendix B.

Using the values obtained from the equations corresponding to each curve, it was studied how long it took for the indoor temperature of the space to fall each degree for the temperature range between 22 ºC and 18 ºC. After performing the evaluations based on the curves defined, it was found that the results, particularly for the temperature decay from 19 to 18 degrees did not match the values observed in the graphic of the figure 16. Hence, the values obtained during the simulation were also used to study the time for that the indoor temperature took to decrease 1 ºC.

The table 11 represents the results obtained for the time it took for the indoor temperature to drop each degree for the morning period using the two methods described in the previous paragraph:

Table 11: Time for 1˚C drop in the indoor temperature for the windowless room for the coldest day obtained with the two methods **(Morning)**

ΔT [˚C]	***t(T-1) [min]***					
	Fitting Equation			**Simulation**		
	LTI	**HTI Constructions**	**HTI Furniture**	**LTI**	**HTI Constructions**	**HTI Furniture**
22-21	3,8	3,2	3,6	3,4	3,1	2,7
21-20	5,5	4,5	5,3	3,9	3,5	2,7
20-19	10,2	7,6	10,1	7,5	9,6	4,7
19-18	36,9	38,8	39,2	30,1	19,8	21,1

Analyzing the results presented in the previous table it was found that for the method using the fitting equation, during the morning, although the time it took for the temperature to drop 4 ˚C was similar in the three cases, it was faster in the "HTI Furniture" (58 minutes), as expected. However, when comparing the results obtained between the "LTI" and "HTI Constructions" scenarios, it can be seen that the time that the indoor temperature took do drop to 18 ˚C was higher for the "LTI" case (56 minutes), as it was not expected.

On the other hand, the analysis of the results obtained using the simulation values show that the temperature took more time to drop 4 ˚C for the "LTI" scenario (45 minutes), as unexpected. As mentioned before, considering the graphic of figure 16, it can be seen that the results obtained using the simulation values were more accurate.

The results in table 12 shows the time that the indoor temperature took to fall 1 ˚C, during the evening for both methods.

Table 12: Time for 1˚C drop in the indoor temperature for the windowless room for the coldest day obtained with the two methods **(Evening)**

ΔT [˚C]	***t(T-1) [min]***					
	Fitting Equation			**Simulation**		
	LTI	**HTI Constructions**	**HTI Furniture**	**LTI**	**HTI Constructions**	**HTI Furniture**
22-21	8,9	6,7	8,8	5,8	4,1	5,5
21-20	15,0	9,4	15,1	10,3	5,6	9,6
20-19	112,2	73,6	119,6	78,4	15,7	79,4
19-18	138,1	188,3	132,6	142,5	148,7	169,5

As can be seen from the results in table 12, for the night period, contrary to what happened during the morning, the results obtained for both cases of high thermal inertia were quite different. On the contrary, the results for the time obtained for the low thermal inertia and high thermal inertia where the thermal mass was added through furniture were similar.

Based on the simulation results it is possible to see that the time it took for the indoor temperature to drop 4 ˚C was longer in the "HTI Furniture" model, as expected. As commented in the analysis of the graphic 19, it is noticeable that there is a large difference in the time recorded for the “LTI” and “HTI Constructions” scenarios. For the “HTI Constructions” case the temperature drops much faster, which is not as expected.

A comparison was made between the results obtained by each method, and it was found that the iterative method that utilize the simulation values was a better approximation for the results.

Although most of the results calculated using the two methods were similar, when looking at the temperature decrease between 19 and 18 degrees it was possible to see that the results obtained are significantly different and, as mentioned before, when analyzing the graphic of the figures 16 it is possible to see that the method where the values obtained during the simulation were used was more accurate, as can be seen in figures 20 and 21.

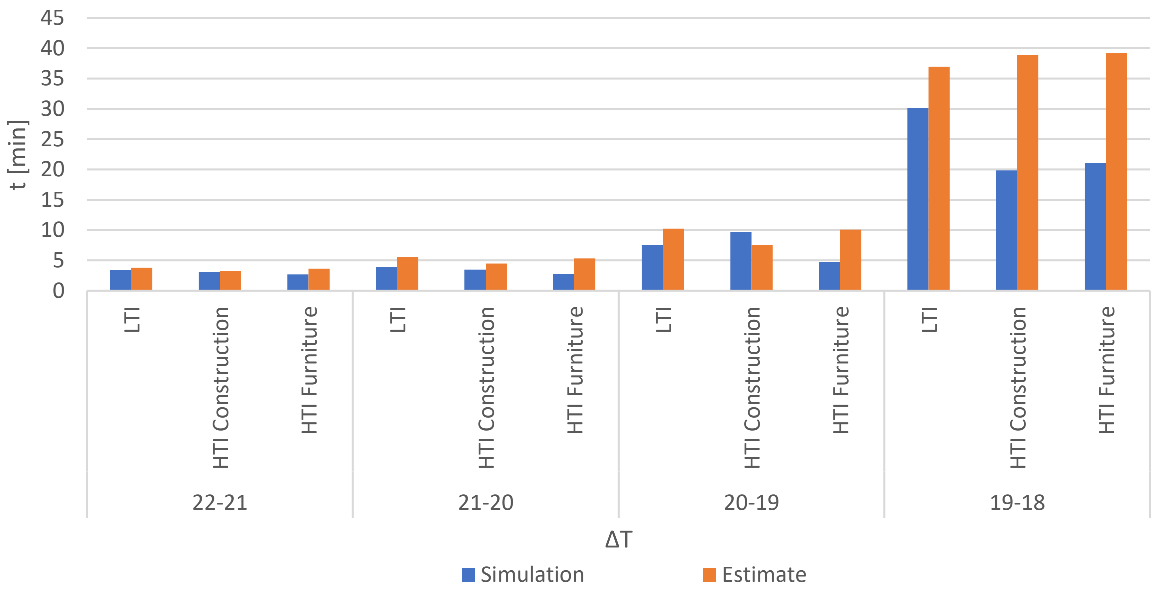

Figure 20: Comparison of the results obtained using the two methods for the windowless room for the coldest day **(Morning)**

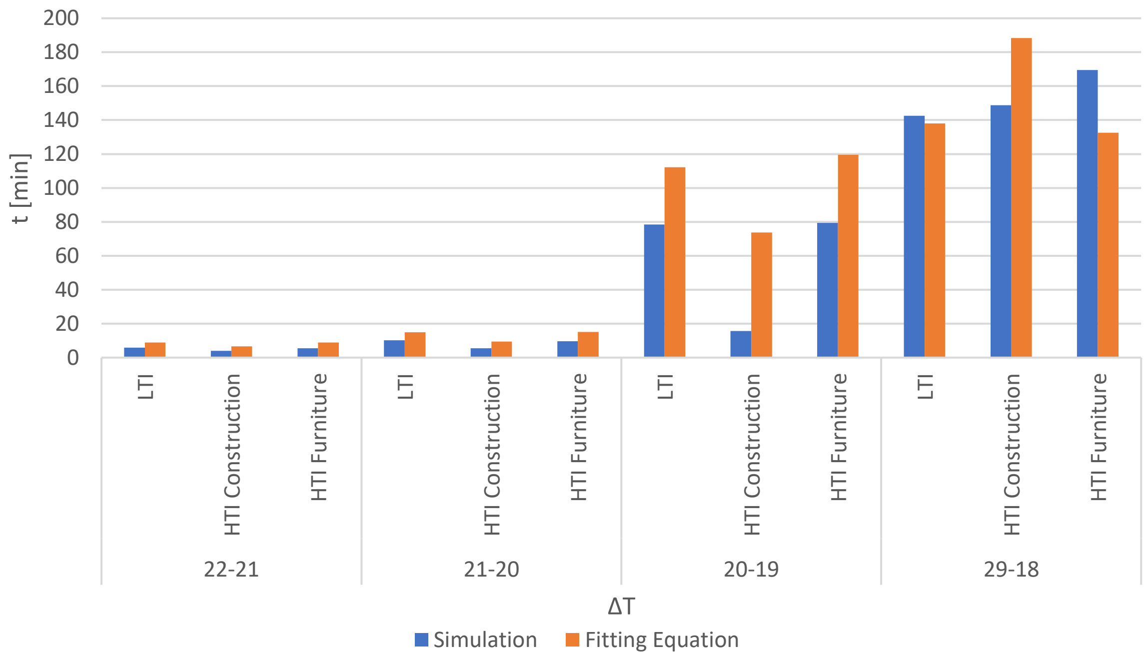

Figure 21: Comparison of the results obtained using the two methods for the windowless room for the coldest day **(Evening)**

4.1.2 Results for the average of the days

Considering the results obtained in the simulation for all the days of the period under study, an average between the time intervals obtained for the temperature decay for each day was performed, to obtain a reference value for this time during the focused month. Since for the coldest day it was found that the results using the values obtained during the simulation were more accurate than the values obtained by the fitting curve, the linear interpolation using simulation values was used for the analysis in question.

During this analysis it was found that on certain days the indoor temperature did not drop to 18 ˚C in the time interval under study (5h). So, for these values it was estimate how long it would take them to reach 18 ˚C. Although these approximations were not a very accurate, it allowed to include all the days and to estimate with better approximation the time of temperature drop, which would not be possible if the days were excluded.

In this way, it was observed that for the coldest days (during January) the temperatures always dropped to 18 ˚C, or nearly so. However, for the mildest days (during February) the temperatures did not always reach 18 ˚C, and in some cases, did not even reach 19 ˚C, especially during the night and in cases of high thermal inertia.

The following table presents the results calculated for the period under study (17 Jan to 17 Feb), for the windowless room during the morning and evening.

Table 13: Time for 1˚C drop in the indoor temperature for the windowless room calculated from the average of all days **(Morning and Evening)**

ΔT [˚C]	***t(T-1) [min]***					
	Morning			**Evening**		
	LTI	**HTI Constructions**	**HTI Furniture**	**LTI**	**HTI Constructions**	**HTI Furniture**
22-21	5,9	4,5	5,7	9,0	6,1	8,3
21-20	7,7	5,9	7,8	53,5	10,6	48,0
20-19	23,0	20,0	26,4	129,2	102,4	138,4
19-18	86,0	434,4	129,2	172,2	366,9	197,0
22-18	**122,6**	**464,8**	**169,0**	**364,0**	**486,1**	**391,8**

Looking at the results presented in table 13, it is possible to see that during the morning, for the low thermal inertia room, the temperature always dropped to 18 ˚C. Also, for the "HTI Furniture" scenario this happened, however, on February 4, 5 and 13 it was verified that it the temperature did not drop to 18 ˚C. It can also be noticed that, during the morning, the time obtained for the decrease of 4 ˚C for the "HTI Constructions" room is quite high, compared to the other models. This is since in this situation the temperature did not drop to 18 ˚C on many days, as expected. In several days, the estimated time that the indoor temperature took to fall 4 ˚C was in the range of 1000 minutes, leading to a very high value when looking at the decay of temperature of 19 to 18 degrees.

For the evening period, it was possible to verified that, as mentioned earlier, the temperature rarely dropped to 18 ˚C, and often does not even drop to 19 ˚C. Due to this phenomenon the time presented in the table is a value that exceeds the studied period (5h). Furthermore, for the "HTI Constructions" model this value was high compared to the others since for this case it was found that the temperature drops more quickly to 19 ˚C and as it rarely drops to 18 ˚C.

For the results obtained using the average time that the indoor temperature took to decay 4 ˚C it was possible to see that, in both periods, the temperature didn't drop to 18 ˚C to the "HTI

Construction" scenario. And for the "HTI Furniture" the time took for the indoor temperature to decrease 4 ˚C was always higher in this case than in the "LTI", as expected.

Considering the results commented so far, it was found that these were not in accordance with what was expected, which led to the belief that there was an anomaly in the development of the model. In this way, it was raised the question of the order of the materials that formed the surrounding surfaces being interchanged, that is, the exterior being switched with the interior, and therefore, the case of low thermal inertia being switched with that of high thermal inertia. So, that question was asked in the Unmet Hours forum [32], which is a site indicated by OpenStudio platform used by the expert's community that use and develop OpenStudio and EnergyPlus. The answers received indicated that the layers were in the correct order, so there was not a bug there. One of the experts suggested some corrections, but even after fixing that, the results still did not match the expected.

4.1.3 Results with internal loads

Finally, the internal loads were applied to the case under study and their influence on the internal temperature variation was verified. In the graphic of the following figures, it is possible to see the effects of the internal loads in the "LTI" room and for the "HTI Furniture" scenario. This simulation was performed for the coldest day.

