Universidade de Aveiro Departamento de Ambiente e Ordenamento
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O COMPORTAMENTO ENERGÉTICO E A REDUÇÃO DE CONSUMO EM EDIFÍCIOS DE SERVIÇOS

ENERGY BEHAVIOUR AND CONSUMPTION REDUCTION IN SERVICE BUILDINGS

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Sistemas Energéticos Sustentáveis, realizada sob a orientação científica do Doutor Nelson Amadeu Dias Martins, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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agradecimentos

To my supervisor Nelson Martins, for his thorough contributions and guidance throughout this process.
To my family, for their endless support.
To my partner, for encouraging me all these years.
To all my teachers who shared their knowledge and led me here.

keywords *Occupant behaviour; Dynamic simulation; Service sector buildings.*

abstract

In view of the current global scenery, in which several nations are striving against global warming, energy efficiency rises as a cost-effective prospect. As the building sector accounts for over one-fifth of the total delivered energy consumed worldwide, it has great potential for implementing rationalization and energy efficiency measures. Service buildings are expected to have the highest growth in energy consumption when compared to residential buildings and are therefore the focus of this thesis.

Energy reduction efforts for service buildings are vast; however, they are concentrated mostly on technological opportunities. Behaviour changes represent a great potential for reducing energy consumption without significant financial costs, but still, they are commonly disregarded. Hence, the present dissertation aims to propose a quantitative methodology to analyze occupants' behaviours and their impact on energy consumption in service buildings.

Results are acquired through the use of dynamic simulation, namely DesignBuilder software. Energy consumption due to behaviour is determined by simulating the occupant interactions with equipment, lighting and HVAC systems. To that end, three occupancy profiles were fixed: standard occupants' interactions are defined by Decree-Law nº 79/2006; efficient occupants have extreme efficient behaviours leading to energy savings; inefficient ones lead to extreme energy waste.

Dynamic simulation results give evidence of the occupancy impact on energy consumption. Efficient behaviours were able to reduce energy consumption by over 34%. However, regardless of the rigorousness of efficient behaviours, waste potential by inefficient occupants was always higher than saving potential. This result highlights the importance of understanding occupant behaviours and its accurate consideration of dynamic simulation tools.

palavras-chave

Comportamento do ocupante; Simulação dinâmica; Edifícios do setor de serviços.

resumo

No atual cenário mundial, no qual diversas nações lutam contra o aquecimento global, a eficiência energética se destaca como uma opção viável. O setor de edifícios é responsável pelo consumo de mais de um quinto da energia total gerada, e por isso possui grande potencial para a implementação de medidas de racionalização e eficiência energética. Espera-se que os edifícios de serviços tenham o maior crescimento no consumo de energia quando comparados aos edifícios residenciais, e, portanto, são o foco desta tese.

As possibilidades de redução de energia para os edifícios de serviços são vastas; no entanto, estas se concentram principalmente em oportunidades tecnológicas. As mudanças de comportamento representam um grande potencial para reduzir o consumo de energia sem custos financeiros significativos, no entanto ainda são geralmente desconsiderados. Dessa forma, a presente dissertação visa propor uma metodologia quantitativa para análise dos comportamentos dos ocupantes e seu impacto no consumo de energia em edifícios de serviços.

Os resultados foram adquiridos através do uso da simulação dinâmica de edifícios, pelo *software* DesignBuilder. O consumo de energia devido ao comportamento foi determinado pela simulação das interações entre os ocupantes e os equipamentos, sistema de iluminação e de aquecimento, ar condicionado e ventilação. Para este fim, foram considerados três perfis de ocupação: o ocupante de referência teve por base as definições do Decreto-Lei nº 79/2006; os ocupantes eficientes possuem comportamentos extremos e eficientes que levam a economias de energia; ocupantes ineficientes causam um desperdício extremo de energia.

Resultados da simulação dinâmica evidenciam o impacto da ocupação no consumo de energia. Comportamentos eficientes

foram capazes de reduzir o consumo em mais de 34%. No entanto, independentemente do rigor dos comportamentos eficientes, o potencial de desperdício de energia pelos ocupantes ineficientes foi, em todos os casos, superior ao potencial de economia energética pelos ocupantes eficientes. Este resultado destaca a importância de compreender os comportamentos dos ocupantes e assegurar sua análise de forma precisa sobre as ferramentas de simulação dinâmica.

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ABBREVIATIONS

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

BPIE – Buildings Performance Institute Europe

BPS – Building Performance Simulation

DOE – U.S. Department of Energy

EIA – Energy Information Administration

EPC – Energy Performance Certificate

EU – European Union

GDP – Gross Domestic Product

GHG – Greenhouse Gas

HVAC – Heating, Ventilation, and Air-Conditioning

LNEG – Laboratório Nacional de Energia e Geologia

LOB – Large Office Buildings

PTEM – Physical-Technical-Economic Model

RCCTE – Regulamento das Características de Comportamento Térmico dos Edifícios

RSECE – Regulamento dos Sistemas Energéticos de Climatização em Edifícios

SOB – Small Office Buildings

U.S. – United States

ZEB – Zero Energy Buildings

1. INTRODUCTION

1.1. Background and motivation

Energy efficiency and climate change are two of the most discussed topical issues all over the world. Since the Second Industrial Revolution, fossil fuels have become an important source of energy. In fact, coal and natural gas represent more than 60% of the worldwide mix of primary fuels used to generate electricity [1].

The burning of coal, natural gas, and oil for both electricity and heat represent the largest single source of global greenhouse gas (GHG) emissions [2]. Urbanization, population growth and the development of new technologies are some of the factors that increase the amount of energy required by society. According to a projection released by Energy Information Administration (EIA) in 2016 [1], global energy consumption is expected to increase by 48% between 2012 and 2040.

However, several nations are determined to fight global warming and are therefore committed to achieving climate and energy targets established in international treaties. For instance, EU member countries agreed, in 2010, to the Europe 2020 Strategy, which sets energy and climate goals to be achieved by 2020. This agreement foresees the reduction of GHG emissions by 20% compared to 1990 levels, 20% of the energy, on a consumption basis, coming from renewables and a 20% increase in energy efficiency [3]. In 2015, 195 countries signed the Paris Agreement during the United Nations Conference on Climate Change (COP21). This treaty, which will be made effective in 2020, has as its main goal the limitation of global warming by less than 2 ºC [4]. To achieve all of its goals, participating nations have been implementing new energy policies and strategies.

In this scenery, energy efficiency raises as a cost-effective way to reduce GHG emissions and improve energy supply security by reducing primary energy consumption and decreasing energy imports [5]. Although energy efficiency levels have improved over the last years, there is still a significant untapped energy efficiency potential, namely in the building sector [6]. Indeed, buildings offer a great potential for energy saving opportunities since their performance level is frequently far below current efficiency potentials [7].

The building sector plays an important role in energy consumption as it accounts for more than one-fifth of the total delivered energy consumed worldwide and is responsible for approximately one-third of GHG emissions [1,7]. In some countries, like Botswana, Switzerland and the United States of America, this sector accounts for more than 40% of national energy consumption [8]. In Europe, buildings are responsible for around 36% of

CO_2 emissions [9] and therefore represent an increasingly important sector in terms of implementing rationalization and energy efficiency measures [10].

Buildings can be broadly divided into residential and non-residential sectors. The second category accounts for 25% or the total building stock in Europe [9] and has the highest growth in energy consumption. This growth is estimated to be over 26% for service buildings between 2005 and 2030; in the same period, a 12% growth in the residential sector is expected [10].

The analysis of buildings' energy performance certificates (EPCs) can be among the most important drivers of energy performance of the European building stock. It is a valuable information tool that indicates the share of buildings yet to be improved in terms of energy performance, as shown in figure 1. EPCs shall be issued for all buildings which are newly constructed or undergo major renovation; all buildings sold or rented out to a new tenant; all buildings where a total useful floor area over 250 m² is occupied by a public authority and frequently visited by the public [11].

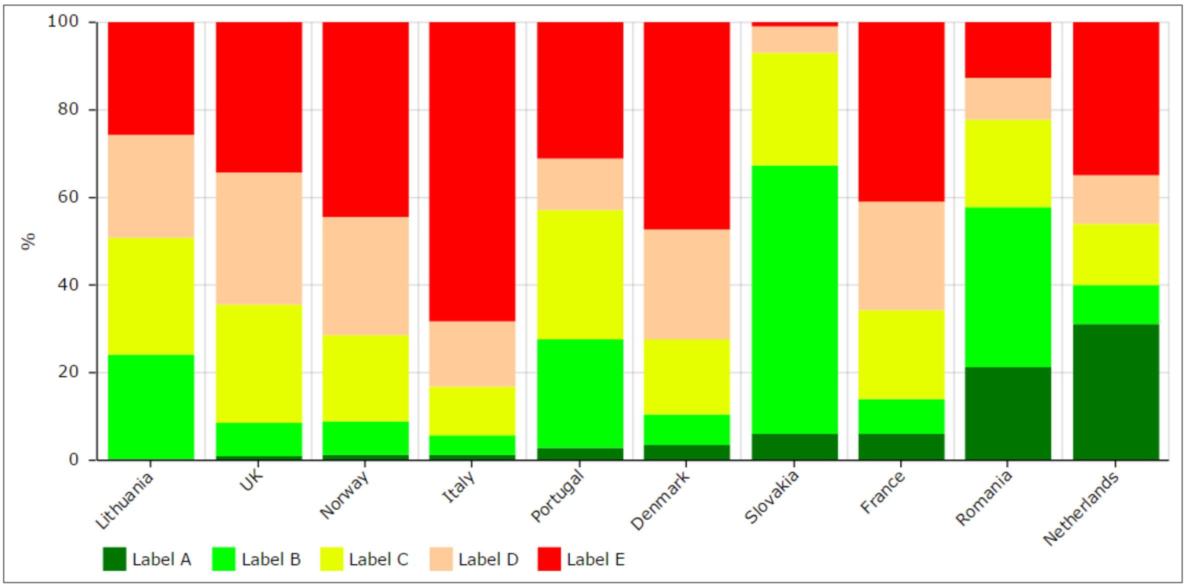


Figure 1: Distribution of non-residential building stock registered in EPC database label by energy class . Source: [11], p.1

Great effort has been made in order to reduce buildings' energy consumption. The number of sustainable construction projects, which consider ecological, social and economic aspects, is growing. In many countries, governments are already requiring all new constructions to use the concept of Zero Energy Buildings (ZEB), in which energy production in-site is equal or superior to the building energy consumption. These constructions integrate renewable energies and efficient techniques to improve energy efficiency in the building. The projects must also give priority to the use of environment-friendly materials and construction techniques [12,13].

However, according to the American Society of Heating, Refrigerating, and Air-Conditioning (ASHRAE), 75% to 85% of all of the buildings that will exist in urban areas in 2030 already exist today. Only 2% of construction projects are new constructions and over 86% of investments in this sector go into existing buildings. Therefore, the greatest opportunity for overall reduction in primary energy use is by increasing energy efficiency of existing service buildings [14].

Energy reduction efforts for existing buildings are numerous and include more energy efficient technologies for heating, cooling and ventilation systems, use of high-efficiency lighting and equipment, intelligent controls, smart glazing, use of renewables, among other alternatives [6,8]. However, these measures are mostly technological. Although energy consumption in buildings is highly influenced by local climates, cultures and by its physical characteristics, people's behaviour is also a major determinant of the energy use. Organizations usually emphasize investments in physical upgrades and new technologies, but behavioural changes are often necessary in order for these technologies to achieve their full potential [15]. Furthermore, since people operate the technologies, failure of the human component can fail the whole mission [8].

While technological opportunities are vast, through behaviour changes it is possible to reduce energy use and GHG emissions immediately and without significant financial costs [16]. Accordingly, there is an emerging interest in this topic. In fact, the World Business Council for Sustainable Development [17] highlights that a lot of building energy is wasted because of inappropriate behaviours and therefore endorses the need for behaviour change.

Over the last decades, several studies have aimed to quantify the impact of occupant behaviour in energy consumption. According to Hoes et al. [18], user behaviour can have a larger influence on a building's energy performance than the thermal process within the building facade. Masoso and Grobler [8] studied the impact of poor occupant behaviour during non-occupied hours in office buildings. Results showed that the building consumed 56% of the energy outside working hours because lights and equipment were left on at the end of the day and because of poor zoning and controls. Dietz et al. [19] offer evidence that behaviour change measures can on their own lead to substantial reductions in energy use and related CO_2 emissions. Nguyen and Aiello [20] suggested that careless energy consumption can result in the use of twice as much energy as the minimum that is possible to achieve.

Although there is an increasing number of research projects, the impact of occupant behaviour on energy use in service buildings and the potential for energy savings are usually neglected. Despite the recognition that human behaviour is an obstacle in the promotion of energy efficiency, there is a great difficulty in quantifying behavioural savings. Current modelling techniques fail to account this impact. Therefore, there is a critical lack of characterization and systematization of how behaviours influence energy consumption and how energy policies can be leveraged [6].

Furthermore, interest in behavioural change reflects a growing recognition that technological solutions alone will not achieve energy conservation goals – policies and behaviour changes are also essential to achieve low-energy buildings [17]. Quantifying the impact of human behaviours in energy consumption is essential to determinate the potential of its reduction. Hence, it is imperative to understand and foresee potential behavioural challenges in order to achieve realistic predictions of energy consumption in buildings and to reduce this consumption to a minimum.

1.2. General objectives

This thesis aims to explore the impact of human behaviour in energy savings of office buildings. This work aims to quantify the effective energy use reduction due to behaviour changes through dynamic simulation with DesingBuilder® software and data collection regarding service buildings' usage patterns. Furthermore, it will be possible to establish which occupant behaviours represent the greatest impact on building energy use by simulating different scenarios and intervention arrangements.

1.3. Research questions and thesis contribution

Two main research questions were formulated:

RQ #1 What is the potential of energy consumption reduction associated with consumer behaviour in service buildings?

RQ #2 Which are the major contributing parameters to the overall reduction of energy consumption?

The main contribution of this study is to propose a quantitative methodology to analyse significant occupants' behaviours and their impact on energy consumption in service buildings. Energy behaviour is a complex topic and therefore it is usually addressed with several limitations in computational simulations. Quantitative studies regarding the influence of behaviours on energy consumption in service buildings are still very scarce and this thesis adds to the state of the art by presenting a computational simulation of occupants' behaviours impacts energy consumption, assuming limit operation profiles.