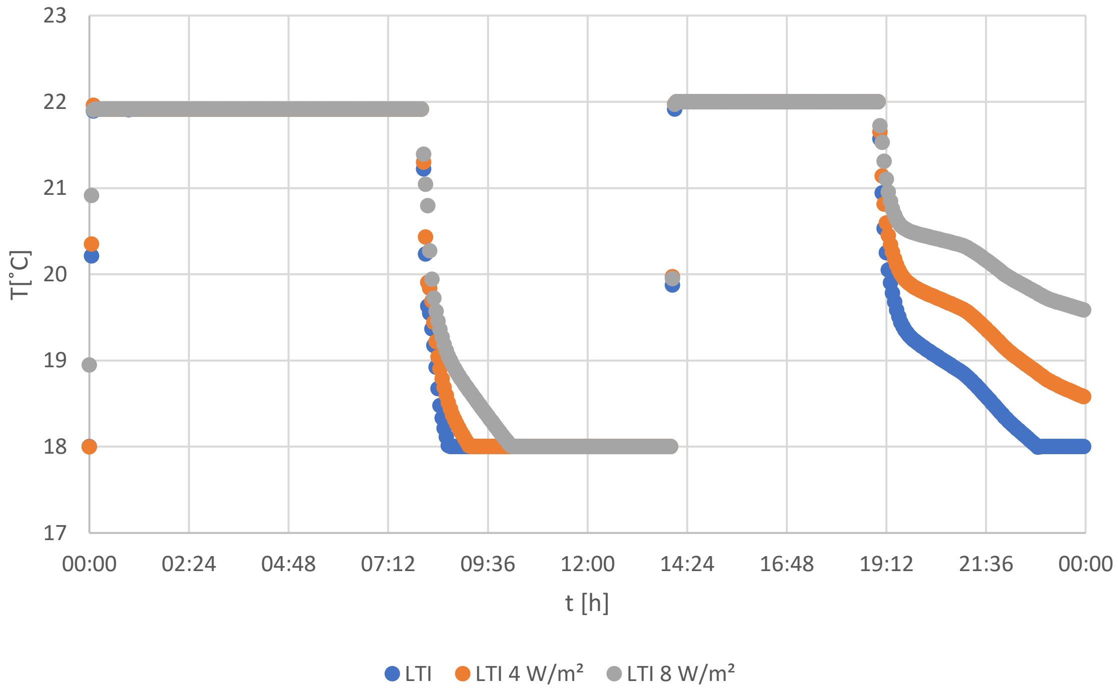

Figure 22: Influence of the internal loads in the "LTI" windowless room

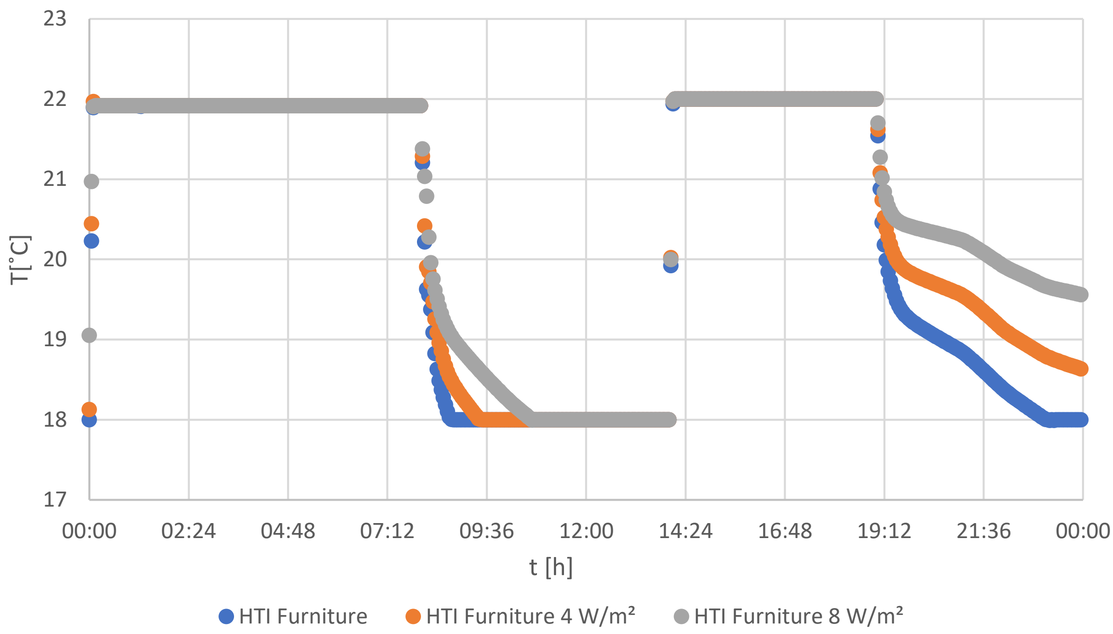

Figure 23: Influence of the internal loads in the "HTI Furniture" windowless room

The results obtained for the 4 W/m² for the morning and evening are presented in table 14. For the internal gains 8 W/m² the results are shown in the table 15.

Table 14: Time for 1˚C drop in the indoor temperature for the windowless room with an internal load of **4 W/m²** for the coldest day obtained using simulations values **(Morning and Evening)**

ΔT [˚C]	*t(T-1) [min]*			
	Morning		Evening	
	LTI	HTI Furniture	LTI	HTI Furniture
22-21	3,9	3,8	7,4	7,0
21-20	4,4	4,5	26,0	22,4
20-19	16,7	17,8	172,7	176,8
19-18	50,0	63,9	-	-

Table 15: Time for 1˚C drop in the indoor temperature for the windowless room with an internal load of **8 W/m²** for the coldest day obtained using simulations values **(Morning and Evening)**

ΔT [˚C]	*t(T-1) [min]*			
	Morning		Evening	
	LTI	HTI Furniture	LTI	HTI Furniture
22-21	6,7	6,7	14,0	9,6
21-20	7,6	7,8	168,7	161,1
20-19	27,5	33,8	-	-
19-18	93,1	116,7	-	-

Results show that for both values of internal gains the time that the indoor temperature decreased one degree increased, and for the case where the internal loads were equal to 4 W/m² it didn't even drop to 18 ˚C and for 8 W/m² it didn't fall to 19 ˚C. In summary, the increase in internal gains has resulted in an increase in the response time it took for the indoor temperature to decrease by 1 ˚C, as would be expected.

In the next figures it is shown a comparison of the time for a 1 ˚C temperature drop between the scenario without internal gains and with both cases where internal gains were introduced.

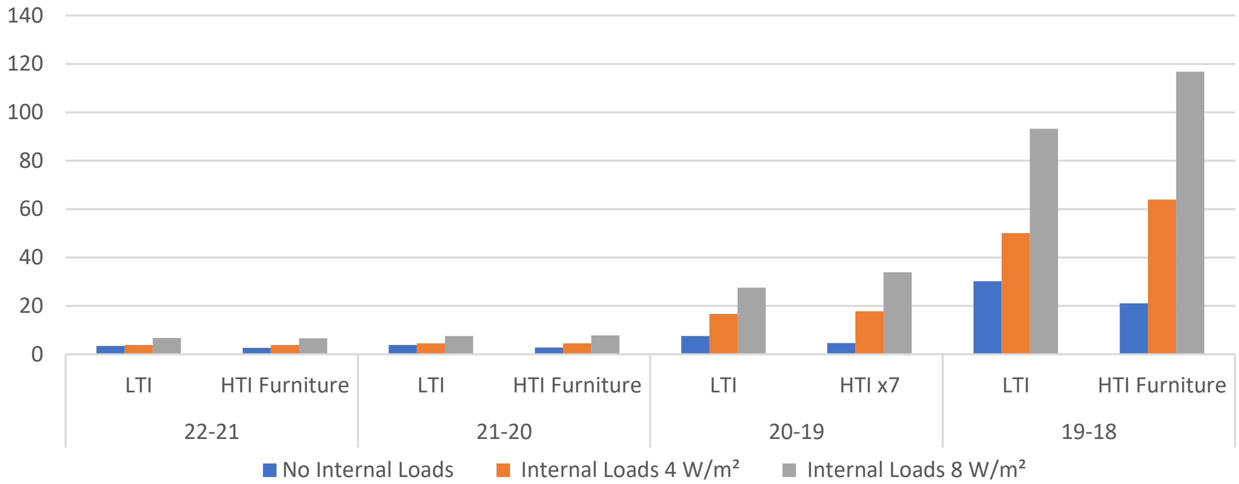

Figure 24: Comparison of the results obtained without internal gains and with 4 and 8 W/m² for the windowless room for the coldest day **(Morning)**

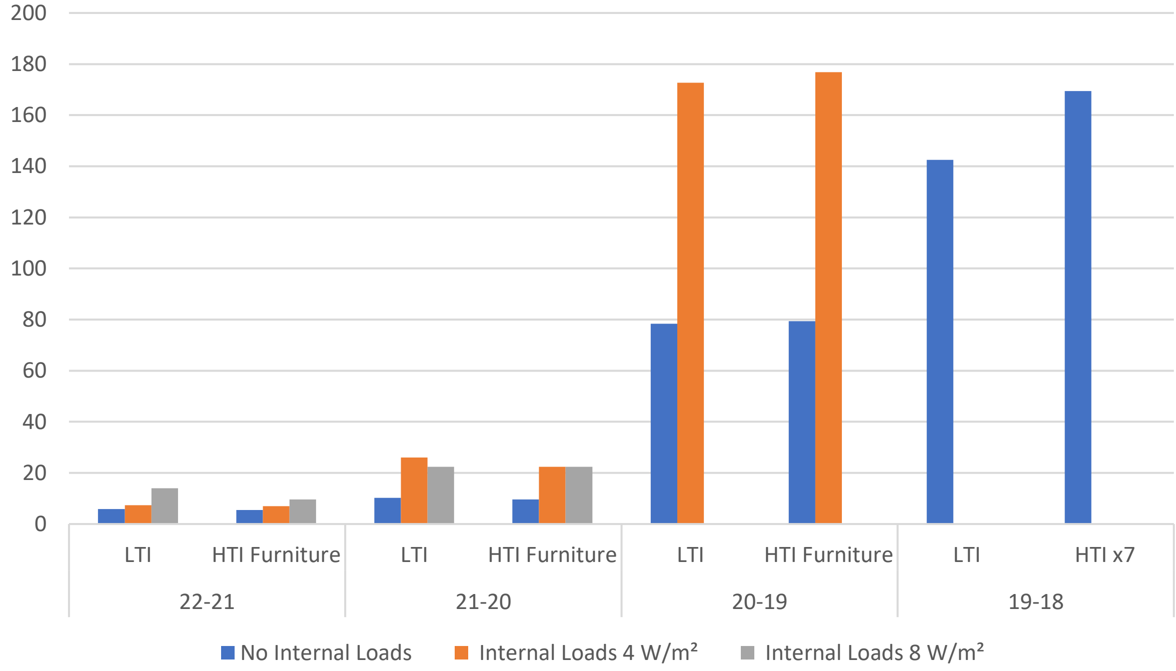

Figure 25: Comparison of the results obtained without internal gains and with 4 and 8 W/m² for the windowless room for the coldest day **(Evening)**

In this case, the graphics of the previous figures show that the increase in internal gains leads to an increase in the time that it takes for the indoor temperature to reach 18 degrees, and during the night the temperature does not even drop to 18 ˚C.

4.2 Results -Model with Windows

4.2.1 Results for the coldest day

For the windowed room, the same analysis was performed. Therefore, the graphic in the following figure represents the evolution of the indoor temperature and the graphic observed in figure 27 the sensible heating rate for the three scenarios under study throughout January 25th. The figures 28 and 29 represent each period of the day, morning, and night, respectively. As in the case without windows, the equation that best fitted the values obtained in the simulation was found for each situation. However, it was again observed that for the last decay of one degree (19 ºC to 18 ºC) these values did not match to the ones observed in the simulation, so the simulation values were used again.

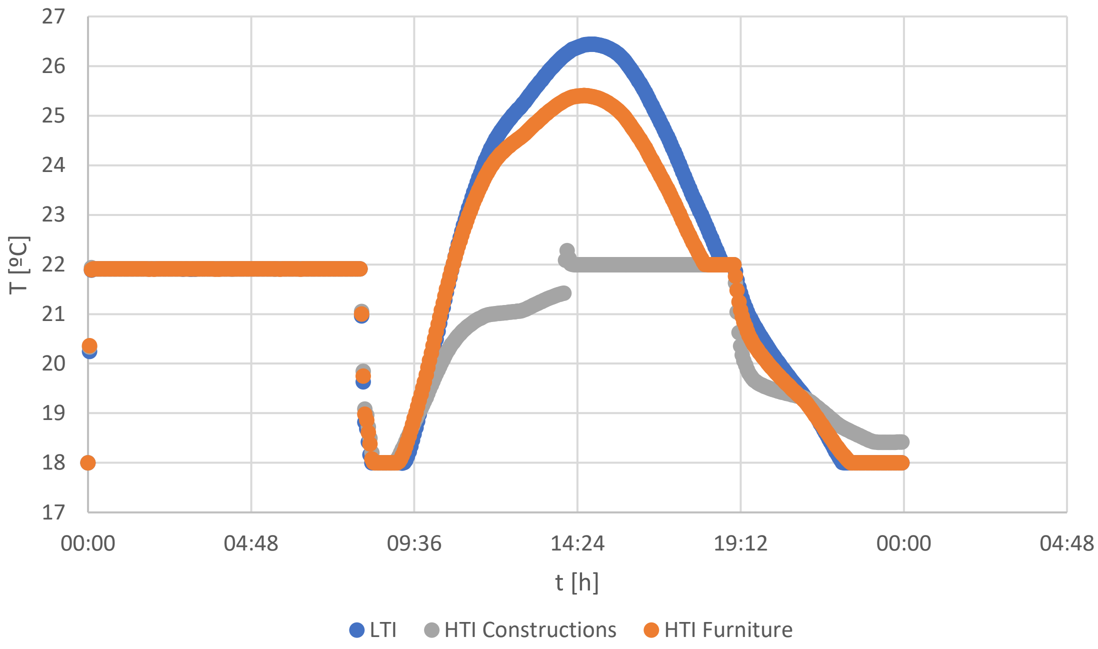

Figure 26: Graphic of indoor temperature evolution of the simulations during the coldest day of the year for the room with windows

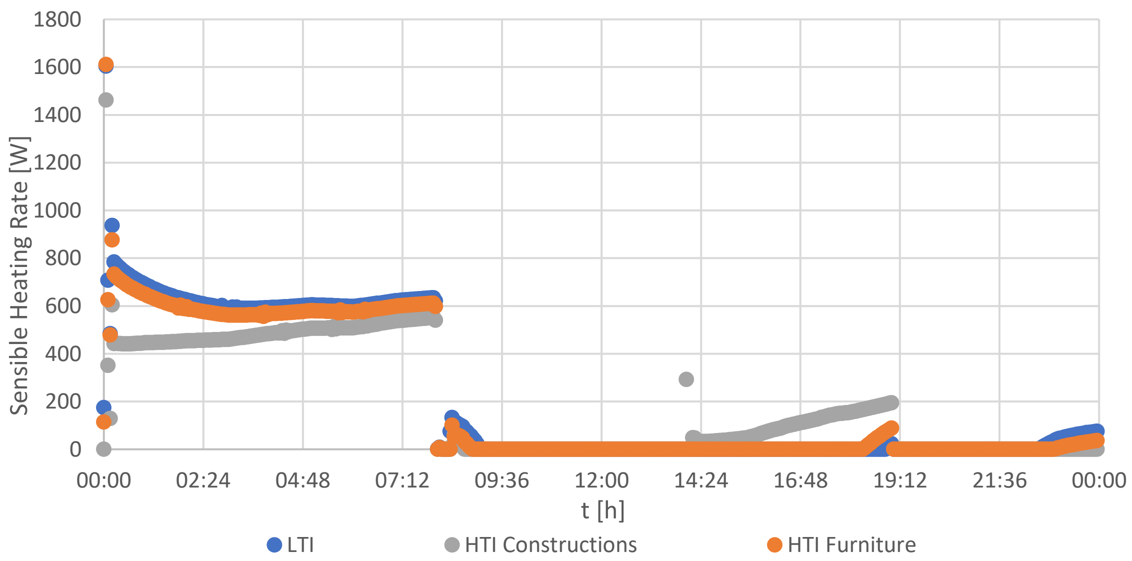

Figure 27: Zone air system sensible heating rate for room with windows

As can be seen in the figure 26, for the space with windows, contrary to what was observed previously for the case without windows, the temperature exceeded 22 ºC for the "LTI" and "HTI Furniture" scenarios, suffering a very sharp increase between 9:30 a.m. and 07:00 p.m. For the "HTI Furniture" this increase was lower than for the "LTI" case, as expected. Meanwhile, for the "HTI Constructions" model, the temperature does not exceed 22 ºC, as would be expected.

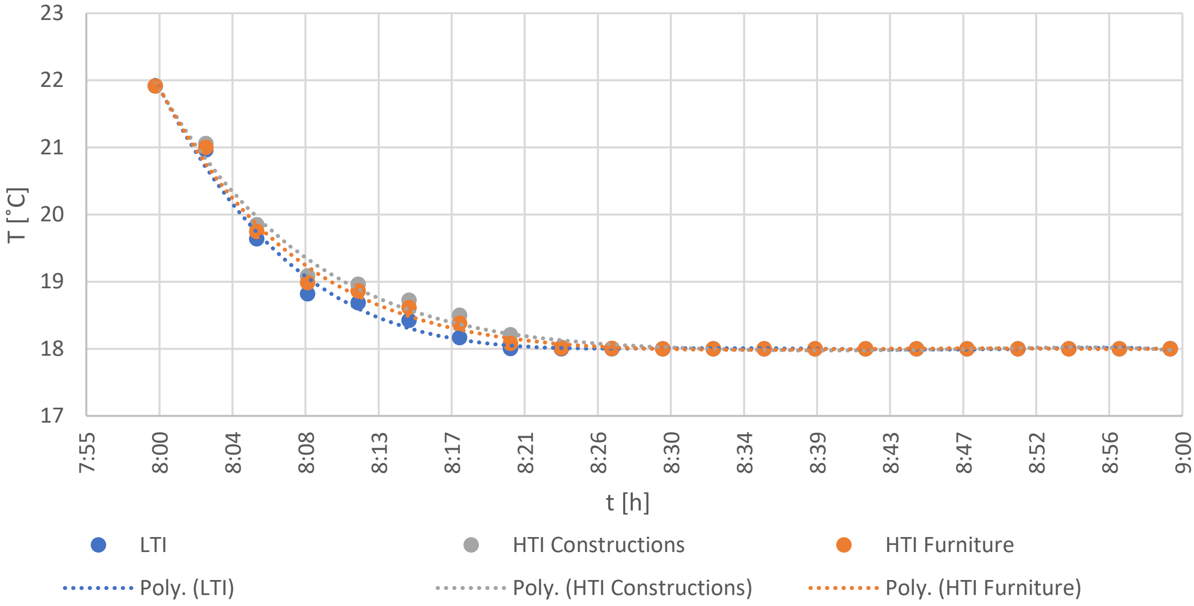

Figure 28: Results for the coldest day morning for the room with windows

In the graphic of the figure 28 it was possible to see that, although the results were similar, the curve corresponding to "HTI Constructions" room had a slower decrease compared to "LTI", as expected. On the other hand, as shown in the graphic of figure 29, during the evening, the "HTI Constructions" curve has a higher slope during the decrease of the first two degrees, which was not expected.

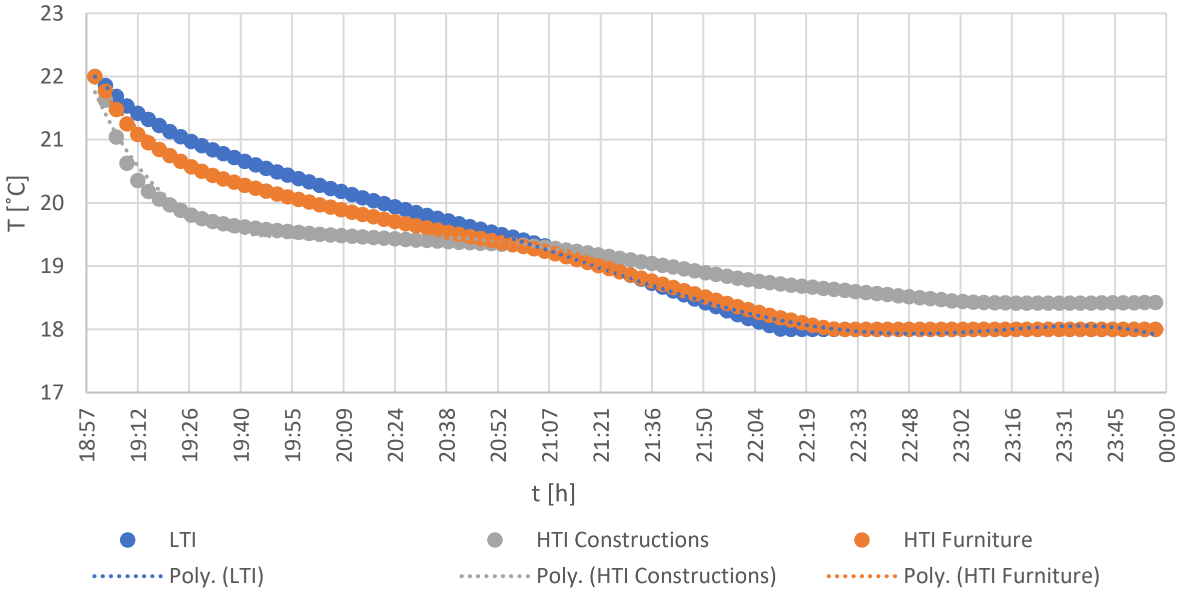

Figure 29: Results for the night of the coldest day for the room with windows

The table 16 show the results obtained for the time that the indoor temperature took to drop 1 ˚C using the two methods specificized in the sub-chapter 4.1.1, for the morning period.

As seen previously, the results obtained using the simulation values were more accurate than those obtained using the curve. So, for the morning, it can be seen that, although the difference between the three simulations were small, the time it took for the indoor temperature to drop 4 ˚C was longer for the cases with high thermal inertia, as expected. However, it was verified that this drop happened in just 30 minutes, which is not as expected.

Table 16: Time for 1˚C drop in the indoor temperature for the room with windows for the coldest day **(Morning)**

ΔT [˚C]	***t(T-1) [min]***					
	Fitting Equation			**Simulation**		
	LTI	**HTI Constructions**	**HTI Furniture**	**LTI**	**HTI Constructions**	**HTI Furniture**
22-21	2,2	2,5	2,3	2,6	2,8	2,7
21-20	2,8	3,4	3,1	2,9	3,2	3,0
20-19	4,2	5,4	4,9	3,8	4,7	4,4
19-18	49,1	48,7	49,6	14,7	19,3	19,9

The table 17 show the results obtained for the time that the indoor temperature took to drop 1 ˚C using the two methods, for the evening.

Table 17: Time for 1˚C drop in the indoor temperature for the room with windows for the coldest day **(Evening)**

ΔT [˚C]	***t(T-1) [min]***					
	Fitting Equation			**Simulation**		
	LTI	**HTI Constructions**	**HTI Furniture**	**LTI**	**HTI Constructions**	**HTI Furniture**
22-21	25,7	9,8	17,9	25,9	6,6	13,9
21-20	57,2	19,5	49,8	54,3	13,4	47,0
20-19	57,1	157,5	77,8	62,5	140,4	80,5
19-18	115,5	89,2	156,8	55,3	-	68,6

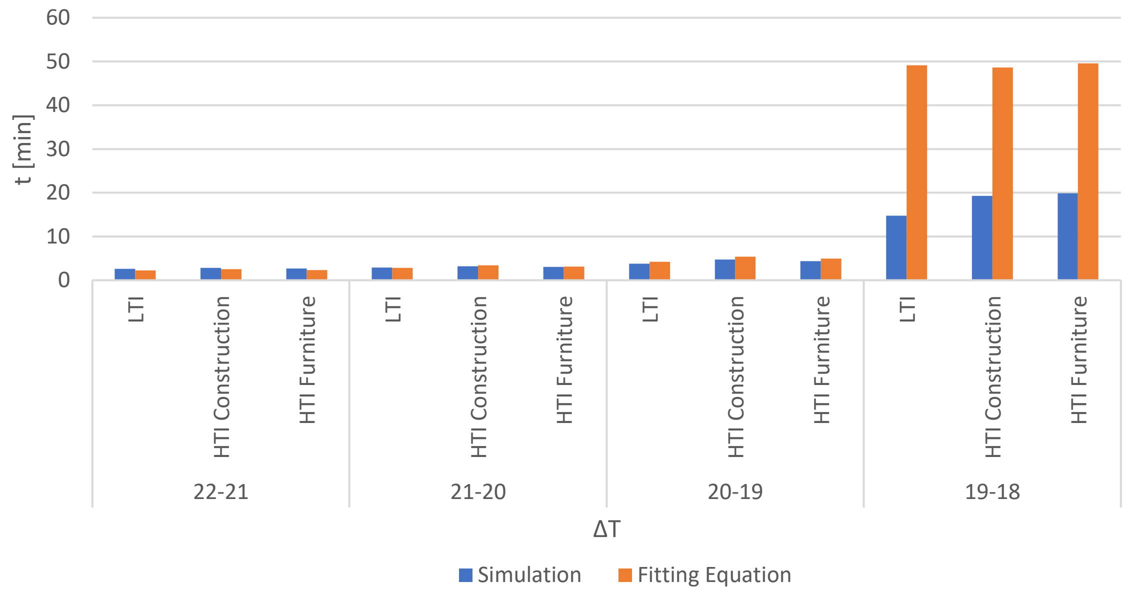

Figure 30: Comparison of the results obtained using the two methods for the room with windows for the coldest day **(Morning)**