Furthermore, dynamic simulation is used to identify and understand the importance of occupants' behaviours determinants in the service sector, and evaluate the potential associated with interventions aiming energy behaviours change. This thesis also proposes to acknowledge which are the parameters that have a greater impact on energy consumption in service buildings and therefore should be the focus of potential interventions. This information is fundamental to justify, in a quantitative perspective, the promotion of energy efficiency measures in service sector buildings by acting over occupants' behaviour.

1.4. Thesis outline

This thesis is organized into five major chapters. Chapter 1 aims to provide the context, motivation, and main objectives and contributions of this work. State of the art is elaborated in Chapter 2, exploring behaviours as a challenging topic, the trends of energy efficiency in service buildings, and the modelling approaches of energy behaviours as a way of quantifying behavioural savings potential.

Chapter 3 covers the design and implementation of the practical share of this dissertation, mainly through the study building characterization. This chapter also includes the general methodology adopted in the simulation of office buildings and the procedures to measure which parameters have the most influence on energy consumption.

At Chapter 4, dynamic simulation results are provided and explored. At first, are discussed general results regarding the variation of the parameters established in the methodology. Then, detailed results are presented and examined.

At last, Chapter 5 highlights the main conclusions of this thesis. Also, the answers to the research questions are summarised and suggestions for future work are outlined.

2. LITERATURE REVIEW

This section reviews the literature on energy consumption in non-residential buildings, mainly in the EU-27. It also explores the factors that affect energy consumption in buildings, among which the impact of occupants' behaviour is highlighted. Regarding behaviours, this section also reviews the literature on what influences occupants' decision-making and what drives people to behave as they do. At last, it assesses building dynamic simulation tools and current techniques to realistically address energy behaviour in the simulations.

2.1. Energy consumption in non-residential buildings

The non-residential sector is quite wide and includes private and public buildings used for healthcare, services and commerce. In 2010 this sector accounted for 13.2% of total final energy consumption in the EU-27, and 29.4% of total electricity consumption [21].

Service buildings account for a large share of Gross Domestic Product (GDP) in the European Union. Half of total value added is generated by this sector, and further growth in importance is expected during the next years. Likewise, energy consumption has a tendency to grow over the years. Between 1990 and 2010, final energy consumption grew more than 40% [21]. In the same period, electricity consumption in the service sector has increased by a remarkable 74% in Europe, as shown in figure 2 [9]. Globally, energy consumption in service sector buildings is expected to grow by an average of 1.6% per year from 2012 to 2040, which makes it the fastest-growing energy demand sector [1].

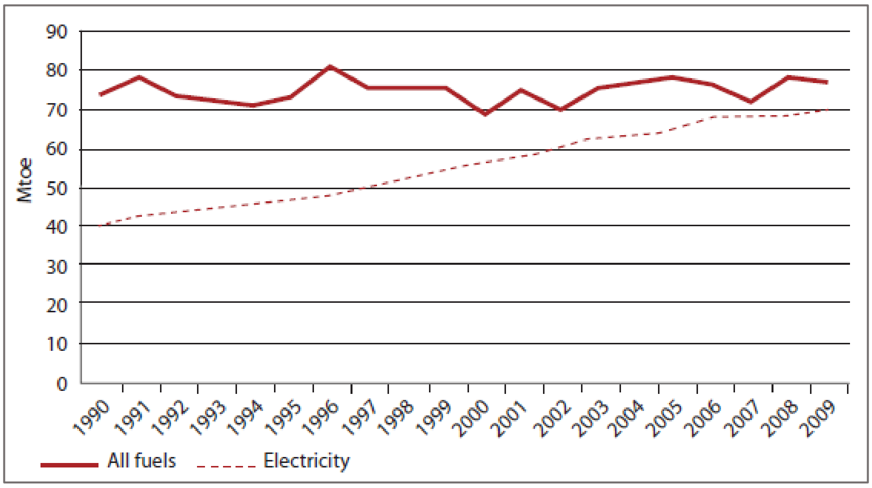


Figure 2: Historical final energy use in the non-residential sector in the EU27, Norway and Switzerland.

Source: [9], p.51

Understanding energy use in the non-residential sector is complex as the energy consumed in each building type is different; e.g., hospitals require much more energy to function than education or office buildings and they also require different settings regarding internal thermal conditions and lighting [22]. In order to understand energy end-uses and CO_2 emissions in this sector, detailed data, still very scarce, is needed. Indeed, finding satisfactory data regarding energy end-uses by building subsector (i.e., public administration, education, health, lodging, etc.) is a tough task, even in developed countries [10]. The European Commission published in 2012 the electricity end-use in the service sector in the EU-27 (figure 3) [21]. However, the report itself informs that "there is much less reliable data available for individual electricity end-uses in the tertiary sector than in the residential sector, and only a few sources attempted to divide total electricity consumption among different end-uses" [21].

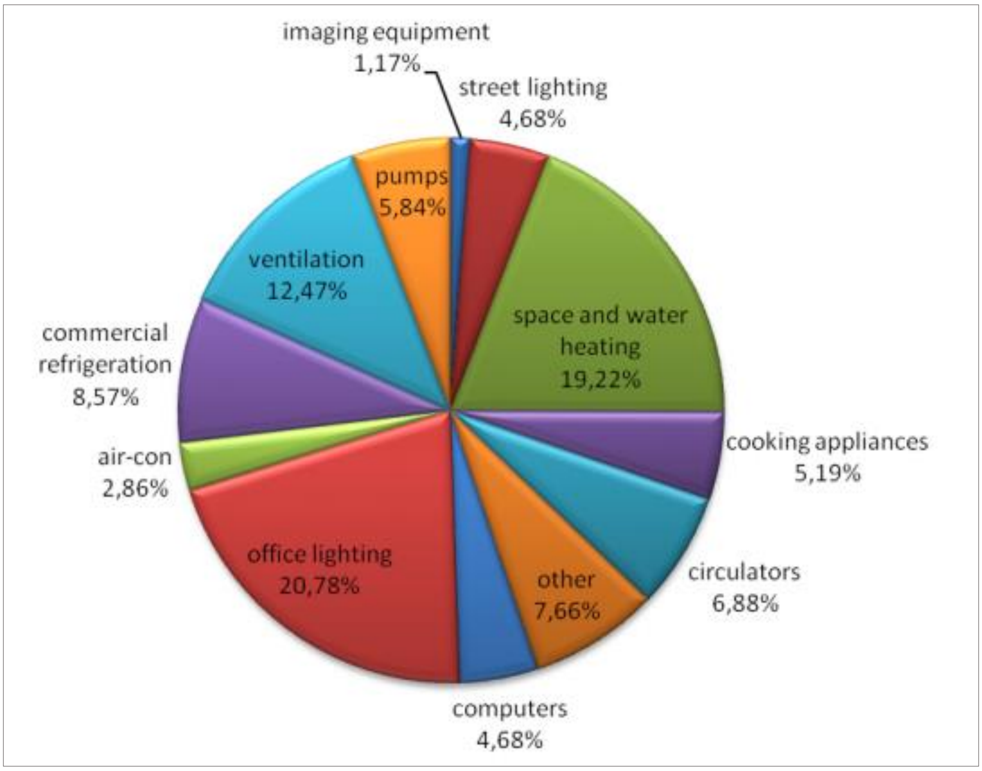


Figure 3: Tertiary electricity consumption breakdown in the EU-27.

Source: [21], p.109

As seen in figure 3, service buildings generally use energy to power equipment for its users and work activities, and to maintain comfortable, healthy, and secure conditions. The range of energy end-uses in any service building typically includes some or all of the following: heating, cooling, hot water, fans and pumps, lighting, and other small power (i.e., computers, photocopiers, controls, security, etc.) [23].

However, one of the most significant barriers to achieving energy efficiency goals in service buildings is the lack of knowledge about the determining factors of real energy use [24]. The amount of energy needed in each building is not only related to end-user equipment and services, but it also depends on several factors that can be divided into seven categories [25]:

1. **Climate** (e.g., outdoor air temperature, solar radiation, wind velocity, etc.)
2. **Building-related characteristics** (e.g., type, area, orientation, etc.)
3. **User-related characteristics** (e.g., user presence, etc.)
4. **Building service systems and operation** (e.g., space cooling/heating, hot water supplying, etc.)
5. **Building occupants' behaviour and activities**
6. **Social and economic factors** (e.g., degree of education, energy cost, etc.)
7. **Indoor environmental quality required**

Among these seven categories, occupants' behaviours indirectly influence both indoor environmental quality required and social and economic factors. Since the impact of behaviour is already contained within the fifth category, there is no need to take them into account when identifying the effects of the last two groups [25].

Some of the categories proposed by Yu et al. [25] deserve further attention, for instance, the study of climate and site layout. Factors such as outdoor air temperature, solar radiation, and wind velocity can deeply affect the energy consumption, e.g., buildings located in cold climates generally have lower cooling energy demand than heating energy demand [25]. The building site layout also should be analysed: its surrounding land and climate, prevailing winds, adjacent buildings, etc. [26]. For example, in urban environments, adjacent constructions may shade the building and affect the intensity of daylight and radiation, which may change lighting and heating demands.

In addition, different local microclimates can also induce very different energy demands on buildings located in the same region, especially when comparing buildings in urban areas with the ones in rural areas. Urban areas usually have higher air temperatures and lower wind speeds due to the high building density, which reduces the natural ventilation potential. Yet, energy losses from the building to the environment are lower in urban areas, which also affect energy demands for heating and cooling [27].

Another significant category is building-related characteristics, which includes several factors that have great influence on the building's energy consumption. Some of these key factors are:

- **Building envelope and insulation:** The building envelope consists of the parts of a building that forms the primary thermal barrier between interior and exterior, including external walls, floors, roofs, ceilings, windows and doors. The envelope determines the energy flow rate within the internal and external environment of the building. Energy loss through the envelope depends on numerous factors, such as the construction technique, materials, design, climate, orientation, and geographical location. The building envelope "plays a key role in determining levels of comfort, natural lighting, and ventilations, and how much energy is required to heat and cool a building" [28] and therefore has a big impact on energy consumption.
- **Size:** Floor space also affects energy consumption in buildings, not necessarily in a proportional manner. In 2016, EIA [22] released data regarding electricity consumption intensities in service buildings according to its areas. Results showed that larger buildings (over 500,000 ft^2) have slightly higher energy intensity than smaller ones (less than 5,000 ft^2). Actually, buildings with floor spaces between 10,000 ft^2 and 25,000 ft^2 are the ones with the lowest energy intensity.
- **Age of the building:** Nowadays there is a very quick development of new technologies related to building energy efficiency. When buildings are constructed or renovated, all parts of the building and the construction process reveal opportunities to improve energy efficiency [28]. Therefore, newer buildings have, overall, better performances regarding energy use, since they tend to have a more efficient envelope and systems.
- **Shape and orientation:** The shape of the building can have a significant influence on the need for heating, and so does the building orientation. The optimum shape is one that transmits the least amount of heat from the interior to the outside during winter season and admits the minimum amount of solar radiation during summer [24]. The building orientation can "provide reductions to cooling loads through minimizing solar penetration through windows, minimizing solar absorption through walls and roofs, and by maximizing cross ventilation" [29].

Despite the complexity of these seven categories, it is possible to analyse and quantify the separate and combined influence of the first four on building energy consumption via dynamic simulation. Current simulation software has a wide variety of parameter settings that allow simulating several situations based upon these four factors [25].

Regarding the buildings' energy performance and their environmental impacts, "there is a tendency to focus on the efficiency of the building geometry and shape, building materials and their thermo-physical characteristics, and on building systems" [24]. However, the occupant behaviour is also a category that demands attention but is still precariously considered in simulations. As previously stated [18-20], it is a known fact that behaviour accounts for a great influence on energy consumption. Occupants are responsible for controlling equipment and systems that account for the massive energy consumption in service buildings, such as lighting and HVAC systems [30,31]. However, as this category involves complex factors and interactions, it is commonly neglected or poorly addressed in simulations. Hence, the following sections of this thesis explore the complexity of human behaviours and their effects on energy consumption in service buildings.

2.2. Building typology

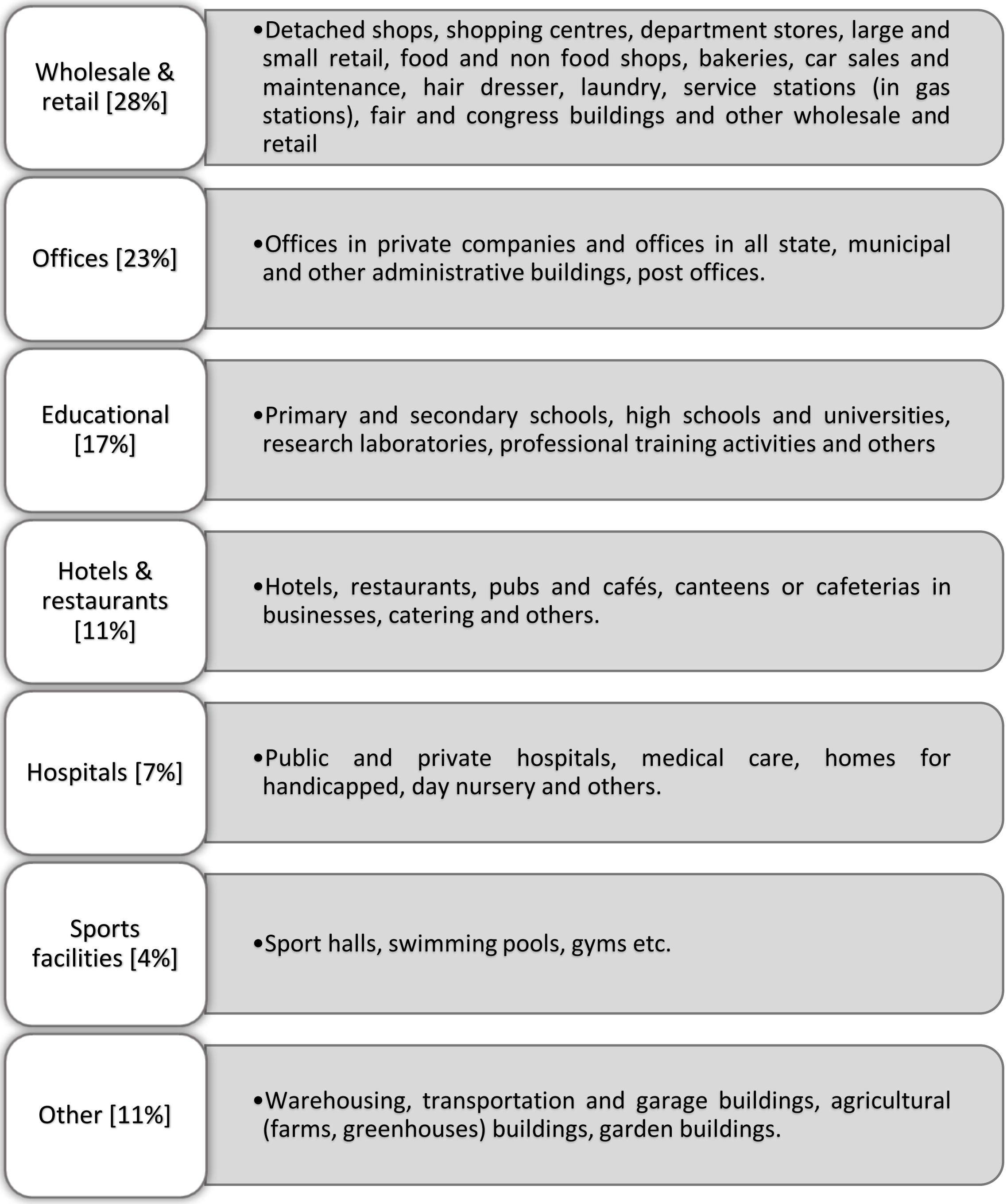
The diversity in terms of typology within the non-residential sector is vast [9]. Buildings are usually classified according to their function, structural system or building materials. There are several ways of classifying buildings, depending on the nature of the study and the purpose of the classification. Although some European countries use the same typology for residential buildings, records of non-residential buildings typologies are diverse and hard to compare [9,32].