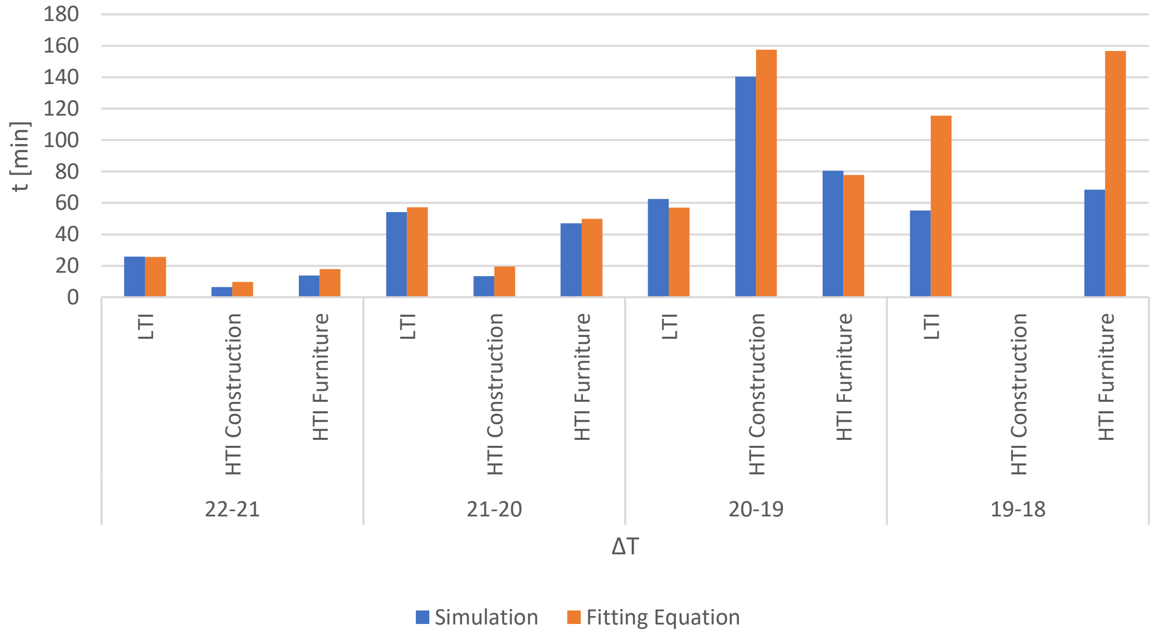

Figure 31: Comparison of the results obtained using the two methods for the room with windows for the coldest day **(Evening)**

Just as was seen in the case without windows, although the two methods present identical values during the decrease of the first three degrees, when we look at the range of temperatures from 19 to 18 degrees, it is observed that the values obtained using linear interpolation are better.

In order to identify the differences between what happened in the space with windows and without windows, the results obtained for the two simulations were compared, as shown in the graphs in the following figures (32 and 33).

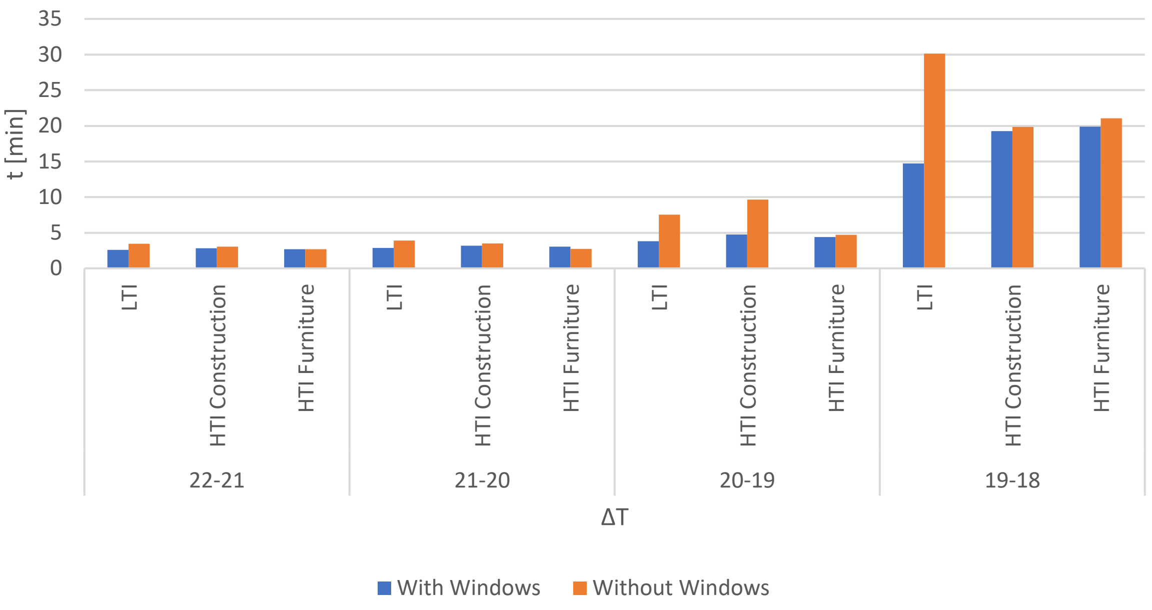

Figure 32: Comparison of the results obtained for the room with and without windows for the coldest day **(Morning)**

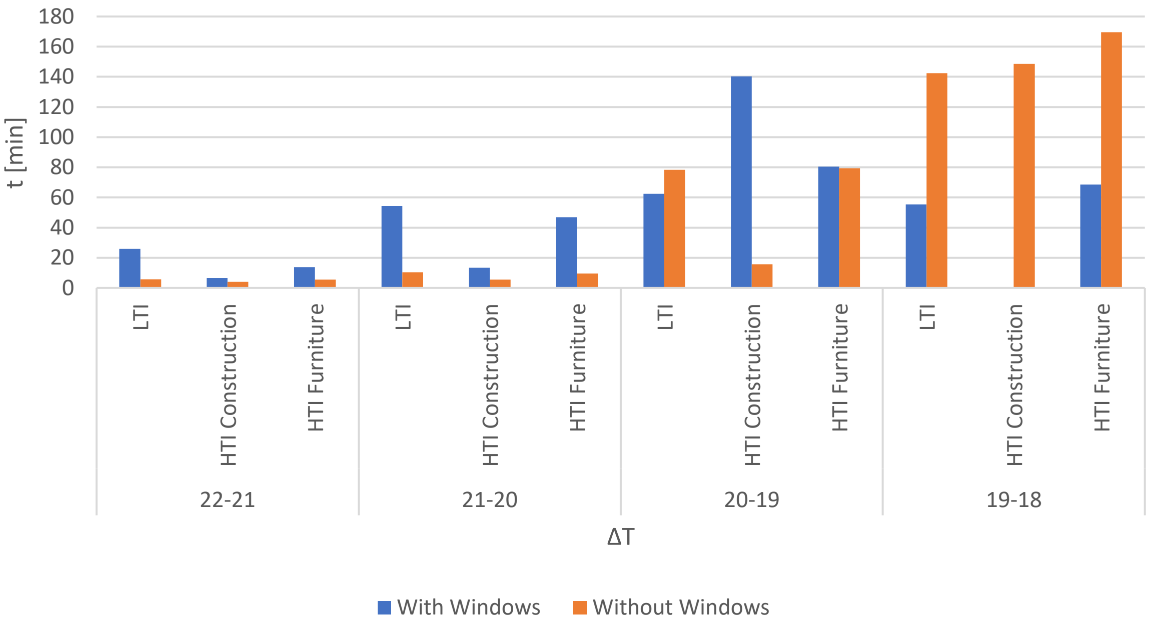

Figure 33: Comparison of the results obtained for the room with and without windows for the coldest day **(Evening)**

Considering the information presented in the charts of the previous figures, it can be observed that, normally, the indoor temperature took longer to decrease in the room without windows, as would be expected, since the U values for the windows are higher than for the walls. However, for the space with high thermal inertia where the constructive solution was modified, for the case with windows it never reaches an interior temperature equal to 18 degrees, while in the compartment with windows this value is reached in almost three hours.

4.2.2 Results for the average of the days

In the results obtained for the windowless room it was possible to estimate a value for the time it took for the indoor temperature to decrease 4 ºC, since, although on some days it was verified that the temperature did not drop to 18 ºC within the studied interval (5h), it always decreased over time. However, for the case with windows it was not possible to make such an estimate, since on most days not only did the temperature not drop to 18 ºC, but also did not decrease all the time, i.e., the temperature reached a value higher than 18 ºC and increased again after that. This was especially true in the morning.

In comparison to what happened in the windowless room, where for the space with low thermal inertia it was observed that the temperature always drops to 18 ºC, for this situation it was found that this did not always happen, and often did not even drop to 19 ºC. It was also verified that for the days where the outside temperature was higher, the inside temperature did not reach 22 ºC at 7:00 p.m. Therefore, on those days it was not possible to evaluate the decay of the four degrees in the range of temperatures sought, for example, for the day February 6th at 7:00 p.m. an inside temperature equal to 27.6 ºC was recorded and, consequently, did not even reach 21 ºC.

In this way, it was not possible to study the average time that the temperature took to decrease between the set temperature values (22 and 18 ºC).

4.2.3 Results with internal loads

The effect of the internal loads on the fluctuation in internal temperature for the windowed room was also evaluated. In the graphics of the following figures, it is possible to see the effects of the internal loads for both scenarios under study for the windowed room on the coldest day.

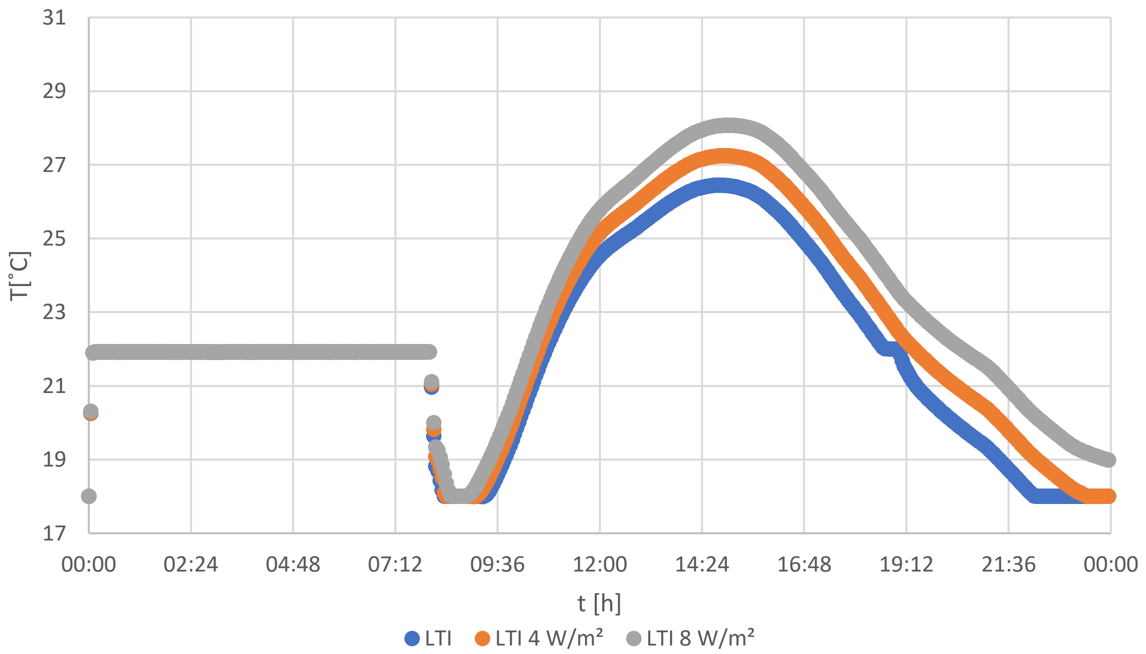

Figure 34: Influence of the internal loads in the “LTI” room with windows

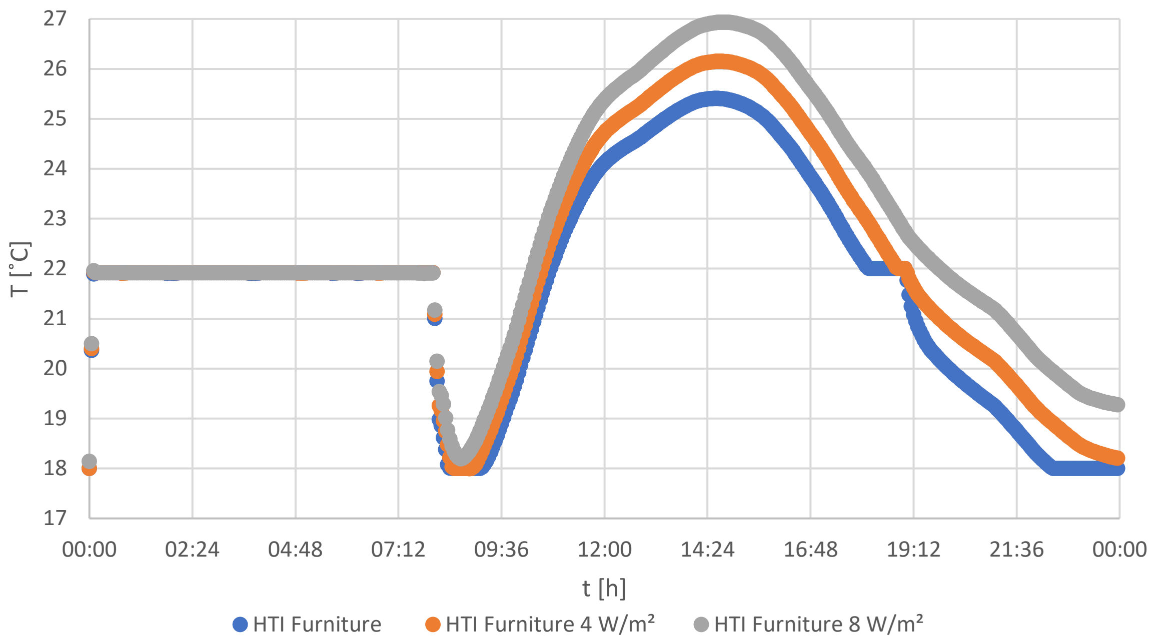

Figure 35: Influence of the internal loads in the "HTI Furniture" room with windows

The Table 18 and 19, illustrate the findings for the 4 W/m² and 8 W/m², respectively.

Table 18: Time for 1˚C drop in the indoor temperature for the room with windows and an internal load of **4 W/m²** for the coldest day obtained using simulations values **(Morning and Evening)**

ΔT [˚C]	*t(T-1) [min]*			
	Morning		**Evening**	
	LTI	**HTI Furniture**	**LTI**	**HTI Furniture**
22-21	2,6	2,7	81,2	48,8
21-20	2,9	3,0	69,4	90,0
20-19	3,8	4,4	47,2	63,5
19-18	14,7	19,9	74,4	98,0

Table 19: Time for 1˚C drop in the indoor temperature for the room with windows and an internal load of **8 W/m²** for the coldest day obtained using simulations values **(Morning and Evening)**

ΔT [˚C]	*t(T-1) [min]*			
	Morning		**Evening**	
	LTI	**HTI Furniture**	**LTI**	**HTI Furniture**
22-21	3,0	3,3	122,8	89,6
21-20	3,5	3,8	51,6	63,8
20-19	9,3	11,3	89,9	-
19-18	20,2	19,2	-	-

The results reveal that for both internal gain values, it took longer for the indoor temperature to drop by 1 ˚C. As expected, the higher the internal gains, the slower the indoor temperature drops.

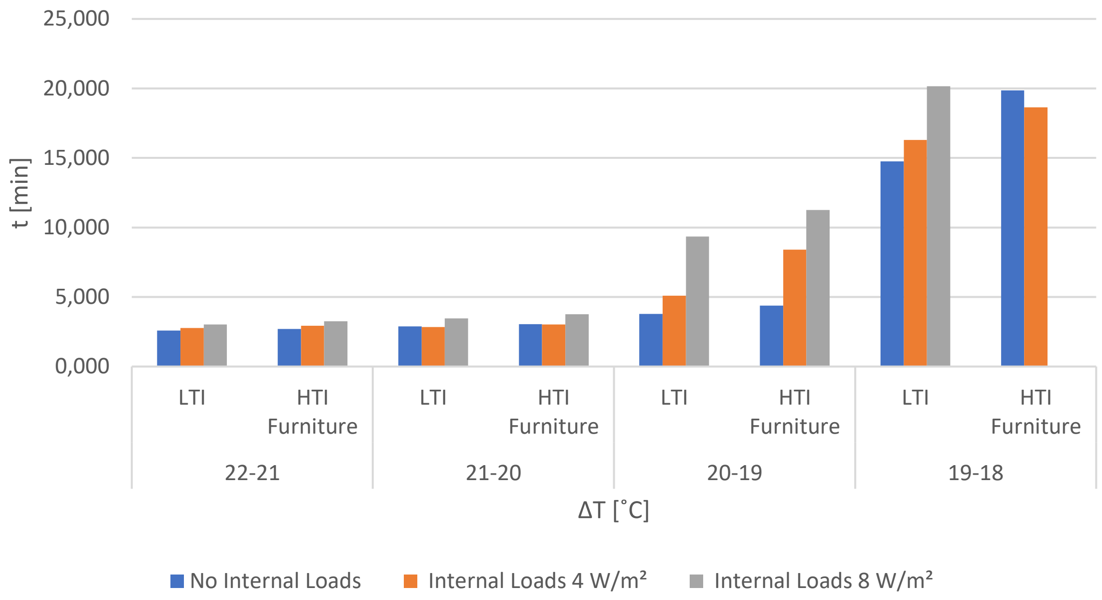

Figure 36: Comparison of the results obtained without internal gains and with 4 and 8 W/m² for the windowed room for the coldest day **(Morning)**

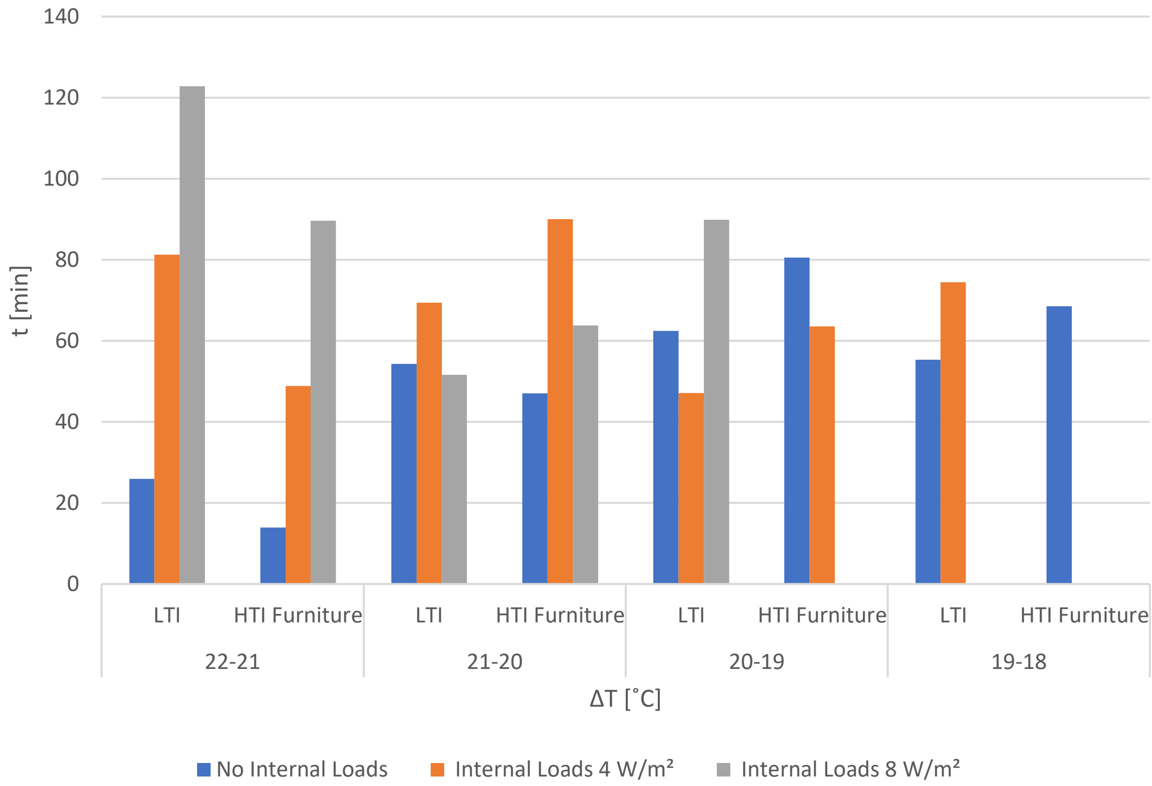

Figure 37: Comparison of the results obtained without internal gains and with 4 and 8 W/m² for the windowed room for the coldest day **(Evening)**

The graphics in the figures 36 and 37, prove what was seen previously, i.e., the increase in internal gains leads to an increase at the time that it takes for the temperature to decrease, and for the high thermal inertia scenarios it does not even reach the 18 degrees.

5 Conclusions and future works

5.1 Conclusions

In the present thesis a parametric investigation on the influence of some significant parameters (i.e., building's thermal inertia and HVAC system) on the time duration in which the electric systems can be switched off without jeopardizing occupants' comfort is reported. Simulations were performed with two models, one with windows and one without windows, in which the internal loads and thermal inertia were varied.

Based on the analysis of the results obtained, we can conclude that they are inconclusive, since, from the point of view of the thermodynamics of the building, they do not conform to normality.

When comparing the results obtained for the case with windows and without windows between the low thermal inertia building and the high thermal inertia building where the order of materials was changed, it was found that the time it took for the indoor temperature to fall by 4 ˚C was greater for the low thermal inertia building, and additionally, for both cases, the temperature took very little time to fall, about 30 to 45 minutes, for the coldest day. As mentioned before, in order to understand these results, an alternative method where the addition of thermal mass to the building through furniture, was implemented. However, it was again verified that these results were also not in accordance with what would be expected, since the results obtained with this solution were too close to the results obtained for the building with low thermal inertia.

Discounting the provisionality of the results, it was possible to understand that for the room with windows, as expected, the interior temperature had a faster decrease than the room without windows, since windows have a higher U values than walls. Since was studied the behavior for the coldest month it was expected that the temperature in the room would decrease more quickly.

Regarding the increase in the internal thermal loads, it was found that increasing them led to an increase in the time during which the indoor temperature took to drop. This was in line with what would be expected.

During the preparation of this thesis, it was detected that the results obtained were not in accordance with normality, since the temperature should fall more slowly for the case with high thermal inertia, which led to believe that there was an anomaly in the simulated model. Thus, the model was reviewed numerous times and even used the Unmet Hours forum [32], referenced by the OpenSudio platform as a site intended to clarify questions and help solve any problems related to the software. The hypothesis was raised that the order of the materials that formed the envelope had been swapped in the program, so, in an attempt to solve this problem, the model was uploaded in the site and the validity of the results was questioned. The answers obtained confirmed that there was no problem related to the surfaces of the model, however, they could not find the reason why the results were incorrect.

5.2 Future works

In order to continue the study carried out and bring the results closer to reality, some of the solutions proposed for future work are:

- Perform a similar study but use the EES program to elaborate a model based on global thermal capacity and thermoelectric analogy, i.e., make the thermal simulation of the building-by-building thermal circuits, analogous to electrical circuits of resistors and capacitors (RC);

- Study how the thickness of the insulation influences the results, finding an optimal thickness for the winter and summer seasons;

- Simulate a real building, with several thermal zones, where it is possible to take temperature measurements inside the building and thus validate the model with experimental values;

- Simulate for the summer months, including the hottest day of the year, and observe the differences in the building's behavior.

References

[1] ADENE, “Portugal Energia,” *Plano Nacional Energia e Clima 2021-2030 (PNEC 2030)*.

[2] H. Akeiber *et al.*, “A review on phase change material (PCM) for sustainable passive cooling in building envelopes,” *Renewable and Sustainable Energy Reviews*, vol. 60. Elsevier Ltd, pp. 1470–1497, Jul. 01, 2016. doi: 10.1016/j.rser.2016.03.036.

[3] A. Foucquier, S. Robert, F. Suard, L. Stéphan, and A. Jay, “State of the art in building modelling and energy performances prediction: A review,” *Renewable and Sustainable Energy Reviews*, vol. 23. pp. 272–288, 2013. doi: 10.1016/j.rser.2013.03.004.

[4] A. Fratean and P. Dobra, “Control strategies for decreasing energy costs and increasing self-consumption in nearly zero-energy buildings,” *Sustainable Cities and Society*, vol. 39, pp. 459–475, May 2018, doi: 10.1016/j.scs.2018.03.019.

[5] J. le Dréau and P. Heiselberg, “Energy flexibility of residential buildings using short term heat storage in the thermal mass,” *Energy*, vol. 111, pp. 991–1002, Sep. 2016, doi: 10.1016/j.energy.2016.05.076.

[6] F. Lu, Z. Yu, Y. Zou, and X. Yang, “Energy flexibility assessment of a zero-energy office building with building thermal mass in short-term demand-side management,” *Journal of Building Engineering*, vol. 50, Jun. 2022, doi: 10.1016/j.jobe.2022.104214.

[7] I. - International Energy Agency, “Energy Policy Review Portugal 2021.” [Online]. Available: www.iea.org/t&c/

[8] L. A. Hurtado, J. D. Rhodes, P. H. Nguyen, I. G. Kamphuis, and M. E. Webber, “Quantifying demand flexibility based on structural thermal storage and comfort management of non-residential buildings: A comparison between hot and cold climate zones,” *Applied Energy*, vol. 195, pp. 1047–1054, 2017, doi: 10.1016/j.apenergy.2017.03.004.

[9] W. J. N. Turner, I. S. Walker, and J. Roux, “Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass,” *Energy*, vol. 82, pp. 1057–1067, Mar. 2015, doi: 10.1016/j.energy.2015.02.011.

[10] D. Darwazeh, J. Duquette, B. Gunay, I. Wilton, and S. Shillinglaw, “Review of peak load management strategies in commercial buildings,” *Sustainable Cities and Society*, vol. 77, Feb. 2022, doi: 10.1016/j.scs.2021.103493.

[11] Y. Chen, P. Xu, J. Gu, F. Schmidt, and W. Li, “Measures to improve energy demand flexibility in buildings for demand response (DR): A review,” *Energy and Buildings*, vol. 177. Elsevier Ltd, pp. 125–139, Oct. 15, 2018. doi: 10.1016/j.enbuild.2018.08.003.