Setting up a uniform typology for the non-residential sector is a complex task because of the broad variety of uses and associated characteristics. There is no homogeneity in terms of size, usage pattern and construction style. In addition to this, some buildings have multiple functions and are harder to classify [9,32].

In general, four main parameters are taken into consideration: the utilization of the building (operational patterns, requirements), the year of construction, the size of the building, and the technical building equipment.

The report "Europe's Buildings under the Microscope", published by Buildings Performance Institute Europe (BPIE) [9] gathered data from several countries to create a building categorization at a European level. Figure 3 reveals the considered categories as well as their share. In each one, a broad division between various subcategories has been taken into account.

The retail and wholesale buildings account for the largest portion of the non-residential stock, while office buildings are the second biggest category. Offices and educational buildings account for 40% of the non-residential floor space and usually have similar heating and cooling conditions to residential buildings but with shorter use.



Wholesale & retail [28%]	•Detached shops, shopping centres, department stores, large and small retail, food and non food shops, bakeries, car sales and maintenance, hair dresser, laundry, service stations (in gas stations), fair and congress buildings and other wholesale and retail
Offices [23%]	•Offices in private companies and offices in all state, municipal and other administrative buildings, post offices.
Educational [17%]	•Primary and secondary schools, high schools and universities, research laboratories, professional training activities and others
Hotels & restaurants [11%]	•Hotels, restaurants, pubs and cafés, canteens or cafeterias in businesses, catering and others.
Hospitals [7%]	•Public and private hospitals, medical care, homes for handicapped, day nursery and others.
Sports facilities [4%]	•Sport halls, swimming pools, gyms etc.
Other [11%]	•Warehousing, transportation and garage buildings, agricultural (farms, greenhouses) buildings, garden buildings.

Figure 4: The non-residential sector in Europe.

Source: [9], p.33

The large percentage of the category “other” probably indicates that further effort is required to separate this floor area in one or more categories. However, “as a vast number of building types should be avoided, it has to be examined to what extend subcategories have to be set up and which additional parameters (size, technical equipment) are the most determining for each of the sub-categories” [9,32].

2.3. Occupant behaviour

Behaviour is the way in which one acts or conducts oneself. It involves people’s response to internal and/or external stimuli under certain conditions. For example, when feeling too warm (internal stimulus), a regular response may be to open a window or to turn a thermostat down. Responding to an external stimulus would be closing the window blinds to avoid glare [33]. In other words, external stimuli correspond to extrinsic variables to the occupant (e.g., air temperature, wind speed), while internal stimuli depend of personal characteristics (e.g., personal background, attitudes, preferences) [34].

Addressing human behaviour is a complex task as it involves a great number of interacting factors crossing different disciplines [6,34]. Many causes influence occupant behaviour and, furthermore, energy consumption patterns involve both technical and social topics. Consequently, such phenomenon must be analysed from both engineering and social science perspectives to be completely understood [24].

From a social science point of view, Kahneman [35] suggests that two agents, which produce fast and slow thinking, characterize the decision-making. He argues that human’s behaviour is guided by fast thinking, i.e., actions that are “fast, automatic, effortless, associative and often emotionally charged; they are also governed by habit and are therefore difficult to control or modify” [35]. Slow thinking is effortful and has less impact on behaviours since it is used only in situations that require attention and are disrupted when attention is drawn away – i.e. monitoring the appropriateness of behaviour in a social situation or filling out a tax form [35].

The psychology of behavioural change is a very important topic, which needs further examination in the context of energy consumption. As people usually prefer to operate in autopilot mode, behaviour changes are difficult, once they require effort, deliberation and time. Accordingly, behaviour change measures can only succeed if they “revolve around the realities of individual human cognition and why people behave as they do” [16]. Young [36] categorized and evaluated different behavioural changes techniques. The results show that informational prompting is untrustworthy and nondurable and providing material incentives can initiate rapid changes in conservation behaviour, but the results are also nondurable. Techniques that employ social pressure and material disincentives showed to be able to initiate rapid change and provide effective results, but at the same time creating a negative psychological resistance from individuals. Commitment techniques encouraging occupants to adopt certain behaviours for a specific amount of time were found to be the most durable and effective. However, securing individual commitment has proven to be difficult to accomplish [36].

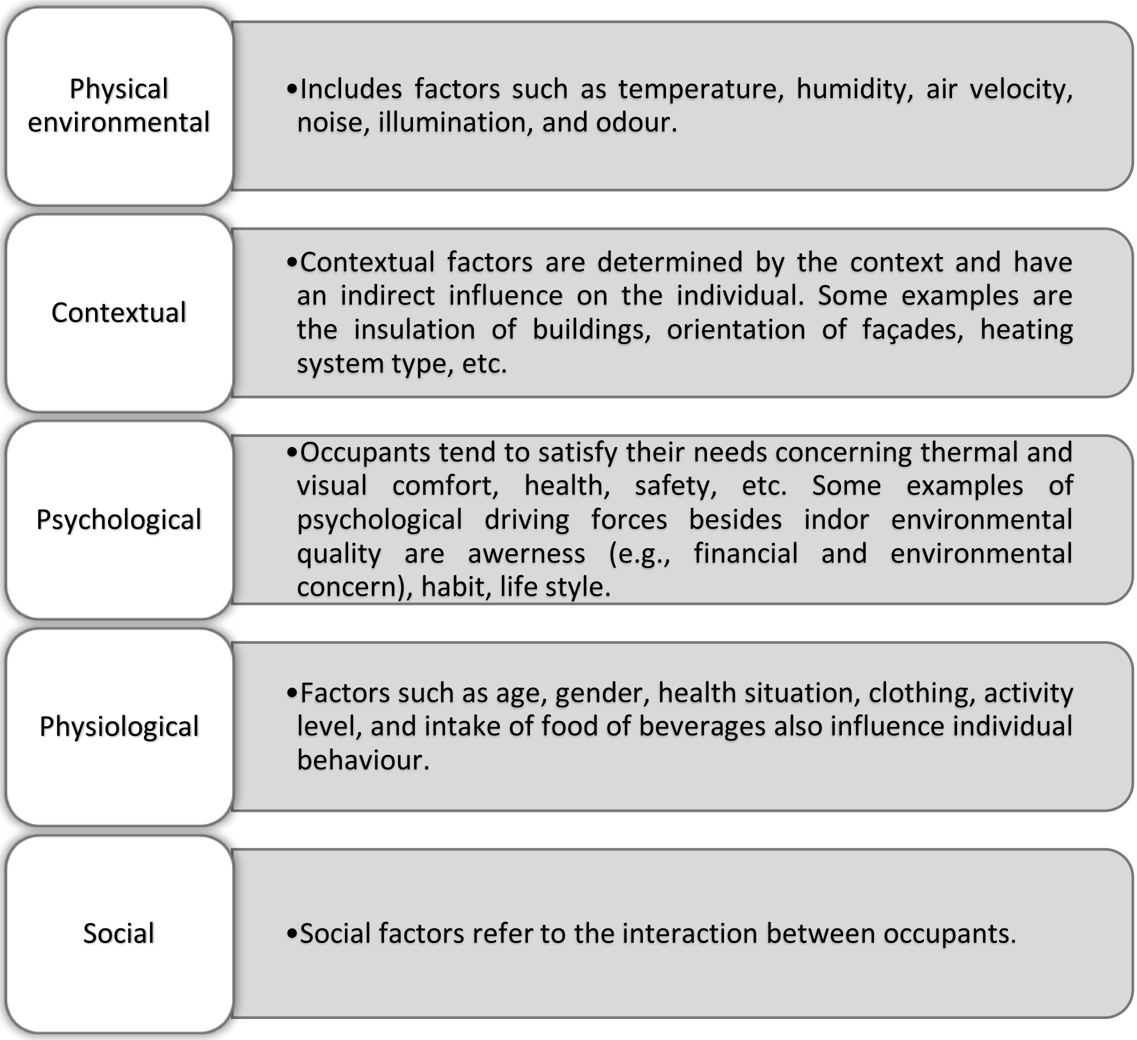
Engineering research on energy use has been mainly focused on the physical-technical-economic model (PTEM), in which users are considered merely occupants of buildings and their behaviours are secondary to building thermodynamics and energy performance. Their patterns of energy and equipment use are generally mimicked in a very static way considering they are statistically assumed [6,18]. Nevertheless, this model recognizes the importance of occupant behaviour and considers that it plays a significant role in long-term energy use. However, this role is mainly due to the expectation of investment in more efficient building equipment and systems, since the PTEM approaches energy efficiency from the perspective that new technologies are the only driver of greater efficiencies [6, 37].

The success of PTEM follows where technologies are proven and users are rational. Inadequate technical expertise or irrational individual behaviour can lead to a failure or significant delay in achieving success [37]. This model allows the quantification of energy reductions through the use of more efficient equipment, but as occupants' behaviour varies, this quantification is not necessarily accurate. Indeed, people's behaviour is conditioned by personal background and experiences and, therefore, occupants react differently when subjected to the same environmental conditions in buildings, depending on their personal characteristics [38].

Over the last decades, engineering and social science researchers about human behaviour have progressed relatively independently. However, it has been recently realized that "to overtake the gap of knowledge about the human behaviour related to the building control systems, these two perspectives must be integrated to form a single and coherent view of energy use" [24]. As consequence, in the recent years, research related to energy and environmental performance of buildings is increasingly focused on human-centred concerns. Studies regarding occupant behaviour and energy consumption are now exploring occupants' preferences, attitudes, and cultural background to explain the complex combination of cognitions and actions that influence the occupant to do an action [24].

Concerning the building science area, occupant behaviour related to building control systems is mainly connected to indoor and outdoor thermal conditions, i.e., the external factors. On the other hand, in the field of social sciences, human behaviour is more frequently related to the internal stimuli [34]. The building operational performance is associated with behavioural patterns both at the individual (e.g., technology use) and organizational levels (e.g., purchasing and infrastructure decisions) [33].

Nonetheless, in the end, both external and internal factors are drivers which lead to a reaction of the building occupant thus affecting energy consumption. Indeed, regarding indoor environmental quality, the occupant reacts in a conscious or unconscious manner to an internal or external stimulus to improve, restore or maintain the comfort conditions. Thus, “the occupant becomes the central operator in control of the energy consumption” [34]. The factors which drive occupants’ behaviours can be divided into five groups: physical environmental factors, contextual factors, psychological factors, physiological factors and social factors, as explained in figure 5 [34].



Physical environmental	•Includes factors such as temperature, humidity, air velocity, noise, illumination, and odour.
Contextual	•Contextual factors are determined by the context and have an indirect influence on the individual. Some examples are the insulation of buildings, orientation of façades, heating system type, etc.
Psychological	•Occupants tend to satisfy their needs concerning thermal and visual comfort, health, safety, etc. Some examples of psychological driving forces besides indor environmental quality are awerness (e.g., financial and environmental concern), habit, life style.
Physiological	•Factors such as age, gender, health situation, clothing, activity level, and intake of food of beverages also influence individual behaviour.
Social	•Social factors refer to the interaction between occupants.

Figure 5: Occupant behaviour determinants by category.

Source: [34]

These factors, however, are restricted to the field or physical environmental sciences, as they only consider the perceived environment. The connection with the environmental education and social sciences is not described and it can drive different behaviours. For instance, there are people who ventilate by opening the windows every day for a certain amount of time, regardless of the environmental conditions, due to concerns about health effects of poor indoor air quality. This conduct is based on knowledge and/or education, not on perception, past experiences, or PTEM variables [34].

This thesis focuses on actions motivated by indoor environmental quality, where occupants act to achieve comfort conditions, once these actions are those with a direct effect on energy consumption [10].

When stimulated by a driver or a combination of them, the occupant tends to react to restore comfortable conditions. There are several possibilities for the occupant to control the indoor environment. The control related actions can be divided into three categories:

1. **Changes which alter the environment to make it more comfortable** (e.g., adjust the heating set-point, open/close a window; turn lights on/off, etc.);
2. **Changes which adapt the occupant to the prevailing environment** (e.g., adjust clothing, consuming hot or cold drinks, etc.);
3. **Actions which influence the indoor environment indirectly** (actions related to the chance of internal heat gains/energy use, e.g., use of hot water and use of appliances and equipment such as TV, refrigerator, etc.).