[12] A. Amadeh, Z. E. Lee, and K. M. Zhang, “Quantifying demand flexibility of building energy systems under uncertainty,” *Energy*, vol. 246, May 2022, doi: 10.1016/j.energy.2022.123291.

[13] Z. Luo *et al.*, “Demand Flexibility of Residential Buildings: Definitions, Flexible Loads, and Quantification Methods,” *Engineering*, Mar. 2022, doi: 10.1016/j.eng.2022.01.010.

[14] D. Mariano-Hernández, L. Hernández-Callejo, A. Zorita-Lamadrid, O. Duque-Pérez, and F. Santos García, “A review of strategies for building energy management system: Model predictive control, demand side management, optimization, and fault detect & diagnosis,” *Journal of Building Engineering*, vol. 33. Elsevier Ltd, Jan. 01, 2021. doi: 10.1016/j.jobe.2020.101692.

[15] M. Taleghani, M. Tenpierik, S. Kurvers, and A. van den Dobbelsteen, “A review into thermal comfort in buildings,” *Renewable and Sustainable Energy Reviews*, vol. 26. pp. 201–215, 2013. doi: 10.1016/j.rser.2013.05.050.

[16] Morris G. Davies, *Building Heat Transfer*. Liverpool, 2004.

[17] W. Chaves and S. Varga, “Análise energética a um edifício com a perspetiva de aplicação de vidros electrocromáticos na redução de consumos.”

[18] “Guia SCE-Indicadores de Desempenho Energético (REH).”

[19] “ASHRAE STANDARD,” 2010. [Online]. Available: www.ashrae.org

[20] G. Reynders, T. Nuytten, and D. Saelens, “Potential of structural thermal mass for demand-side management in dwellings,” *Building and Environment*, vol. 64, pp. 187–199, Jun. 2013, doi: 10.1016/j.buildenv.2013.03.010.

[21] A. Reilly and O. Kinnane, “The impact of thermal mass on building energy consumption,” *Applied Energy*, vol. 198, pp. 108–121, 2017, doi: 10.1016/j.apenergy.2017.04.024.

[22] G. Evola, L. Marletta, and V. Tanasiev, “Combining thermal inertia, insulation and ventilation strategies for improving indoor summer thermal comfort e-SAFE: Energy and Seismic Affordable Renovation Solutions View project Passive Strategies for Building Renovation in Temperate Climate View project,” 2013. [Online]. Available: https://www.researchgate.net/publication/272166397

[23] R. Lamberts, “Rogério de Souza Versage METAMODELO PARA ESTIMAR A CARGA TÉRMICA DE EDIFICAÇÕES CONDICIONADAS ARTIFICIALMENTE Tese submetida ao Programa de Pós Graduação em Engenharia Civil da Universidade Federal de Santa Catarina para a obtenção do Grau de Doutor em Engenharia Civil. Florianópolis 2015.”

[24] “Energy Simulation in Building Design.”

[25] J. C. Kelly, “Title of Thesis: SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR TWO COMPLEX AND ENERGY INTENSIVE BUILDINGS ON UMD CAMPUS.”

[26] E. P. Nikolopoulou, “‘Parametric analysis & performance optimization of thermal mass solar walls,’” 2017.

[27] K. Mohamed Amine, S. Leila, B. Soumaya, and K. M. A, “The impact of facade materials on the thermal comfort and energy efficiency of offices buildings,” *J. Build. Mater. Struct*, vol. 5, pp. 55–64, 2018, doi: 10.5281/zenodo.1285954.

[28] W. J. Cole, E. T. Hale, and T. F. Edgar, “Building energy model reduction for model predictive control using OpenStudio,” in *Proceedings of the American Control Conference*, 2013, pp. 449–454. doi: 10.1109/acc.2013.6579878.

[29] “Frank P Incropera-Fundamentals of heat and mass transfer-John Wiley (2007) - 6ªEDICAO (1)”.

[30] R. Manuel dos Santos Teixeira and V. Manuel da Silva Leal, “Avaliação e pré-dimensionamento de um dispositivo de mudança de fase para mitigação de ondas de calor,” 2019.

[31] H. Johra and P. Heiselberg, “Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review,” *Renewable and Sustainable Energy Reviews*, vol. 69. Elsevier Ltd, pp. 19–32, Mar. 01, 2017. doi: 10.1016/j.rser.2016.11.145.

[32] Big Ladder Software, “Unmet Hours.”

Appendices

Appendix A: Input of building construction data

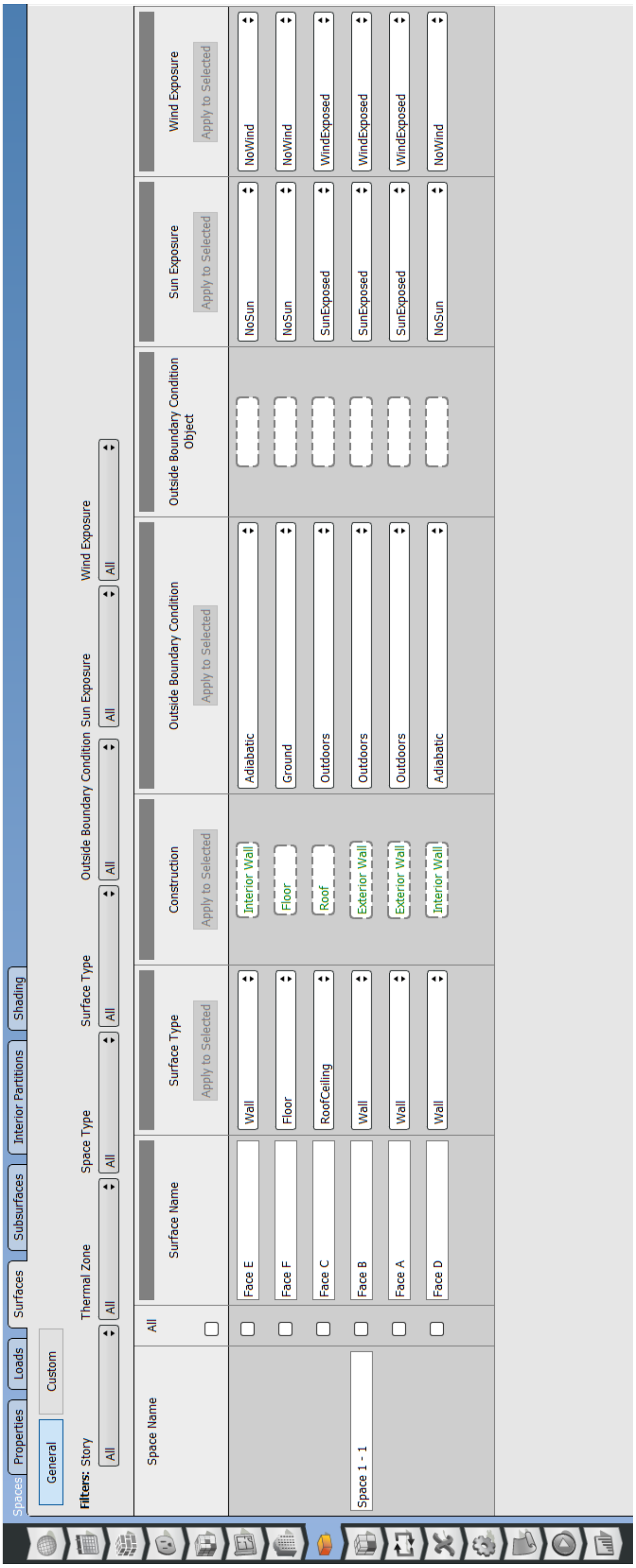

Figure A 1: Surfaces specifications

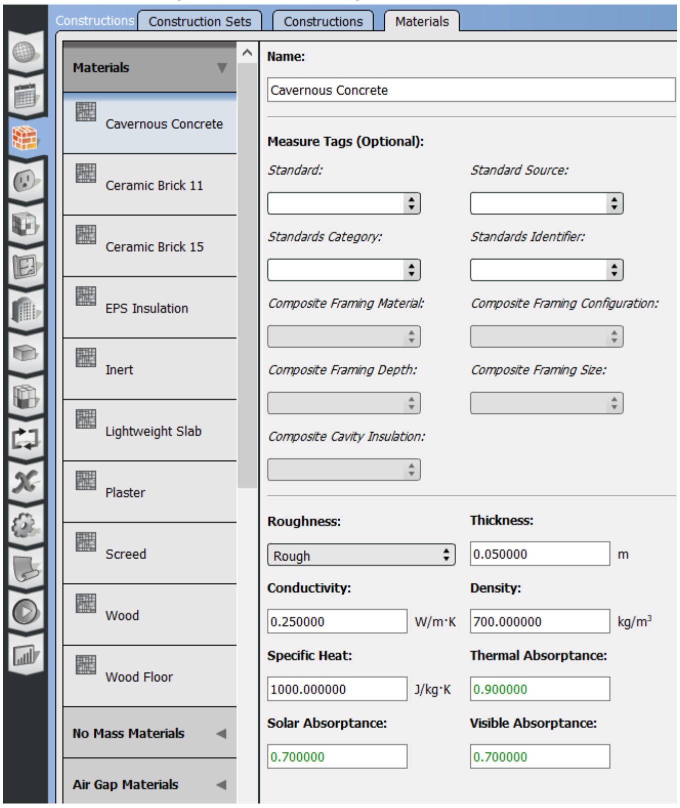

Figure A 2: Material generation

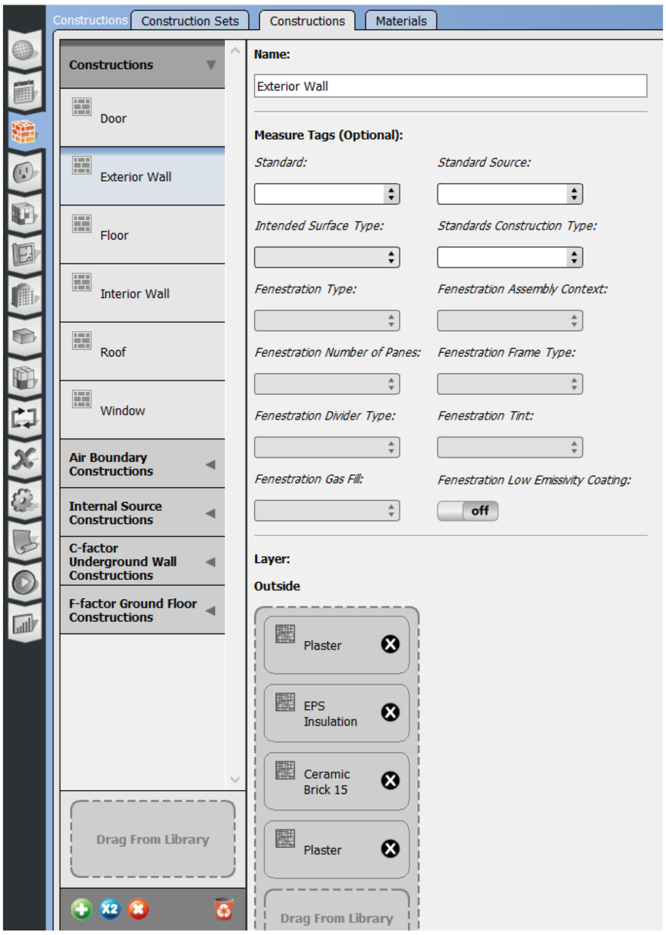

Figure A 3: Surfaces Creation

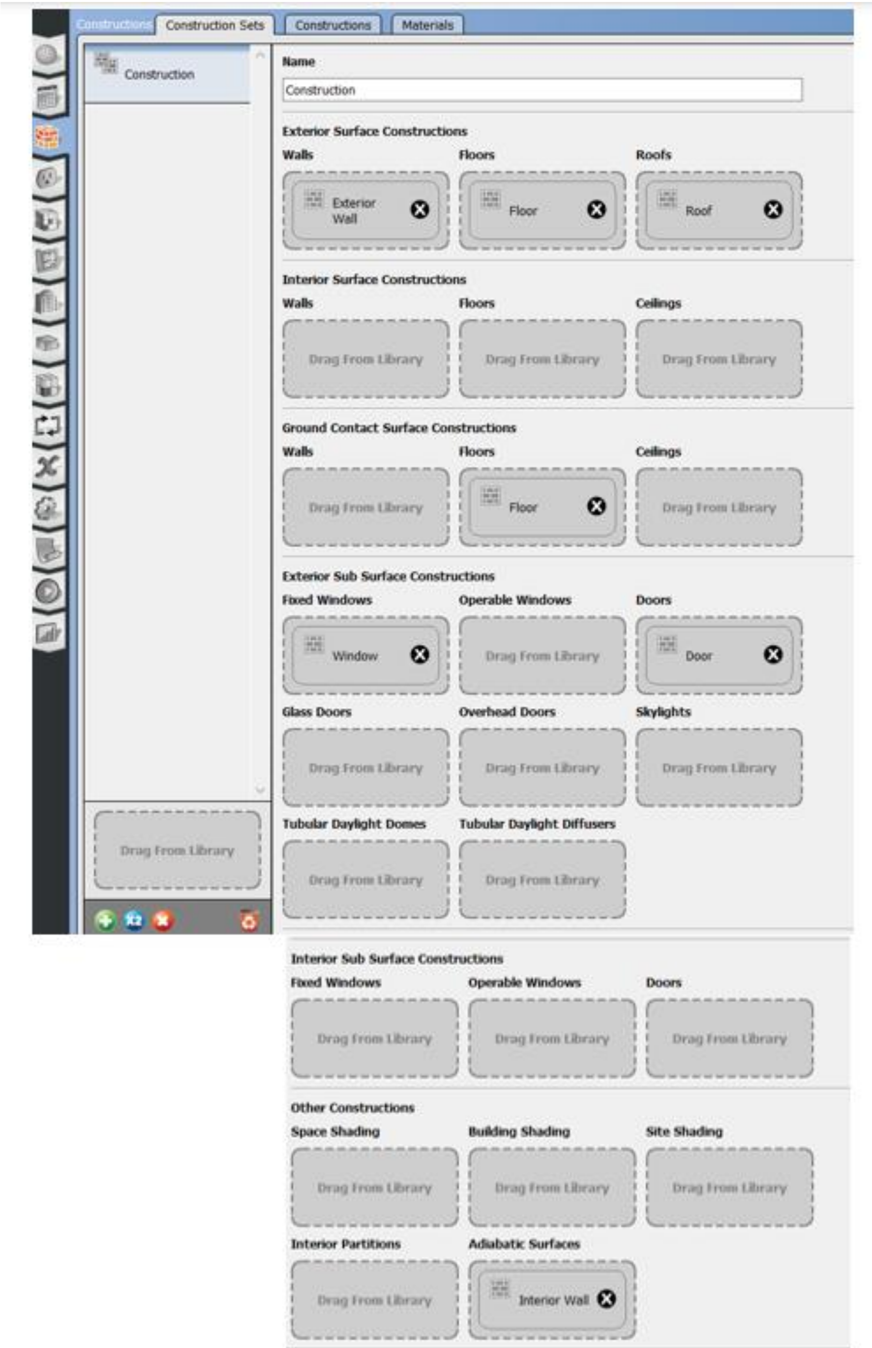

Figure A 4: Construction settings

Appendix B: Simulation Analysis

Table B 1: Comparison of the results obtained through the simulation and the approach curve for the windowless room during the morning

	LTI			*HTI (x7)*			*HTI Construction*		
Time	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**
08:00	21,9	22,0	0,4	21,9	22,0	0,4	21,9	22,0	0,3
08:03	21,0	20,7	1,3	21,0	20,7	1,2	21,1	20,8	1,1
08:06	19,6	19,7	0,5	19,7	19,9	0,5	19,8	20,0	0,6
08:09	18,8	19,1	1,3	19,0	19,2	1,2	19,1	19,3	1,3
08:12	18,7	18,6	0,5	18,9	18,8	0,4	19,0	18,9	0,4
08:15	18,4	18,3	0,6	18,6	18,5	0,7	18,7	18,6	0,8
08:18	18,2	18,1	0,2	18,4	18,3	0,5	18,5	18,4	0,7
08:21	18,0	18,0	0,3	18,1	18,2	0,4	18,2	18,2	0,1
08:24	18,0	18,0	0,1	18,0	18,1	0,3	18,0	18,1	0,6
08:27	18,0	18,0	0,0	18,0	18,0	0,1	18,0	18,1	0,3
08:30	18,0	18,0	0,0	18,0	18,0	0,0	18,0	18,0	0,1
08:33	18,0	18,0	0,0	18,0	18,0	0,1	18,0	18,0	0,0
08:36	18,0	18,0	0,0	18,0	18,0	0,1	18,0	18,0	0,1
08:39	18,0	18,0	0,0	18,0	18,0	0,1	18,0	18,0	0,1
08:42	18,0	18,0	0,0	18,0	18,0	0,0	18,0	18,0	0,1
08:45	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,1
08:48	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,0
08:51	18,0	18,0	0,0	18,0	18,0	0,0	18,0	18,0	0,1
08:54	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,1
08:57	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,1
09:00	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,1

Table B 2: Comparison of the results obtained through the simulation and the approach curve for the windowless room during the night

	LTI			HTI (x7)			HTI Construction		
Time	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**
19:00	22,0	21,7	1,2	22,0	21,7	1,4	22,0	21,6	1,7
19:03	21,6	21,4	1,0	21,5	21,3	1,1	21,4	21,1	1,0
19:06	20,9	21,0	0,3	20,9	21,0	0,4	20,5	20,7	1,2
19:09	20,5	20,7	0,9	20,5	20,7	1,0	19,9	20,3	2,1
19:12	20,2	20,5	1,1	20,2	20,4	1,1	19,9	20,0	0,8
19:15	20,0	20,2	0,9	20,0	20,2	1,0	19,7	19,7	0,1
19:18	19,9	20,0	0,7	19,8	20,0	0,8	19,5	19,5	0,1
19:21	19,8	19,9	0,5	19,7	19,8	0,5	19,2	19,3	0,2
19:24	19,7	19,7	0,2	19,6	19,7	0,3	19,1	19,1	0,1
19:27	19,6	19,6	0,1	19,6	19,6	0,1	18,9	18,9	0,0
19:30	19,5	19,5	0,0	19,5	19,5	0,1	18,8	18,8	0,1
19:33	19,4	19,4	0,1	19,4	19,4	0,2	18,7	18,7	0,2
19:36	19,4	19,3	0,2	19,4	19,3	0,3	18,6	18,6	0,2
19:39	19,4	19,3	0,3	19,3	19,3	0,4	18,6	18,5	0,3
19:42	19,3	19,2	0,4	19,3	19,2	0,5	18,5	18,5	0,3
19:45	19,3	19,2	0,5	19,3	19,2	0,5	18,5	18,4	0,3
19:48	19,3	19,2	0,5	19,3	19,2	0,5	18,4	18,4	0,4
19:51	19,2	19,1	0,5	19,2	19,1	0,5	18,4	18,4	0,4
19:54	19,2	19,1	0,5	19,2	19,1	0,5	18,4	18,3	0,3
19:57	19,2	19,1	0,4	19,2	19,1	0,4	18,4	18,3	0,3
20:00	19,2	19,1	0,4	19,2	19,1	0,4	18,4	18,3	0,3
20:03	19,2	19,1	0,3	19,2	19,1	0,3	18,4	18,3	0,2
20:06	19,1	19,1	0,2	19,1	19,1	0,2	18,3	18,3	0,2
20:09	19,1	19,1	0,2	19,1	19,1	0,2	18,3	18,3	0,1
20:12	19,1	19,1	0,1	19,1	19,1	0,1	18,3	18,3	0,0
20:15	19,1	19,1	0,0	19,1	19,1	0,0	18,3	18,3	0,0
20:18	19,1	19,1	0,0	19,1	19,1	0,1	18,3	18,3	0,1
20:21	19,1	19,1	0,1	19,1	19,1	0,1	18,3	18,3	0,1
20:24	19,1	19,1	0,2	19,1	19,1	0,2	18,3	18,3	0,2
20:27	19,0	19,1	0,2	19,0	19,1	0,3	18,3	18,3	0,2
20:30	19,0	19,1	0,3	19,0	19,1	0,3	18,3	18,3	0,3
20:33	19,0	19,1	0,3	19,0	19,1	0,3	18,3	18,3	0,3
20:36	19,0	19,1	0,3	19,0	19,1	0,3	18,3	18,3	0,3
20:39	19,0	19,0	0,4	19,0	19,0	0,4	18,3	18,3	0,3
20:42	19,0	19,0	0,4	19,0	19,0	0,4	18,3	18,3	0,3
20:45	18,9	19,0	0,4	18,9	19,0	0,4	18,3	18,3	0,3
20:48	18,9	19,0	0,3	18,9	19,0	0,3	18,3	18,3	0,3
20:51	18,9	19,0	0,3	18,9	19,0	0,3	18,3	18,3	0,2
20:54	18,9	19,0	0,3	18,9	19,0	0,3	18,2	18,3	0,2
20:57	18,9	18,9	0,2	18,9	18,9	0,2	18,2	18,3	0,1
21:00	18,9	18,9	0,2	18,9	18,9	0,2	18,2	18,3	0,1
21:03	18,9	18,9	0,2	18,9	18,9	0,1	18,2	18,2	0,0
21:06	18,8	18,9	0,1	18,8	18,9	0,1	18,2	18,2	0,0
21:09	18,8	18,8	0,1	18,8	18,8	0,1	18,2	18,2	0,0
21:12	18,8	18,8	0,0	18,8	18,8	0,0	18,2	18,2	0,1

21:15	18,8	18,8	0,0	18,8	18,8	0,0	18,2	18,2	0,1
21:18	18,7	18,7	0,0	18,8	18,7	0,1	18,2	18,2	0,1
21:21	18,7	18,7	0,1	18,7	18,7	0,1	18,2	18,1	0,1
21:24	18,7	18,7	0,1	18,7	18,7	0,1	18,1	18,1	0,1
21:27	18,7	18,6	0,1	18,7	18,7	0,1	18,1	18,1	0,2
21:30	18,6	18,6	0,1	18,7	18,6	0,2	18,1	18,1	0,2
21:33	18,6	18,6	0,2	18,6	18,6	0,2	18,1	18,1	0,2
21:36	18,6	18,6	0,2	18,6	18,6	0,2	18,1	18,1	0,2
21:39	18,6	18,5	0,2	18,6	18,5	0,2	18,1	18,0	0,1
21:42	18,5	18,5	0,2	18,6	18,5	0,2	18,1	18,0	0,1
21:45	18,5	18,5	0,2	18,5	18,5	0,2	18,0	18,0	0,1
21:48	18,5	18,4	0,2	18,5	18,5	0,2	18,0	18,0	0,1
21:51	18,5	18,4	0,2	18,5	18,5	0,2	18,0	18,0	0,0
21:54	18,4	18,4	0,2	18,5	18,4	0,2	18,0	18,0	0,0
21:57	18,4	18,4	0,2	18,4	18,4	0,2	18,0	18,0	0,0
22:00	18,4	18,3	0,2	18,4	18,4	0,2	18,0	18,0	0,1
22:03	18,3	18,3	0,2	18,4	18,4	0,1	18,0	18,0	0,1
22:06	18,3	18,3	0,2	18,4	18,3	0,1	18,0	18,0	0,1
22:09	18,3	18,3	0,1	18,3	18,3	0,1	18,0	18,0	0,1
22:12	18,3	18,3	0,1	18,3	18,3	0,1	18,0	18,0	0,1
22:15	18,3	18,2	0,1	18,3	18,3	0,1	18,0	18,0	0,1
22:18	18,2	18,2	0,1	18,3	18,3	0,0	18,0	18,0	0,1
22:21	18,2	18,2	0,0	18,3	18,3	0,0	18,0	18,0	0,0
22:24	18,2	18,2	0,0	18,3	18,3	0,0	18,0	18,0	0,0
22:27	18,2	18,2	0,0	18,2	18,2	0,0	18,0	18,0	0,0
22:30	18,1	18,2	0,1	18,2	18,2	0,0	18,0	18,0	0,0
22:33	18,1	18,1	0,1	18,2	18,2	0,1	18,0	18,0	0,1
22:36	18,1	18,1	0,2	18,2	18,2	0,1	18,0	18,0	0,1
22:39	18,1	18,1	0,2	18,2	18,2	0,1	18,0	18,0	0,1
22:42	18,1	18,1	0,3	18,1	18,2	0,2	18,0	18,0	0,1
22:45	18,0	18,1	0,3	18,1	18,2	0,2	18,0	18,0	0,1
22:48	18,0	18,1	0,4	18,1	18,1	0,2	18,0	18,0	0,2
22:51	18,0	18,1	0,4	18,1	18,1	0,2	18,0	18,0	0,2
22:54	18,0	18,1	0,3	18,1	18,1	0,2	18,0	18,0	0,2
22:57	18,0	18,1	0,3	18,1	18,1	0,3	18,0	18,0	0,2
23:00	18,0	18,0	0,2	18,0	18,1	0,3	18,0	18,0	0,2
23:03	18,0	18,0	0,2	18,0	18,1	0,3	18,0	18,0	0,2
23:06	18,0	18,0	0,1	18,0	18,1	0,3	18,0	18,0	0,1
23:09	18,0	18,0	0,1	18,0	18,0	0,2	18,0	18,0	0,1
23:12	18,0	18,0	0,0	18,0	18,0	0,2	18,0	18,0	0,1
23:15	18,0	18,0	0,0	18,0	18,0	0,0	18,0	18,0	0,0
23:18	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,0
23:21	18,0	18,0	0,1	18,0	18,0	0,1	18,0	18,0	0,0
23:24	18,0	18,0	0,2	18,0	18,0	0,2	18,0	18,0	0,1
23:27	18,0	18,0	0,2	18,0	18,0	0,3	18,0	18,0	0,1
23:30	18,0	18,0	0,2	18,0	17,9	0,3	18,0	18,0	0,2
23:33	18,0	18,0	0,3	18,0	17,9	0,3	18,0	18,0	0,2
23:36	18,0	18,0	0,3	18,0	17,9	0,3	18,0	18,0	0,2
23:39	18,0	18,0	0,2	18,0	17,9	0,3	18,0	18,0	0,2
23:42	18,0	18,0	0,2	18,0	17,9	0,3	18,0	18,0	0,2