This thesis focuses on the exploration of the first set of actions, for they are the ones most directly related to energy consumption in service buildings.

2.4. Effect of occupant behaviour on energy consumption in buildings

So far, the influence of the building occupants' behaviour on energy consumption has already been stated. Energy consumption in buildings can vary even when systems are identical, suggesting that consumption is not only related to the physical characteristics of the building and installed HVAC equipment. In fact, the actual amount of energy used in buildings is often different from the calculated or expected use [39]. Large discrepancies between predicted and actual building energy performances are commonly observed, typically averaging around 30% and reaching as high as 100% in some cases [40]. Maier et al. [41] investigated 22 identical houses over 2 years. Their results showed great differences between houses equipped with the same ventilation system. Thus, as the houses were identical, the discrepancy in heating consumption between the houses was associated with occupants' behaviour.

The presence of occupants alone is already responsible for changes in the internal environment of the buildings because of the bodies' heat transfer [10]. However, the most significant impact on energy consumption is related to the way occupants interact with the building in order to have comfortable internal environmental conditions.

Behaviours considered relevant to buildings occur at many levels, from individual to institutional. The everyday uses of space and equipment significantly affect the building's overall performance. Occupants affect the energy consumption by controlling the building's internal conditions, such as lighting, ventilation, temperature, etc. [33]. In addition to behaviour due to the individual's personal characteristics, behaviour in service buildings is also related to the differing roles, schedules, social interactions, personal context, among other variables [16].

Over the last decades, several research projects tried to quantify the impact of occupants' behaviour in a building's total energy consumption. Bonte et al. [38] found out that the impact of occupant actions leads to a variation of the relative standard deviation higher than 45% and that these actions have a more significant impact on buildings under a warmer climate. After simulating different behaviours related to operation and control of energy service systems of private offices, Hong and Lin [42] concluded that an austere work style could save up to 50% of energy consumption. Clevenger and Haymaker [43] studied the impact of uncertainties regarding the behaviour of building occupants on energy modelling simulations. Their results show that predicted energy consumption changes by more than 150% from lower to higher values established by experts as representative of "typical" occupant behaviour.

Therefore, users' behaviour is clearly a key factor to achieve energy efficiency goals. Nowadays energy consumption must be reduced to the minimum possible amount due to resources shortage and climate changes, and therefore the understanding and quantifying of occupants' behaviours impact on energy consumption in buildings have become imperative [10].

To quantify such impact, several studies [24,31,39] have tried to relate occupants' behaviour and environment control systems in order to establish patterns regarding opening/closing windows, on/off the heating systems, etc. and its relation with internal and external climate conditions [10]. Some of the key building operations which can directly affect the building performance due to different occupants' behaviour are:

- **Heating, Ventilation and Air Conditioning (HVAC);**
- **Lighting;**
- **Generic electric loads.**

According to Wang et al. [31], while still maintaining the same level of indoor thermal comfort, various operation practices for buildings may result in significantly different energy consumption levels. Their results show the level of uncertainty associated with the use of a building's HVAC system (-15.8% to 70.3%), plug load (- 11.3% to 7.0%), and lighting (-5.8% to 9.0%), due to different employee behaviours. However, the proportional influence of end-uses is not the same for every building and "identifying which end-users have the greatest potential for savings is a first step to changing the behavioural impact in a building" [31]. The following subsections explore behaviour drivers and patterns of the three key processes in buildings referred above.

2.4.1. HVAC systems

Heating, ventilation and air conditioning (HVAC) systems are among the largest energy consumers in buildings. Almost 50% of the energy demand is used to support indoor thermal comfort conditions in service buildings. In Australia and the Middle East, more than 70% of the energy consumption in non-residential buildings is due to HVAC systems. In Europe, this value drops to 40% [44]. The energy consumed by HVAC systems depends not only on its performance and operational parameters but also on the decisions of its users. Inefficient operation and maintenance of an HVAC system can lead to great energy wastage, poor indoor air quality and even environmental damage. Accordingly, energy optimization of HVAC systems is very important to achieve energy efficiency in buildings [40].

Individual user behaviour can affect HVAC systems through the adjustment of thermostats in workspaces, inefficient operation of windows and doors, overriding heating timer settings, leaving blinds open at night, leaving ventilation fans on, etc. [23].]. In short, energy consumption due to heating and cooling is related to temperature set point, a number of heated/cooled rooms, and heating/cooling duration and frequency of use and cross effects associate to contradictory control (e.g., natural over ventilation while heating). These factors can vary among users and may have different levels of importance. A summary of the driving forces for energy-related behaviour with respect to space heating is shown in table 1 [45].

Table 1: Driving forces for energy-related behaviour with respect to heating [45, p.20 – adapted].

	Biological	Psychological	Social	Physical Environment	Building/Equipment Properties
Temperature Set Point	Gender	Expectations	Ownership	Exterior air temperature	Building insulation level
	Clothing	Interaction frequency with heating controls		Outdoor air humidity	Ventilation type
		Window opening			
Heating Duration	Clothing	Understanding how controls function	Ownership	Exterior air temperature	Building insulation level
		Window opening	Government interventions	Outdoor air humidity	Heating system type
				Wind speed	Level of control
# of Rooms Heated		Interaction frequency with heating controls			Level of control

The heating and cooling behaviour is also deeply influenced by the weather. Buildings located in cold climates induce a greater use of heating and have less cooling demand. On the other hand, when located in warm climates, there is less need for heating, but cooling demand increases [46].

Energy-efficient HVAC systems can be achieved by new configurations of traditional systems to make a better use of their existing parts [44]. Therefore, a way of reducing HVAC systems' energy demand is by establishing temperature settings which are efficient and provide energy savings, but without deeply affecting comfortable conditions. A study conducted by Brown et al. [47] showed that small reductions of the default temperature seem to have more effect on energy consumption than larger ones. If the reduction in default temperature is too large (i.e., 20 ºC to 17 ºC), occupants tend to manually increase their temperature settings, while with a small reduction (i.e., 20 ºC to 19 ºC), occupants did not modify the default.

Window operation is one of the most influential occupants' behaviours regarding HVAC systems, once it has crucial effects on indoor climate and energy consumption due to natural ventilation and infiltrations [30]. Generally, in temperate climates, windows are the most usual thermal control and ventilation device. Opening windows allows natural ventilation and can promote energy savings in warmer seasons by reducing the need for air conditioning and mechanical ventilation systems. For selected locations, namely in small cities and in the suburbs of large cities, it can also provide a healthier and more comfortable indoor environment when compared to mechanical ventilation [10,30].

Several researchers explore human behaviour regarding opening/closing windows. Warren and Parkins [48] verified that exterior air temperature is responsible for 76% of interactions between occupants and windows. Solar gains (8%) and wind velocity (4%) are also factors that influence occupants' behaviours in this matter. They also found out that fresh air is the most common reason for opening windows in both winter (51%) and summer (74%). After studying the occupants' behaviour in several buildings in various countries, Nicol [49] discovered that occupants tend to open windows when external temperatures were over 10 ºC. The higher the external temperature, the greater the probability of opening windows. Roetzel et al. [50] reported an inverse linear correlation between wind velocity and window opening, evidencing that wind is a driver for closing windows. Wind direction, solar radiation, rainfall and weather season are also factors which influence users' behaviour regarding windows [34].

2.4.2. Lighting

Artificial lighting load represents up to 30% of overall building energy consumption [31]. Advanced lighting control is one of the most effective measures for energy efficiency. According to Williams et al. [51], multiple control strategies including the use of technological solutions along with behaviours changes can lead up to 40% savings. Tzempelikos [52] studied the impact of manual light switching on lighting energy consumption in a typical office building and concluded that energy savings can reach up to 57% for perimeter zones and 45% for interior darker zones, resulting in area-average savings of 50% for the entire floor.

Automated systems can turn off or dim lights at a lower level when the available natural light on the workspace exceeds a pre-determined target value. However, occupants tend to override these systems and change their luminous environment with no specific pattern. Switching behaviours depend mostly on the available daylight, time of the day, type of electric lighting, type of switch and location relative to the closest window [52].

Users can affect the energy consumption by lighting by leaving lights on when not needed, overriding automatic controls and/or not making use of task lighting or daylighting [23]. Per Hunt [53], occupants are more likely to switch on the lights when illuminance levels are less than 100 lx. Pigg et al. [54] found a strong relationship between the propensity of switching the lights off and the length of absence from the room, stating that occupants are more likely to switch off the lights when leaving the room for long periods.

Shades and blinds affect daylight availability and lighting behaviours. Occupants manipulate them mainly to avoid direct sunlight and overheating, and they seem to remain deployed until the end of the working day or until visual conditions become intolerable [55]. Increasing the available daylight usually leads occupants to use less electric light, reducing the total energy consumption. Increasing natural lighting can also improve occupants' mood, performance and well-being.

Regarding default lighting settings, the initial setting influence the occupants' lighting choices. More specifically, they are more likely to keep the original default settings if it has simulated daylight [56]. According to Boyce et al. [57], occupants can tolerate deviations from their preferences within a limited range of their desired standards. This range can vary from one user to another, but their results suggest that is greater than 100 lx.

2.4.3. Generic electric loads

Any device that plugs into wall outlets distributed throughout a building is a plug load [58]. Plug loads can account for up to 50% of the general energy consumption depending on the building type and attributes [59]. Regarding office buildings, they are responsible for an average 9% but as much as 28% depending on the nature of the work [58]. Improving practices regarding plug loads can have an expressively effect on the building energy consumption. There are two common ways to save energy from plug loads: the first is to replace the company's appliances with more efficient ones, and the second is through users' behaviour changes to control them more efficiently.

According to the New Buildings Institute, there are five steps to achieve more efficient energy use regarding plug load in offices: reviewing, removing, replacing, reducing, and retraining. Reviewing consists in identifying office equipment and focusing on devices which use the most energy. Removing means to eliminate or unplug unnecessary devices. Then, when it is time to replace them, the most energy-efficient devices for the job should be chosen. The fourth step (reducing) involves technological solutions and behavioural changes to turn off equipment or power it down when not in use. The last step targets the occupants and consists in retraining the staff to make sure they understand why, when and how to power down the equipment [60].

Users can affect energy consumption by leaving equipment on when not needed, not making use of sleep/hibernate software functions, etc. [23]. In fact, turning equipment off when they are not needed (i.e., at night and during lunch breaks and weekends) can significantly reduce energy use, see Wang et al. [30]. Sustainable occupant behaviours can lead up to a 40% plug load energy saving [59].

However, changing occupants' behaviours in this matter can be quite difficult and ineffective. Metzger et al. [58] explored the most effective ways to reduce plug load energy through three primary approaches, in which two included behavioural change and the third one was by an automated energy management system that turned off equipment when a pod was unoccupied for more than 15 minutes. While the control system resulted in almost 45% of energy savings, behavioural change techniques accounted for less than 15%. Webber et al. [61] also explored occupant behaviour regarding plug loads and found out that turn-off rate during non-working hours "vary widely over the types of office equipment, from 0 percent (for fax machines) to 75 percent (for wide-format printers). For most equipment types, turn-off rates are under 50 percent" [61].

2.5. Buildings dynamic simulation and behaviour modelling

Building performance simulation (BPS) calculates the thermal loads and energy use of residential and service buildings. Simulation allows for the acceleration of design process and an increase of efficiency; it also enables the comparison of a wider range of design variants, leading to more optimal designs. Through simulation, it is possible to have a better understanding of the consequences of design decisions [62]. Therefore, the BPS has become an important method of assessment during the design process and in the renovation of existing buildings to predict energy use based on the building's physical characteristics and usage patterns [63]. The importance of energy simulation is increasing with the tendency of more complex building designs and higher performance requirements on sustainability [18].

Building energy models have been around since the early 1980s. The first software developed to calculate energy use in buildings was based on oversimplified methods, in which mathematic formulations were elementary and characterized by lots of simplified suppositions. Nowadays, computational technologies have allowed the development of improved methods, which can simulate several variables simultaneously and with no need for simplified suppositions [10]. Besides the energy consumption, simulation software tools can be used to calculate indoor temperatures, needs for heating and cooling, levels of ventilation, consumption needs of HVAC systems, the interior comfort of occupants, etc. [64]. With the simulation results, architects and building service engineers can predict the building's energy usage and make decisions to achieve energy efficiency goals and measure environmental impacts and costs involved.

There are many simulation software tools available today with different complexity levels, different characteristics and specific applications [10,64]. Nevertheless, even the most sophisticated program cannot perfectly replicate a real dynamic regarding energy consumption, once “the simulation is a theoretical representation of the status and operation of a building” [65]. The accuracy of energy modelling simulations ranges from ±10% to 40% for non-residential models [43].

Current dynamic simulation tools focus on the influence of variables such as climate, construction characteristics, systems and equipment. These variables added to operating hours and maintenance may alter the building performance. For instance, the accuracy of the climate characteristics considered in the simulation depends on the certainty of the available meteorological data [10].

The behaviour of the building’s occupants can also have a significant impact on energy consumption, but it is not yet accurately addressed in simulations. Although it is considered that “over the last forty years thermal processes in building energy performance simulation have been brought to perfection (…), user behaviour has a much larger influence on the energy performance of a building than the thermal process within the building façade” [18].

The simple presence of individuals can affect energy demand: an unoccupied building requires little or no energy; on the other hand when occupied, a great amount of energy is necessary to ensure comfortable conditions for its occupants regarding temperature, lighting, ventilation, etc. [10]. Occupants affect the building energy use through the temperature set points, heating/cooling schedules, etc., and it may differ from the software predictions [10,62]. A vast number of multidisciplinary studies provide valuable insights into the circumstances and potential triggers of occupancy control actions in buildings. However, integrative modelling approaches, that consider all relevant aspects of energy behaviours while finding a balance between disciplines, are not yet mature [6].

The complexity of human behaviour hinders that simulation tools achieve more accurate results. If exposed to the exact same conditions a number of times, the occupant will not react in the exact same manner every time and therefore when addressing behaviours there are always elements of randomness [45]. Also, comfortable conditions are not the same for every occupant and these individual differences create an obstacle for modelling occupant behaviours in buildings. Thus, occupants’ behaviours are one of the most significant sources of uncertainty in the prediction of energy use by simulation programs [10,42].

Building simulation tools are based on deterministic (fully predictable and repeatable) factors and in current design tools occupants’ actions are conventionally represented in terms of static schedules or predefined rules (e.g., the window always open if the indoor temperature exceeds a certain limit) [65,66]. In such way, an occupant behaviour simulation could refer to a computer simulation generating fixed occupant schedules, representing a fictional behaviour of a building occupant over the course of a single day. Usually, in simulation programs the occupant behaviour is not specifically addressed, but only modelled by means of its effect (e.g., the infiltration rate may be modelled as a fixed value that does not vary over time, with the assumption that occupants will open/close windows in a way to always meet the established target) [45]. This simplification does not properly model the real influence of occupant behaviour on the building's energy consumption and indoor environment [66] and therefore is an important limitation of energy simulation tools [65]. In fact, Hoes et al. [18] conducted a study on the effects of occupant behaviour on the simulated energy performance of buildings and concluded that the simple approach used nowadays for design assessments applying numerical tools are inadequate for buildings that have close interactions with the occupants.

In the meantime, building energy codes and targets are increasingly stringent and therefore any source of uncertainty should be surpassed [67]. To ensure more realistic simulations, some of the existing energy modelling programs allow the integration of occupant behaviour models. According to Yan et al. [66], four main approaches have been used to include occupant behaviour in current BPS programs.

1. **User-defined profiles and rules**: Allow users to define and input temporal schedules of thermostat settings, occupants, lighting use, plug-loads, and HVAC systems operation. It is also possible to include specified deterministic rules regarding building operation (e.g., windows will be open if indoor temperature is higher than a chosen value). Although this approach is easy to use, it has some limitations due to lack of flexibility and simplification of real individual behaviours.
2. **User customized code**: The user can write a custom code to implement new or overwrite existing building operations and supervisory controls. This approach allows more flexibility but requires advanced user experience and deep knowledge of a specific simulation software.
3. **User customized tools**: Users can implement occupant behaviour models by adding new codes and recompiling the simulation program. This approach also requires professional computer programming experience and knowledge regarding modelling approach.

4. **Co-simulation**: Allows different simulation tools to run simultaneously and exchange information in a collaborative manner. The integration of BPS programs with behaviour software tools may be able to consider the impacts of occupant behaviours in a more realistic way. However, most BPS programs do not support co-simulation yet and only a few advanced users have started using this approach integrating a separate software module of behaviour models with EnergyPlus.

Numerous researchers have tried to model occupant behaviours in BPS based on field studies and/or experiments. A particular effort has been done on occupancy modelling (occupant presence), window-opening, light-switching, and clothing level adjustments as a function of one or more environmental variables. However, after studying current behaviour models and the contextual factors which influence occupants' behaviours, O'Brien and Gunay [67] concluded that various influential factors are largely neglected (i.e., availability and accessibility of personal control, interior design, visibility of energy use, occupancy patterns and social constraints, etc.). They justify this recurrent flaw by highlighting the difficulty of measuring or quantifying behaviours, possible misunderstanding of behaviour triggers, and also the elevated cost of observational studies.

Nevertheless, even if occupant behaviour models were already established, there are several challenges in implementing them in BPS tools, once they do not allow the input detailed information and its influence on behaviours. For example, variables such as visual, thermal, and acoustic comfort can trigger a different behaviour from the one adopted for the simulation and yet they are either poorly addressed or simply not incorporated into most BPS tools. Furthermore, the diversity of occupant behaviour is yet another obstacle for its precise modelling and integration in simulation software. It is important to ensure that building design and operation do not consider only identical occupants to achieve more accurate results [67].

Despite the shortcomings of building simulation, BPS tools have experienced a substantial growth in the last decades. A lot of research is being made in this field, especially about modelling occupants' behaviour. Since simulating human behaviour is a complex task, more extensive and long-term studies are needed to obtain more realistic behaviour models regarding energy use [10,68].

2.6. Epitome

Occupants' behaviours have a significant influence on energy consumption in service buildings [41-43]. However, the amount of energy consumed due to occupancy is almost impossible to be accurately predicted, once the behaviour is associated with several factors that cannot be measured, such as psychological and physiological characteristics. It is common to focus on the energy efficiency of the buildings' constructive features, but the importance of considering occupant behaviour has already been stated [34]. Thus, extensive research has been made regarding energy behaviour in different fields (e.g., engineering, economics, sociology) with particular frameworks.

Also, energy consumption may vary depending on the building typology and physical characteristics. Therefore, the lack of an information pattern among different countries regarding service buildings creates another obstacle for characterizing the influence of occupant behaviours in buildings' energy consumption. Records of building typologies and characteristics, energy end use, etc., are diverse and hard to compare and recent studies attempts in this matter have yet a long way to go [9,32].

In summary, energy behaviours are complex and influenced by a wide range of variables which have not yet been fully understood. "Integrative studies are needed in order to provide a comprehensive understanding of energy usage behaviours, including the social, economic, technological, institutional, infrastructural and individual dimensions of energy behaviours, as well as their complex relations" [6].

Building Performance Simulation (BPS) tools have become indispensable to predict energy use during the design of new buildings and renovation of the existing ones. Although most of current BPS tools provide accurate results when considering the buildings' physical characteristics, the simulation is not yet realistic when considering occupants' behaviours. Most BPS tools address behaviours as static schedules and assume that all occupants repeat the same actions under certain circumstances, which has already proven not to be true.

The limitations of building dynamic simulations regarding human behaviours are well known and several studies aim to overcome such obstacles. Occupant behaviour models have not yet been established and BPS tools do not enable the consideration of several fundamental variables which influence human behaviours, such as physiological, psychological and social factors. Therefore, one of the main challenges nowadays is to be able to accurately simulate a building's energy performance with current tools and to predict which share of this consumption is due to occupants' behaviour.

3. METHODOLOGY

3.1. Summary

This chapter aims to describe the general methodology adopted in the simulation of office buildings, followed by the characterization of the building model on which the simulations will be carried out, as well as all parameters considered in the simulations. This section also addresses the methodology used to measure which parameters have the most influence on energy consumption for this type of building.

3.2. Objectives and general methodology

The methodology proposed in this thesis is based on the building dynamics simulation considering extreme operation profiles, representing limit energy behaviours of service buildings occupants using DesignBuilder software. The main objective is to evaluate the impact of occupants' behaviours on energy consumption of office buildings as well as to identify which parameters are responsible for the most significant impact on the building energy consumption.

In order to achieve a large variability of results, five main factors were considered and combined in the methodology:

1. **Occupant profile**: Three scenarios considering how occupants behave regarding energy and equipment usage.
2. **Location**: Two different geographical locations and climates.
3. **Size**: Two sizes of buildings in order to evaluate the influence of scale.
4. **Constructive solution**: Two constructive solution levels regarding thermal insulation.
5. **Building's energy efficiency**: Two levels of energy efficiency in HVAC systems to assess the influence of technology.

Occupant behaviours were characterized by three representative scenarios. The first scenario corresponds to the reference occupant, which is intended to be representative of the average energy behaviour. In the second scenario, extreme efficient behaviours leading to energy savings are considered. The third and last scenario involves limit inefficient behaviours, which lead to extreme energy waste. Occupants' behaviours were addressed in terms of their influence in HVAC systems, lighting and generic electric loads once they are the key building operations that can directly affect the building performance due to different occupants' behaviours.

As previously discussed, energy consumption in office buildings may vary depending on their size, geographical location, local climate, etc. Thus, two building sizes were considered: 500 m² and 100 m². Two locations were chosen based on their climate zones: Portugal, representing temperate climates and Brazil for tropical climates.

Regarding the building's constructive solutions, a few parameters were chosen in order to achieve desirable U values. In order to characterize equipment's energy, the EPCs standards were taken into account and two categories were designed: one in which all equipment is equivalent to category A++, and a second one equivalent to category D.

Other data necessary to energy simulations are specified in the remaining sections of this chapter. So that the energy performance of this building type could be characterized, information from several sources was combined in order to gather the inputs which would be necessary for the simulation.

3.3. Study building characterization

This thesis aims to study the energy consumption in office buildings under different circumstances and so several variables were considered. Therefore, the structures of the buildings were simplified and a quadrangular geometry was adopted so that the building orientation would not interfere with the results. The building models are displayed in figure 6, where "**a**" comprehends a building with a gross area of 100 m² (small office buildings – SOB) and "**b**", 500 m² (large office building – LOBs). Total useful building floor area depends on the wall thickness; hence it varied depending on the adopted constructive solution.

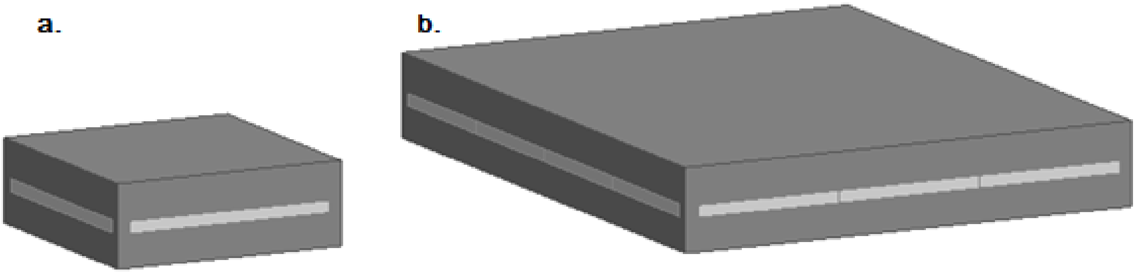


Figure 6: Building model representations relative to floor areas of (a) 100 m² and (b) 500 m².

The reason why the design is not complex is the necessity of making the simulations simpler and more concise, focusing the analysis on the relevant entrance data, which evaluate the five aspects described above.

3.3.1. Location

As previously described, building models were developed in two locations to evaluate the influence of different climates in energy consumption. Aveiro, Portugal, represents temperate climates and Salvador, Brazil, was chosen to represent tropical climates. Table 2 shows their geographical location.

Table 2: Geographic coordinates of Aveiro and Salvador.

Location	Latitude	Longitude
Aveiro	40º38'39'' N	8º38'43'' W
Salvador	12º58'15'' S	38º30'38'' W

Latitude influences natural lighting and HVAC necessity. Since locations differ, so does the sun path diagram, as exposed in figure 7 for Aveiro (**a**) and Salvador (**b**). This diagram is used in the calculation of natural illuminance.

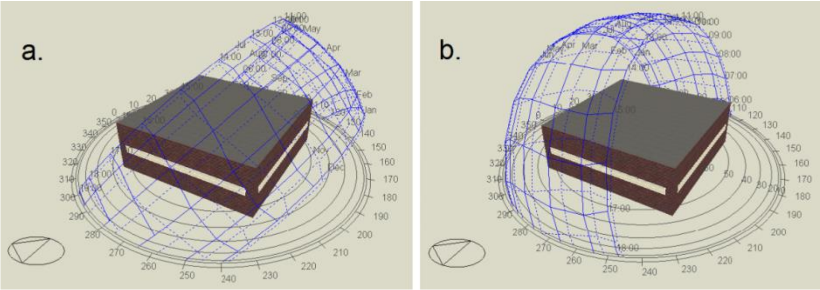


Figure 7: Sun path diagram for Aveiro (a) and Salvador (b).

A great amount of other information is needed in order to achieve adequate results in dynamic simulations, such as temperatures, seasons, and solar azimuth. DesignBuilder already has a location template for Salvador, which has all the necessary information and therefore was adopted with no changes. Aveiro, however, did not have a fixed template, so one was created from weather data available at the software SCE-CLIMAS[1]. Relevant data considered at DesignBuilder regarding temperatures and seasons are indicated in table 3.

Table 3: Seasons division and average temperatures in DesignBuilder software.

	Season	Aveiro	Salvador
Months	Winter	October - March	April - September
	Summer	April - September	October - March
Average temperature [ºC]	Winter	14.16	25.03
	Summer	25.52	26.77

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[1] Software that contains data regarding weather statistics and reference year to perform dynamic simulations of systems and buildings. Provided by LNEG.

3.3.2. Building activities

In DesignBuilder, activity level was defined by a template in which data regarding the building utilization was inputted. Occupancy levels and schedule, equipment usage and lighting levels are defined by Decree-Law nº 79/2006 [69] as shown in table 4 and figure 8.

Table 4: Representative occupancy levels and equipment loads of office buildings [70].

Parameter	Density
Occupancy	15 m² people^{-1}
Equipment	15 W m^{-2}

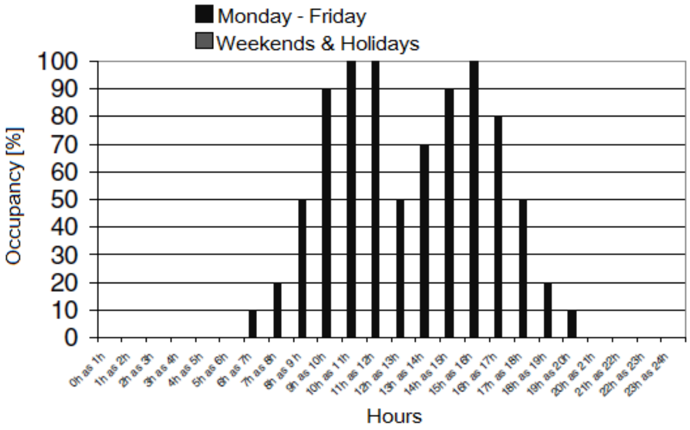


Figure 8: Occupancy schedules [69].

Table 5 brings other inputs to the building model. DesignBuilder already offers pre-defined templates and some of the proposed data was adopted. Minimum fresh air value was considered according to ASHRAE standards [70].

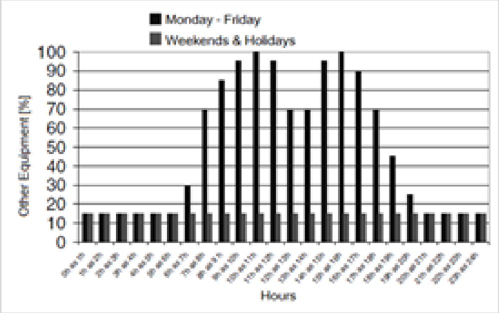
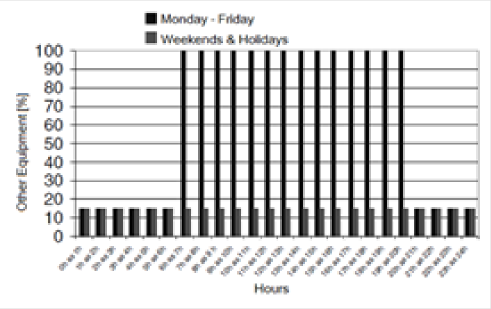
Table 5: Activity template of the building model.