23:45	18,0	18,0	0,1	18,0	18,0	0,2	18,0	18,0	0,2
23:48	18,0	18,0	0,0	18,0	18,0	0,1	18,0	18,0	0,1
23:51	18,0	18,0	0,1	18,0	18,0	0,1	18,0	18,0	0,0
23:54	18,0	18,0	0,2	18,0	18,1	0,3	18,0	18,0	0,2
23:57	18,0	18,1	0,5	18,0	18,1	0,6	18,0	18,1	0,4

Table B 3: Comparison of the results obtained through the simulation and the approach curve for the room with windows during the morning

	LTI			***HTI (x7)***			***HTI Construction***		
Time	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**	**Simulation**	**Estimate**	**Error**
08:00	21,9	21,9	0,2	21,9	21,9	0,1	21,9	21,9	0,1
08:03	21,2	21,1	0,8	21,0	21,1	0,2	21,1	20,9	0,8
08:06	20,2	20,4	0,9	19,7	20,4	3,2	20,0	20,2	1,0
08:09	19,6	19,9	1,5	19,0	19,9	4,6	19,3	19,7	1,6
08:12	19,5	19,5	0,1	18,9	19,5	3,3	19,3	19,2	0,2
08:15	19,4	19,2	0,7	18,6	19,2	3,1	19,1	18,9	0,9
08:18	19,2	19,0	1,0	18,4	19,0	3,1	18,9	18,7	1,2
08:21	18,9	18,8	0,7	18,1	18,8	3,7	18,6	18,5	0,7
08:24	18,7	18,6	0,2	18,0	18,6	3,3	18,4	18,3	0,1
08:27	18,5	18,5	0,1	18,0	18,5	2,7	18,2	18,2	0,4
08:30	18,3	18,4	0,3	18,0	18,4	2,1	18,0	18,2	0,7
08:33	18,2	18,3	0,4	18,0	18,3	1,7	18,0	18,1	0,6
08:36	18,1	18,2	0,5	18,0	18,2	1,2	18,0	18,1	0,4
08:39	18,0	18,1	0,6	18,0	18,2	0,8	18,0	18,0	0,2
08:42	18,0	18,1	0,4	18,0	18,1	0,5	18,0	18,0	0,0
08:45	18,0	18,0	0,1	18,0	18,0	0,3	18,0	18,0	0,1
08:48	18,0	18,0	0,1	18,0	18,0	0,0	18,0	18,0	0,1
08:51	18,0	18,0	0,2	18,0	18,0	0,1	18,0	18,0	0,2
08:54	18,0	17,9	0,3	18,0	18,0	0,2	18,0	18,0	0,2
08:57	18,0	17,9	0,3	18,0	18,0	0,3	18,0	18,0	0,2
09:00	18,0	17,9	0,3	18,0	18,0	0,3	18,0	18,0	0,2

Table B 4: Comparison of the results obtained through the simulation and the approach curve for the room with windows during the night

	LTI			HTI (x7)			HTI Construction		
Time	Simulation	Estimate	Error	Simulation	Estimate	Error	Simulation	Estimate	Error
19:00	22,0	22,0	0,0	22,0	21,9	0,5	22,0	21,8	1,1
19:03	21,9	21,8	0,1	21,8	21,7	0,4	21,6	21,4	1,1
19:06	21,7	21,7	0,1	21,5	21,5	0,1	21,0	21,1	0,2
19:09	21,5	21,6	0,1	21,2	21,3	0,4	20,6	20,8	0,9
19:12	21,4	21,4	0,1	21,1	21,2	0,4	20,4	20,6	1,1
19:15	21,3	21,3	0,0	21,0	21,0	0,3	20,2	20,4	1,0
19:18	21,2	21,2	0,0	20,8	20,9	0,2	20,1	20,2	0,7
19:21	21,1	21,1	0,0	20,7	20,8	0,1	20,0	20,1	0,4
19:24	21,0	21,0	0,0	20,7	20,7	0,1	19,9	19,9	0,2
19:27	21,0	21,0	0,0	20,6	20,6	0,0	19,8	19,8	0,1
19:30	20,9	20,9	0,1	20,5	20,5	0,0	19,7	19,7	0,1
19:33	20,8	20,8	0,1	20,4	20,4	0,1	19,7	19,7	0,2
19:36	20,8	20,7	0,1	20,4	20,3	0,1	19,7	19,6	0,3
19:39	20,7	20,7	0,1	20,3	20,3	0,2	19,6	19,6	0,4
19:42	20,7	20,6	0,2	20,3	20,2	0,2	19,6	19,5	0,5
19:45	20,6	20,6	0,1	20,2	20,2	0,3	19,6	19,5	0,5
19:48	20,5	20,5	0,1	20,2	20,1	0,3	19,6	19,5	0,5
19:51	20,5	20,5	0,1	20,1	20,1	0,2	19,6	19,5	0,5
19:54	20,4	20,4	0,1	20,1	20,1	0,2	19,5	19,5	0,4
19:57	20,4	20,4	0,0	20,1	20,0	0,2	19,5	19,5	0,4
20:00	20,3	20,3	0,0	20,0	20,0	0,2	19,5	19,5	0,3
20:03	20,3	20,3	0,0	20,0	19,9	0,1	19,5	19,5	0,2
20:06	20,2	20,2	0,1	19,9	19,9	0,1	19,5	19,5	0,2
20:09	20,2	20,2	0,1	19,9	19,9	0,0	19,5	19,5	0,1
20:12	20,1	20,2	0,1	19,9	19,9	0,0	19,5	19,5	0,0
20:15	20,1	20,1	0,2	19,8	19,8	0,1	19,5	19,5	0,1
20:18	20,0	20,1	0,2	19,8	19,8	0,1	19,5	19,5	0,1
20:21	20,0	20,0	0,2	19,7	19,8	0,1	19,4	19,5	0,2
20:24	19,9	20,0	0,2	19,7	19,7	0,2	19,4	19,5	0,3
20:27	19,9	19,9	0,2	19,7	19,7	0,2	19,4	19,5	0,3
20:30	19,8	19,9	0,2	19,6	19,7	0,2	19,4	19,5	0,3
20:33	19,8	19,8	0,2	19,6	19,6	0,2	19,4	19,5	0,3
20:36	19,8	19,8	0,2	19,6	19,6	0,2	19,4	19,5	0,4
20:39	19,7	19,7	0,2	19,5	19,6	0,2	19,4	19,5	0,4
20:42	19,7	19,7	0,1	19,5	19,5	0,2	19,4	19,4	0,3
20:45	19,6	19,6	0,1	19,5	19,5	0,2	19,4	19,4	0,3
20:48	19,6	19,6	0,1	19,4	19,5	0,2	19,4	19,4	0,3
20:51	19,5	19,5	0,0	19,4	19,4	0,1	19,4	19,4	0,3
20:54	19,5	19,5	0,1	19,4	19,4	0,1	19,3	19,4	0,2
20:57	19,5	19,4	0,1	19,3	19,3	0,0	19,3	19,4	0,1
21:00	19,4	19,4	0,2	19,3	19,3	0,0	19,3	19,3	0,1
21:03	19,4	19,3	0,2	19,3	19,3	0,1	19,3	19,3	0,0
21:06	19,3	19,3	0,3	19,2	19,2	0,1	19,3	19,3	0,0
21:09	19,3	19,2	0,3	19,2	19,2	0,1	19,3	19,3	0,1
21:12	19,2	19,2	0,3	19,1	19,1	0,2	19,3	19,2	0,1
21:15	19,2	19,1	0,3	19,1	19,1	0,2	19,2	19,2	0,1

21:18	19,1	19,0	0,3	19,1	19,0	0,2	19,2	19,2	0,1
21:21	19,0	19,0	0,3	19,0	19,0	0,2	19,2	19,2	0,1
21:24	19,0	18,9	0,3	19,0	18,9	0,2	19,2	19,1	0,1
21:27	18,9	18,9	0,3	18,9	18,9	0,2	19,1	19,1	0,2
21:30	18,9	18,8	0,2	18,9	18,8	0,2	19,1	19,1	0,2
21:33	18,8	18,8	0,2	18,8	18,8	0,2	19,1	19,0	0,2
21:36	18,7	18,7	0,2	18,8	18,7	0,2	19,0	19,0	0,2
21:39	18,7	18,6	0,2	18,7	18,7	0,2	19,0	19,0	0,2
21:42	18,6	18,6	0,1	18,7	18,6	0,2	19,0	19,0	0,2
21:45	18,5	18,5	0,1	18,6	18,6	0,2	19,0	18,9	0,2
21:48	18,5	18,5	0,0	18,6	18,5	0,1	18,9	18,9	0,1
21:51	18,4	18,4	0,1	18,5	18,5	0,1	18,9	18,9	0,1
21:54	18,4	18,4	0,2	18,5	18,4	0,1	18,9	18,8	0,1
21:57	18,3	18,3	0,2	18,4	18,4	0,0	18,8	18,8	0,1
22:00	18,2	18,3	0,4	18,4	18,4	0,0	18,8	18,8	0,0
22:03	18,2	18,3	0,5	18,3	18,3	0,1	18,8	18,8	0,0
22:06	18,1	18,2	0,6	18,3	18,3	0,1	18,8	18,8	0,0
22:09	18,1	18,2	0,6	18,2	18,2	0,1	18,7	18,7	0,0
22:12	18,0	18,1	0,7	18,2	18,2	0,2	18,7	18,7	0,0
22:15	18,0	18,1	0,6	18,1	18,2	0,2	18,7	18,7	0,0
22:18	18,0	18,1	0,4	18,1	18,1	0,2	18,7	18,7	0,0
22:21	18,0	18,1	0,3	18,1	18,1	0,3	18,7	18,7	0,0
22:24	18,0	18,0	0,2	18,0	18,1	0,4	18,6	18,7	0,0
22:27	18,0	18,0	0,0	18,0	18,1	0,4	18,6	18,6	0,0
22:30	18,0	18,0	0,1	18,0	18,0	0,3	18,6	18,6	0,0
22:33	18,0	18,0	0,2	18,0	18,0	0,2	18,6	18,6	0,0
22:36	18,0	18,0	0,2	18,0	18,0	0,1	18,6	18,6	0,1
22:39	18,0	17,9	0,3	18,0	18,0	0,0	18,6	18,6	0,1
22:42	18,0	17,9	0,3	18,0	18,0	0,1	18,5	18,6	0,1
22:45	18,0	17,9	0,4	18,0	18,0	0,1	18,5	18,6	0,1
22:48	18,0	17,9	0,4	18,0	18,0	0,2	18,5	18,5	0,1
22:51	18,0	17,9	0,4	18,0	18,0	0,2	18,5	18,5	0,1
22:54	18,0	17,9	0,4	18,0	18,0	0,2	18,5	18,5	0,2
22:57	18,0	17,9	0,3	18,0	18,0	0,2	18,5	18,5	0,2
23:00	18,0	17,9	0,3	18,0	18,0	0,2	18,5	18,5	0,2
23:03	18,0	18,0	0,3	18,0	18,0	0,2	18,4	18,5	0,2
23:06	18,0	18,0	0,2	18,0	18,0	0,2	18,4	18,5	0,2
23:09	18,0	18,0	0,2	18,0	18,0	0,2	18,4	18,5	0,1
23:12	18,0	18,0	0,1	18,0	18,0	0,1	18,4	18,4	0,1
23:15	18,0	18,0	0,0	18,0	18,0	0,1	18,4	18,4	0,0
23:18	18,0	18,0	0,0	18,0	18,0	0,1	18,4	18,4	0,0
23:21	18,0	18,0	0,1	18,0	18,0	0,0	18,4	18,4	0,1
23:24	18,0	18,0	0,2	18,0	18,0	0,0	18,4	18,4	0,1
23:27	18,0	18,0	0,2	18,0	18,0	0,1	18,4	18,4	0,1
23:30	18,0	18,0	0,2	18,0	18,0	0,1	18,4	18,4	0,2
23:33	18,0	18,0	0,3	18,0	18,0	0,1	18,4	18,4	0,2
23:36	18,0	18,1	0,3	18,0	18,0	0,1	18,4	18,4	0,2
23:39	18,0	18,0	0,3	18,0	18,0	0,1	18,4	18,4	0,2
23:42	18,0	18,0	0,2	18,0	18,0	0,1	18,4	18,4	0,2
23:45	18,0	18,0	0,2	18,0	18,0	0,1	18,4	18,4	0,1

23:48	18,0	18,0	0,1	18,0	18,0	0,1	18,4	18,4	0,1
23:51	18,0	18,0	0,1	18,0	18,0	0,0	18,4	18,4	0,1
23:54	18,0	18,0	0,2	18,0	18,0	0,1	18,4	18,5	0,2
23:57	18,0	17,9	0,5	18,0	18,0	0,2	18,4	18,5	0,4