Parameter		SOB	LOB
Activity template		Generic office area	
Floor area [m²]		100	500
Occupancy	Density [people m^{-2}]	0.0667	
	Schedule	Decree-Law nº 79/2006 (figure 7)	
Metabolic	Activity	Light office work	
Environmental Control	Heating setpoint [ºC]	20.0	
	Cooling setpoint [ºC]	25.0	
	Minimum fresh air [L s^{-1} m^{-2}]	0.3	
	Target illuminance [lux]	500.0	
Office Equipment	Gain [W m^{-2}]	Occupant profile (table 4)	
	Schedule	Occupant profile (table 4)	

The occupancy and office equipment usage schedules depend on the occupant profile, as shown in Table 6. Reference occupant was characterized as the one who follows the schedules defined by Decree-Law nº 79/2006. Efficient occupants reduce equipment loads by improving its performance. Inefficient occupants switch on all equipment at the beginning of the day and only turn them down after working hours.

Putting a computer in energy economy mode reduces its power consumption by making optimum use of the energy-saving potential. According to Reis [10], this potential is up to 26%. Therefore, for efficient occupants, an equipment gain of 11 W m^{-2} was considered.

Table 6: Office equipment gain and schedule due to occupant profile.

Occupant Profile	Gain [W m^{-2}]	Equipment Schedule
Reference	15	
Efficient	11	
Inefficient	15	

3.3.3. Constructive solutions

Two different constructive solutions were considered in this study. From the “project construction template”, only external walls, ceiling and ground floor characteristics were changed as shown in tables 7 and 8. To characterize the well-insulated solution, other European-country standards were analysed, as they are more restricted in that matter. Only the insulation material was changed for the poorly-insulated building, respecting the maximum surface thermal coefficient transmission allowed for opaque elements (Portaria 349-B/2013 [71]).

Table 7: Constructive solutions of a well-insulated building

Surface	Materials	Thickness [m]	U [W m^{-2} $^{o}C^{-1}$]
External Walls	Brickwork Outer XPS Extruded Polystyrene Concrete Block (medium) Gypsum Plastering	0.300 0.100 0.100 0.020	0.269
Roof (flat)	Asphalt MW Glass Wool Air Gap Plasterboard	0.010 0.200 0.200 0.020	0.150
Ground Floor	Polyethylene/Polythene Urea Formaldehyde Foam Cast Concrete Floor Screed Carpet & Rubber Pad	0.010 0.170 0.200 0.070 0.020	0.200

Table 8: Constructive solutions of a poorly-insulated building

Surface	Materials	Thickness [m]	U [W m^{-2} $^{o}C^{-1}$]
External Walls	Brickwork Outer Concrete Block (medium) Gypsum Plastering	0.300 0.100 0.020	1.293
Roof (flat)	Asphalt MW Glass Wool Air Gap Plasterboard	0.010 0.013 0.200 0.020	1.219
Ground Floor	Polyethylene/Polythene Urea Formaldehyde Foam Cast Concrete Floor Screed Carpet & Rubber Pad	0.010 0.003 0.200 0.070 0.020	1.222

3.3.4. Openings

This section mainly characterizes external and internal windows, shading, doors and vents. As these parameters are not relevant to the present study, “Project glazing template” was adopted. Only the percentage of the window to the wall was changed to 15%, as limited by RCCTE.

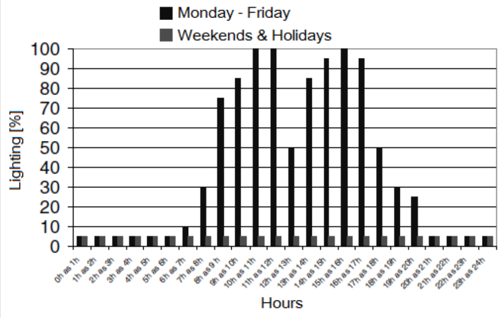
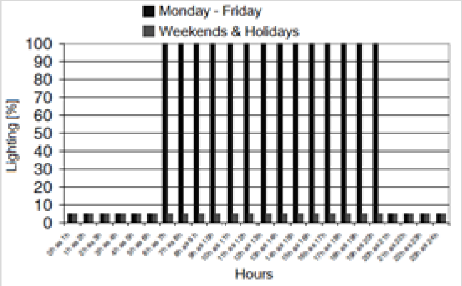
All building models, regardless their size or constructive solution, have the same openings characteristics. “Project external glazing” is composed of two layers of generic clear glass 3 mm and an air gap of 13 mm between them. This template has a calculated U-Value of 1.960 W m^{-2} K^{-1}.

3.3.5. Lighting

Lighting template “Portugal” was chosen. As RCCTE does not establish any value for lighting power density, 10.20 W m^{-2} was adopted as suggested by the template.

Lighting schedules depend on occupancy profiles (table 9). Reference occupant follows the schedule defined by Decree-Law nº 79/2006. Efficient occupant only switches on artificial lighting when natural lighting provides less than 500 lux. Inefficient occupant switches on artificial lighting at the beginning of the day, and only switch it off when leaving the office.

Table 9: Lighting schedule due to occupant profile

Occupant Profile	Lighting Schedule
Reference	
Efficient	Depends on natural lighting levels (lux).
Inefficient	

3.3.6. HVAC

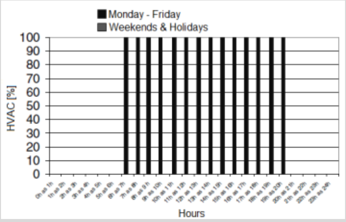
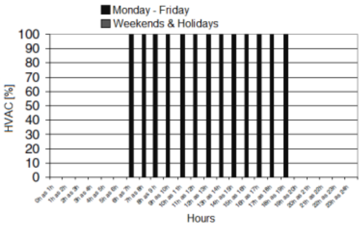
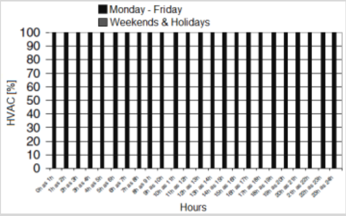
For HVAC system, a packaged direct expansion unit was chosen since it is recommended for office buildings and has low installation costs [10]. Mechanical ventilation controls the minimum fresh air rate, which is established by RSECE [69] as shown in table 10.

Table 10: Lighting schedule due to occupant profile [69]

Building Typology	Minimum fresh air rate	
Office Buildings	35 [m^3 h^{-1} $occupant^{-1}$]	5 [m^3 h^{-1} m^{-2}]

HVAC schedules depend on occupancy profiles (table 11). Reference occupants turn on the HVAC system when they arrive at the office, and turn it off at the end of the day. Efficient occupants also turn the system on at the beginning of the day but turn it off one hour before leaving the office. Inefficient occupant only turns off HVAC system on weekends and holidays.

Table 11: HVAC schedule due to occupant profile

Occupant Profile	HVAC Schedule
Reference	
Efficient	
Inefficient	

Regarding energy efficiency, two classes were considered: A++ and D. For both heating and cooling systems, seasonal CoP (SCOP) is established by the Commission Delegated Regulation (EU) nº 626/2011 as shown in table 12 [72].

Table 12: Energy efficiency classes for air conditioning [72]

Energy Efficiency Class	Heating system seasonal CoP	Cooling system seasonal CoP
A++	4.60 ≤ SCOP < 5.10	6.10 ≤ SCOP < 8.50
D	2.50 ≤ SCOP < 2.80	3.60 ≤ SCOP < 4.10

3.4. Building models

The combination of all parameters results in forty-eight building models. They were organized as shown in table 13.

Table 13: Building models and its characteristics

Model number	Occupancy	Location	Size [m²]	Constructive Solution	Energy Efficiency Class
1	Standard	Aveiro	100	Well-Insulated	A++
2	Standard	Aveiro	100	Well-Insulated	D
3	Standard	Aveiro	100	Poorly-Insulated	A++
4	Standard	Aveiro	100	Poorly-Insulated	D
5	Standard	Aveiro	500	Well-Insulated	A++
6	Standard	Aveiro	500	Well-Insulated	D
7	Standard	Aveiro	500	Poorly-Insulated	A++
8	Standard	Aveiro	500	Poorly-Insulated	D
9	Standard	Salvador	100	Well-Insulated	A++
10	Standard	Salvador	100	Well-Insulated	D
11	Standard	Salvador	100	Poorly-Insulated	A++
12	Standard	Salvador	100	Poorly-Insulated	D
13	Standard	Salvador	500	Well-Insulated	A++
14	Standard	Salvador	500	Well-Insulated	D
15	Standard	Salvador	500	Poorly-Insulated	A++
16	Standard	Salvador	500	Poorly-Insulated	D
17	Efficient	Aveiro	100	Well-Insulated	A++
18	Efficient	Aveiro	100	Well-Insulated	D
19	Efficient	Aveiro	100	Poorly-Insulated	A++
20	Efficient	Aveiro	100	Poorly-Insulated	D
21	Efficient	Aveiro	500	Well-Insulated	A++
22	Efficient	Aveiro	500	Well-Insulated	D
23	Efficient	Aveiro	500	Poorly-Insulated	A++
24	Efficient	Aveiro	500	Poorly-Insulated	D
25	Efficient	Salvador	100	Well-Insulated	A++
26	Efficient	Salvador	100	Well-Insulated	D
27	Efficient	Salvador	100	Poorly-Insulated	A++
28	Efficient	Salvador	100	Poorly-Insulated	D
29	Efficient	Salvador	500	Well-Insulated	A++
30	Efficient	Salvador	500	Well-Insulated	D
31	Efficient	Salvador	500	Poorly-Insulated	A++
32	Efficient	Salvador	500	Poorly-Insulated	D
33	Inefficient	Aveiro	100	Well-Insulated	A++
34	Inefficient	Aveiro	100	Well-Insulated	D
35	Inefficient	Aveiro	100	Poorly-Insulated	A++
36	Inefficient	Aveiro	100	Poorly-Insulated	D
37	Inefficient	Aveiro	500	Well-Insulated	A++
38	Inefficient	Aveiro	500	Well-Insulated	D
39	Inefficient	Aveiro	500	Poorly-Insulated	A++
40	Inefficient	Aveiro	500	Poorly-Insulated	D
41	Inefficient	Salvador	100	Well-Insulated	A++
42	Inefficient	Salvador	100	Well-Insulated	D
43	Inefficient	Salvador	100	Poorly-Insulated	A++
44	Inefficient	Salvador	100	Poorly-Insulated	D
45	Inefficient	Salvador	500	Well-Insulated	A++
46	Inefficient	Salvador	500	Well-Insulated	D
47	Inefficient	Salvador	500	Poorly-Insulated	A++
48	Inefficient	Salvador	500	Poorly-Insulated	D

4. RESULTS AND DISCUSSION

4.1. Summary

This chapter aims to present and discuss the dynamic simulations results. All forty-eight building models were created at DesignBuilder software, resulting in different energy consumptions divided into three categories: equipment, lighting, and HVAC. Energy waste and saving potentials due to occupancy were established based on standard occupant results, i.e., standard values were considered as a reference. All results are displayed in Appendix A.

First, general results are presented regarding the impact of occupancy profiles in each of the other four studied parameters. The main objective was to analyse separately the influence of occupants. To that end, for each parameter, all others were disregarded, i.e., in order to analyse occupants effect related to location, average values were calculated for all buildings in both locations regardless their size, constructive solution, and energy efficiency class. The building model groups for average calculations are detailed in Appendix B.

Later on, in section 3.3, detailed results are discussed, considering the influence of all five studied parameters in each of the three energy consumption categories of DesignBuilder simulation. At last, a discussion section aims to summarize all relevant results obtained in this study.

4.2. Occupants’ influence

This section discloses general results, namely based on energy consumption and saving potentials for each occupancy profile due to the other four studied parameters, separately. In order to compile the following information, average values of energy consumption were calculated regardless variations due to all other parameters.

4.2.1. Location

Simulations were made for two different locations. Aveiro, Portugal, was chosen to represent temperate climates, while Salvador, Brazil, represents tropical climates. Average values of all forty-eight building models’ annual energy consumption were calculated only considering variations due to location and occupancy profiles. For example, the energy consumption of standard occupants in Aveiro was calculated as the average energy consumption results for building models 1 to 8.

Results showed that energy consumption can vary up to 17.85% depending on the building's location. This rate was different for each occupant profile, although in all cases buildings situated in Salvador demanded more energy than those located at Aveiro (figure 9).

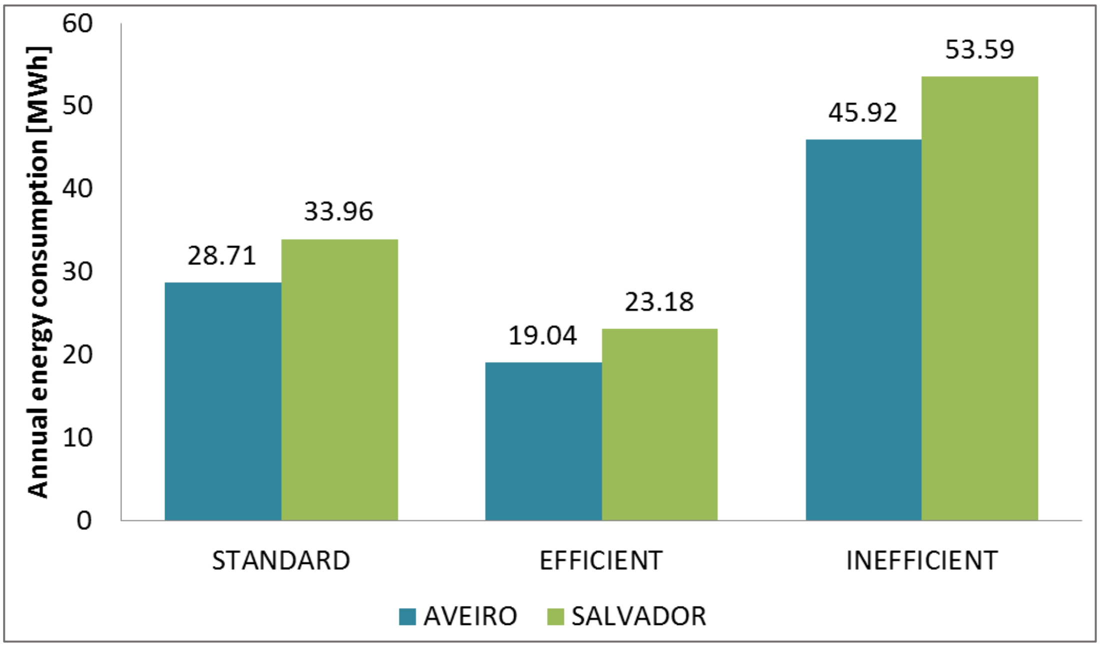


Figure 9: Annual energy consumption by location and occupant profile.

Table 14 shows the energy consumption breakdown for each of the three categories analysed by DesignBuilder (equipment, lighting, and HVAC). These results are averaged values of all scenarios and therefore do not take into account consumption differences due to size, constructive solution, and energy efficiency class.

Table 14: Annual energy consumption breakdown regarding location and occupancy profile.

Location	**Occupancy**	**Equipment [MWh year^{-1}]**	**Lighting [MWh year^{-1}]**	**HVAC [MWh year^{-1}]**
Aveiro	Standard	14.11	7.40	7.20
	Efficient	10.35	2.75	5.94
	Inefficient	25.13	10.78	10.01
Salvador	Standard	14.11	7.40	12.45
	Efficient	10.35	2.34	10.45
	Inefficient	25.13	10.78	17.68

For each occupancy profile, the energy demanded by equipment remained the same in both locations. The same happened to the energy demand by lighting for standard and inefficient occupants. As efficient occupants take natural lighting in consideration, artificial lighting usage was lower in Salvador, as it is closer to the Equator and therefore has a higher illuminance throughout the year.

On the other hand, energy demand by HVAC was higher in Salvador regardless the occupant profile. Although there is no need for heating at any time, cooling is needed throughout the entire year. In Aveiro, heating is needed from November to April, although mostly from December to February. Cooling demands electricity throughout the whole year, but mostly from April to November.

As energy demand differs, so does energy saving potentials. Even though gross energy demand in Aveiro tends to be lower, both energy saving and waste potentials are greater when compared to buildings in Salvador. Figure 10 brings the results for both inefficient and efficient occupants when compared to standard results.

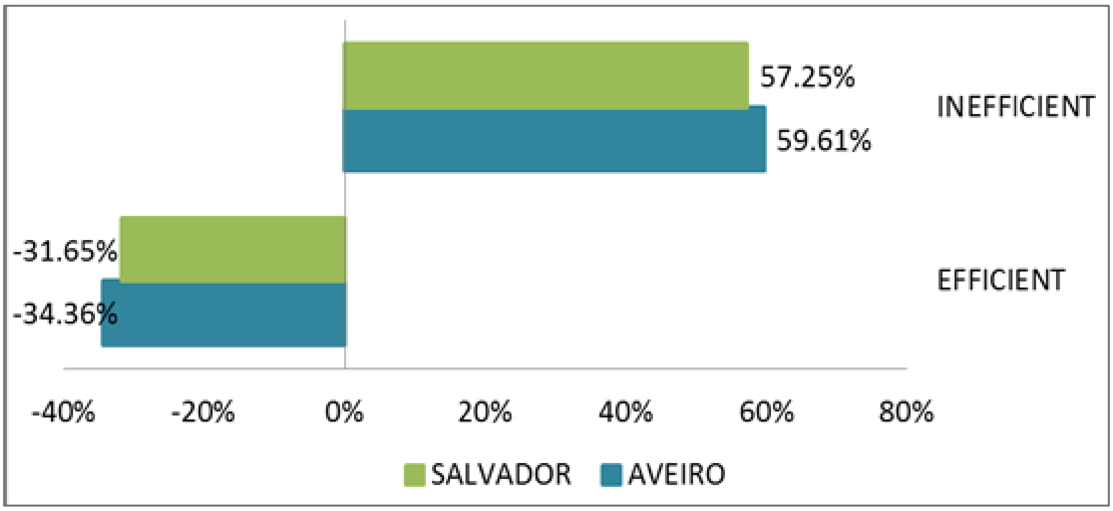


Figure 10: Energy saving potential by location and occupant profile, in relation to standard occupants.

It was also analysed the importance of each category (equipment, lighting, and HVAC) in the building's total energy demand for each occupancy profile, as shown in figure 11. It can be observed that regardless the occupant, HVAC has a higher importance in Salvador. This outcome was expected since, as shown in table 14, energy demand by equipment and lighting remain the same for both locations for standard and inefficient occupants.

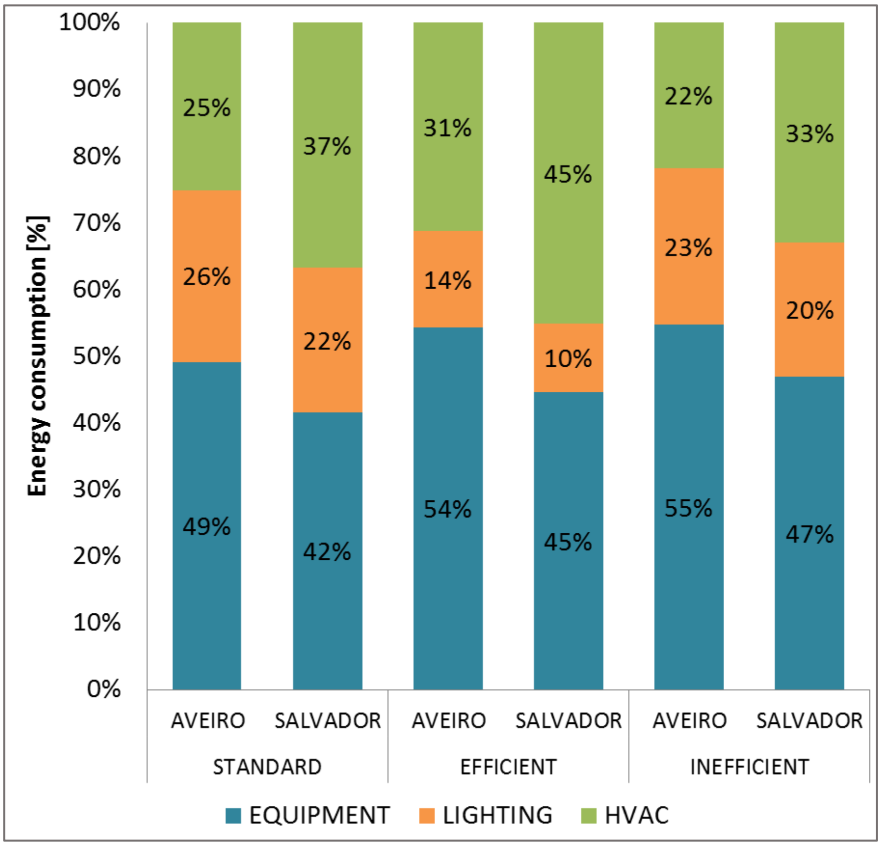


Figure 11: Energy consumption by category, location and occupant profile, in relation to standard occupants.

4.2.2. Size

The same analysis was made taking the building's size into account instead of its location. Average values of all forty-eight building models' annual energy consumption were calculated only considering variations due to size and occupancy profiles. For example, annual energy consumption of standard occupants for SOB was calculated as the average energy consumption results for building models 1-4 and 9-12.

Figure 12 shows total energy consumption by square meter, considering the building gross area. For all cases, LOB were exactly 5 times bigger than the SOB. Energy consumption increase ratio, however, was 5.16 for standard occupants, 5.15 for efficient occupants and 5.22 for inefficient ones.

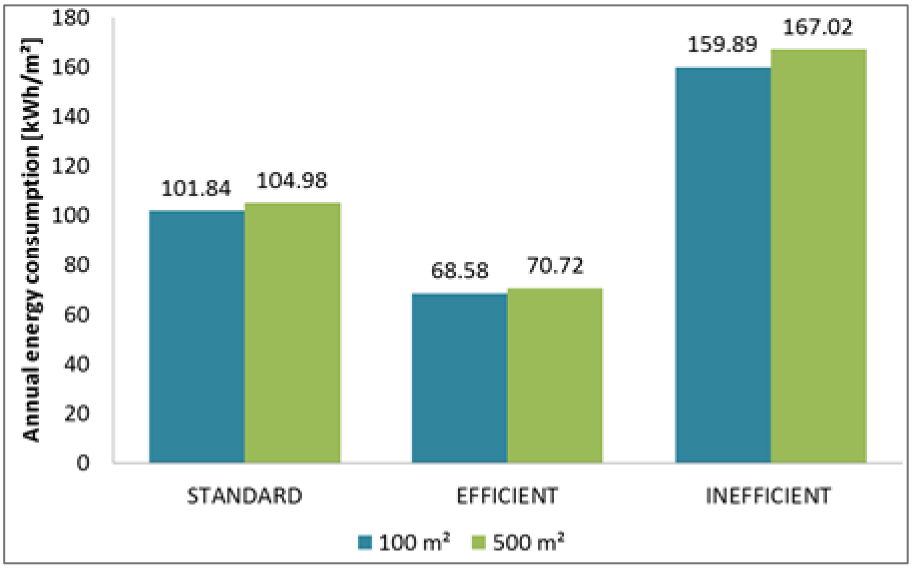


Figure 12: Annual energy consumption by gross size and occupant profile.

However, it is important to consider that the building gross size differs from its useful floor area. Average useful floor areas are 82.10 for SOB and 458.60 for LOB, resulting in a ratio of 1:5.59. When considering energy consumption by square meter of useful floor area, energy demand increased in a lower ratio than size, as shown in figure 13.

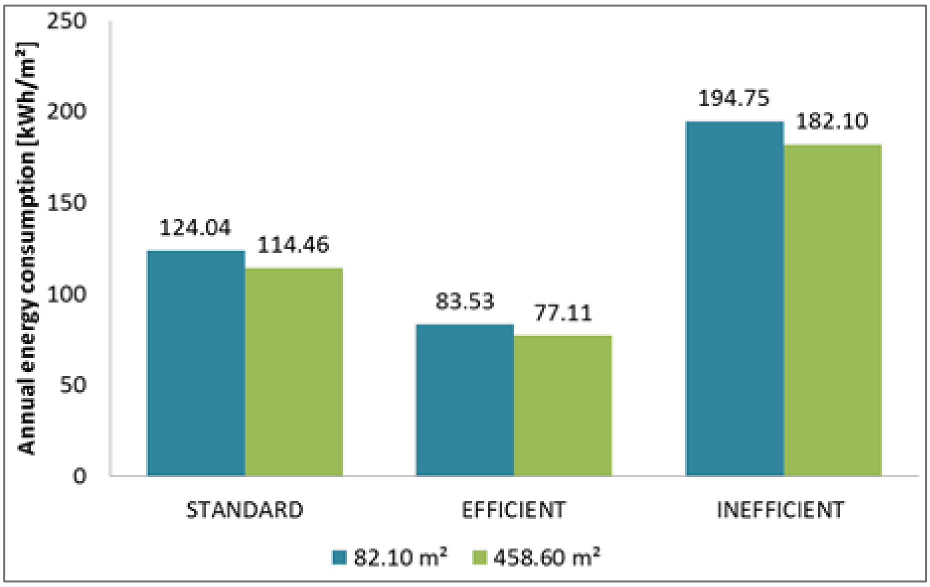


Figure 13: Annual energy consumption by useful floor area and occupant profile.

Nevertheless, when analysing the energy consumption breakdown (table 15), it can be noted that energy demand by equipment between LOB and SOB follows a ratio of 1:5.59 in all cases, i.e., the same as the buildings useful floor area. For standard and inefficient occupants, the same happens when analysing energy consumption by lighting.

Table 15: Annual energy consumption breakdown regarding size and occupancy profiles.

Size [m²]	Occupancy	Equipment [MWh year^{-1}]	Lighting [MWh year^{-1}]	HVAC [MWh year^{-1}]
100	Standard	4.28	2.25	3.65
	Efficient	3.14	0.60	3.12
	Inefficient	7.63	3.27	5.09
500	Standard	23.94	12.55	16.00
	Efficient	17.57	4.53	13.28
	Inefficient	42.62	18.29	22.60

From table 15 it may also be mentioned that, while energy demand by equipment shows a great variation between standard and inefficient occupant results, lighting and HVAC were not affected by the same rate. While equipment is the category with the most discrepancy for inefficient occupants, lighting is the one with most discrepancy for efficient ones. Energy saving potential by lighting is higher than other categories once it does not depend on a schedule, but also on natural lighting. In fact, efficient occupants can demand up to 3.75 times less energy due to lighting; for equipment and HVAC this value lowers to 1.36 and 1.21, respectively.

Energy saving potentials of efficient occupants were nearly the same regardless the building size, as shown in figure 14. When it comes to energy waste, however, inefficient occupants are responsible for a higher energy waste potential in larger buildings. It may also be observed that saving potential is smaller than waste potential. This is in fact reassured when analysing table 15. Note that inefficient occupants demand almost twice as much energy for equipment than standard occupants. Evidently, efficient measures are not able to reduce energy demand at the same ratio.

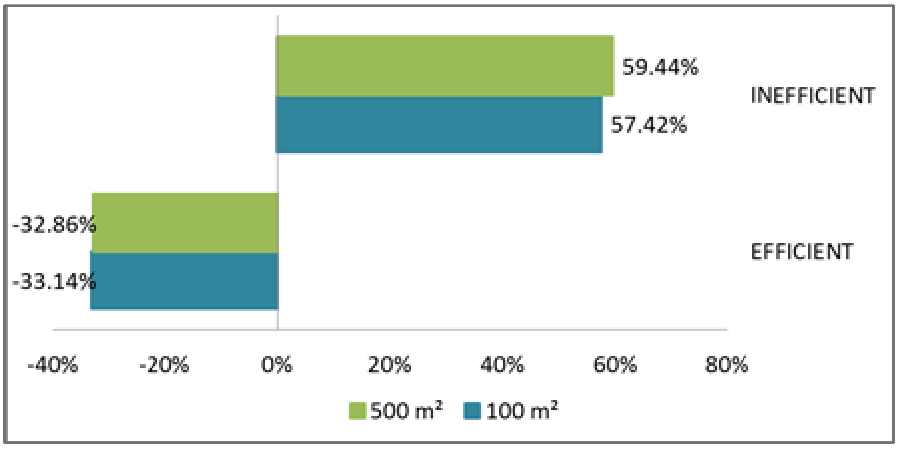


Figure 14: Energy saving potential by size and occupant profile, in relation to standard occupants.

Finally, energy consumption by each of the three analysed categories was evaluated according to the building's size and occupancy profile. Figure 15 shows that in all scenarios, the importance of equipment and lighting grows, while HVAC energy consumption has lower importance. While energy demand by equipment and lighting presented an average increase rate of 5.59 and 6.24, respectively, energy demand by HVAC in LOB is, on average, 4.36 times higher than in SOB.

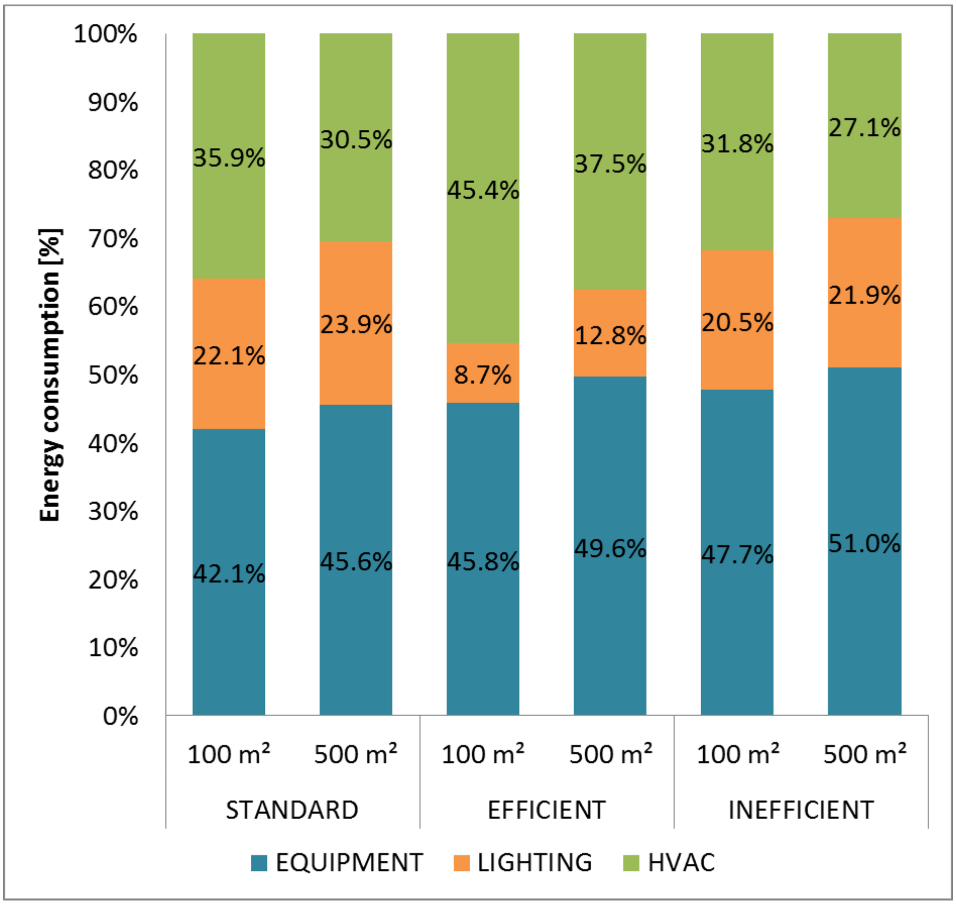


Figure 15: Energy consumption by category, size and occupant profile, in relation to standard occupants.

4.2.3. Constructive solution

Building models were created with two constructive solutions. This parameter altered not only energy consumption but also the useful building floor area, as shown in table 16. This useful area varies from one constructive solution to another because of the external wall thickness: for well-insulated buildings, external walls are 0.10 [m] thicker because there is an extra insulation board.

Table 16: Difference in useful building area due to a constructive solution.

Constructive Solution	SOB useful building area [m²]	LOB useful building area [m²]
Well-Insulated	80.28	454.28
Poorly Insulated	83.91	462.91

It is expected from the literature that poorly insulated buildings demand more energy than the well-insulated ones, mainly due to HVAC usage. This trend was indeed observed in dynamic simulation results, as shown in figure 16. Average values of all forty-eight building models' annual energy consumption were calculated only considering variations due to constructive solutions and occupancy profiles. For example, annual energy consumption of standard occupants for well-insulated buildings was calculated as the average energy consumption results for building models 1, 2, 5, 6, 9, 10, 13 and 14.

The impact of constructive solution over energy demand, however, is lower than location and size. In fact, energy demand of poorly insulated buildings was up to 7.18% higher than the demand for well-insulated ones.

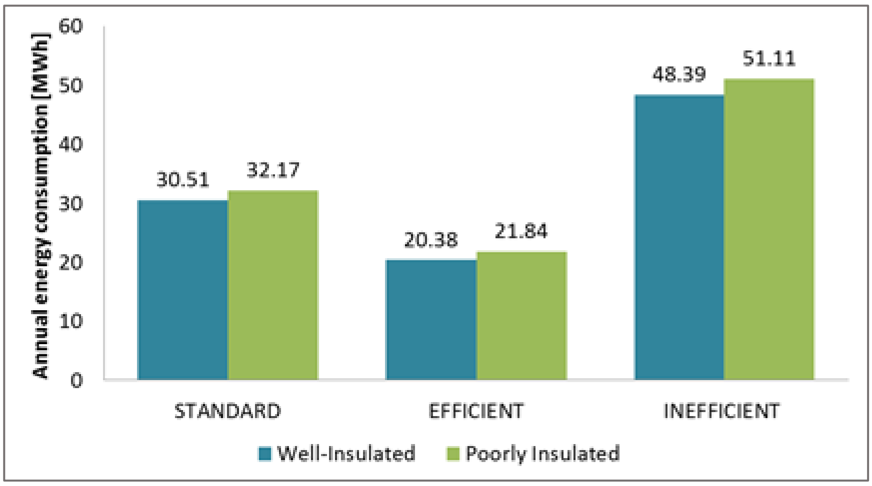


Figure 16: Annual energy consumption by constructive solution and occupant profile.

Energy saving and waste potentials due to occupancy patterns also presented a very slight variation for both well and poorly insulated buildings. When compared to standard occupants, efficient measures can reduce energy demand by 33.00%. Inefficient occupants can increase demand by 58.43%.

Table 17 exposes the energy consumption breakdown for each of the categories analysed in DesignBuilder simulations. It can be noted that not only HVAC had an increase in energy demand, but also equipment and lighting.

Table 17: Annual energy consumption breakdown regarding constructive solution and occupancy profiles.

Constructive Solution	Occupancy	Equipment [MWh year^{-1}]	Lighting [MWh year^{-1}]	HVAC [MWh year^{-1}]
Well Insulated	Standard	13.95	7.31	9.24
	Efficient	10.23	2.54	7.60
	Inefficient	24.84	10.66	12.89
Poorly Insulated	Standard	14.27	7.48	10.41
	Efficient	10.47	2.59	8.79
	Inefficient	25.41	10.90	14.80

DesignBuilder calculations for equipment and lighting energy demand depend only on the schedule and useful floor area, except for lighting usage by efficient occupants. Therefore, there is a slight increase in these demands on poorly insulated buildings, since useful floor area is bigger. The most significant energy demand growth, as expected, was from HVAC usage (figure 17).

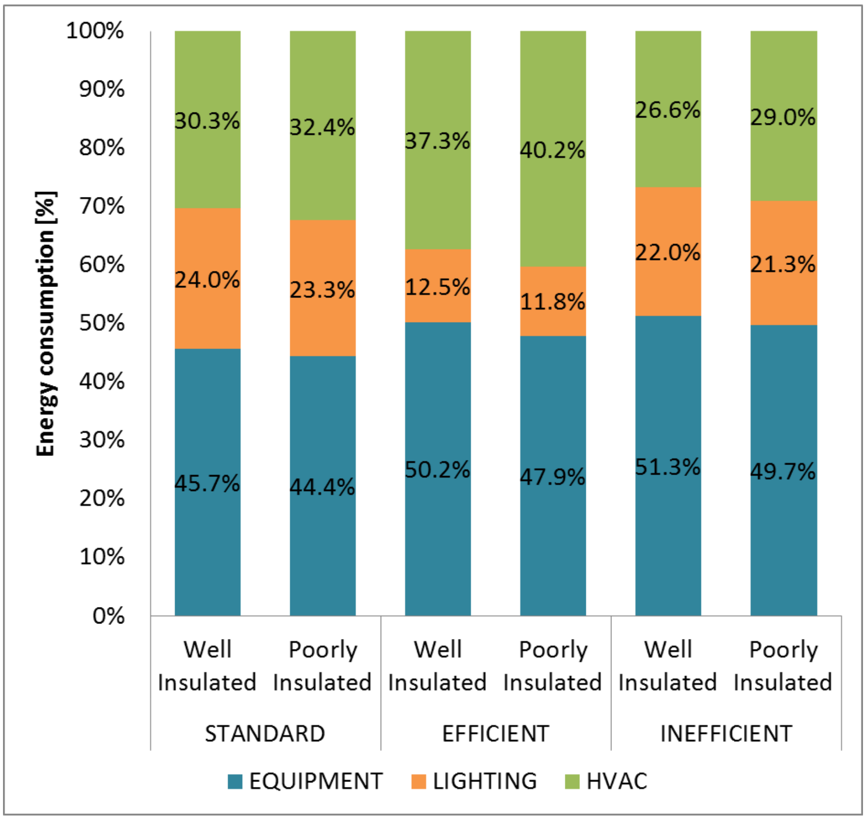


Figure 17: Energy consumption by category, size and occupant profile, in relation to standard occupants.

4.2.4. Energy efficiency class

For half of the building models, HVAC system had an energy efficiency class equivalent to A++. For the other half, COP values equivalent to class D were imputed. The impact of this change in the final energy consumption can be seen in figure 18. Note that energy efficiency class can increase energy consumption by 29.48%.

This results were obtained by the average values of all forty-eight building models' annual energy consumption, only considering variations due to energy efficiency class and occupancy profiles. For example, annual energy consumption of standard occupants for A++ systems was calculated as the average energy consumption results for building models 1, 3, 5, 7, 9, 11, 13 and 15.

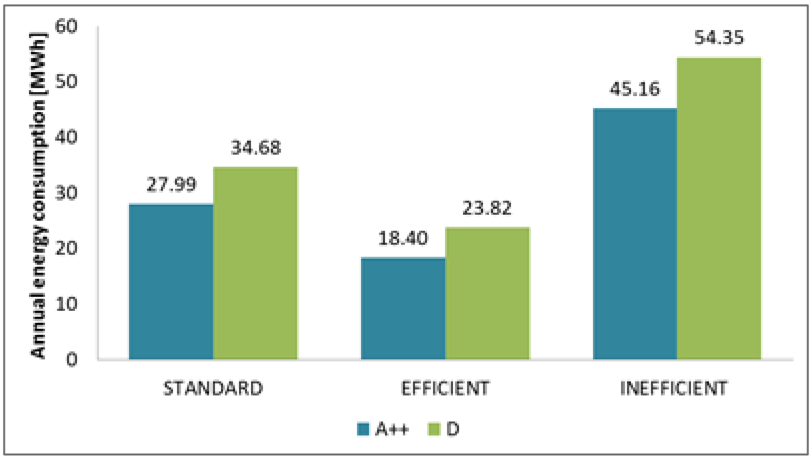


Figure 18: Total energy consumption by constructive solution and occupant profile.

Energy efficiency class affected only HVAC systems. As it can be observed at table 18, for all occupancy profiles, energy demand by equipment and lighting were exactly the same regardless the energy efficiency class. However, this parameter nearly doubled energy demand by HVAC.

Table 18: Annual energy consumption breakdown regarding energy efficiency class and occupancy profiles.

Energy Efficiency Class	Occupancy	Equipment [MWh year^{-1}]	Lighting [MWh year^{-1}]	HVAC [MWh year^{-1}]
A++	Standard	14.11	7.40	6.48
	Efficient	10.35	2.56	5.48
	Inefficient	25.13	10.78	9.25
D	Standard	14.11	7.40	13.17
	Efficient	10.35	2.56	10.91
	Inefficient	25.13	10.78	18.44

Energy saving and waste potentials also varied depending on the energy efficiency class. Efficient occupants had a higher saving potential with A++ systems when compared to standard occupants results (figure 19). Meanwhile, inefficient occupants are also more likely to demand more energy with A++ HVAC systems.

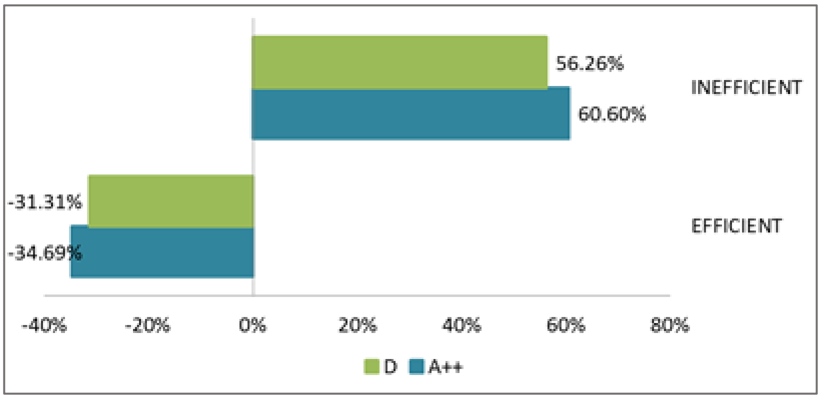


Figure 19: Energy saving potential by energy efficiency class and occupant profile, in relation to standard occupants.

As expected from table 18, as energy demand by equipment and lighting remain the same regardless energy efficiency class, HVAC importance grows from A++ to D buildings, as it can be seen in figure 20.

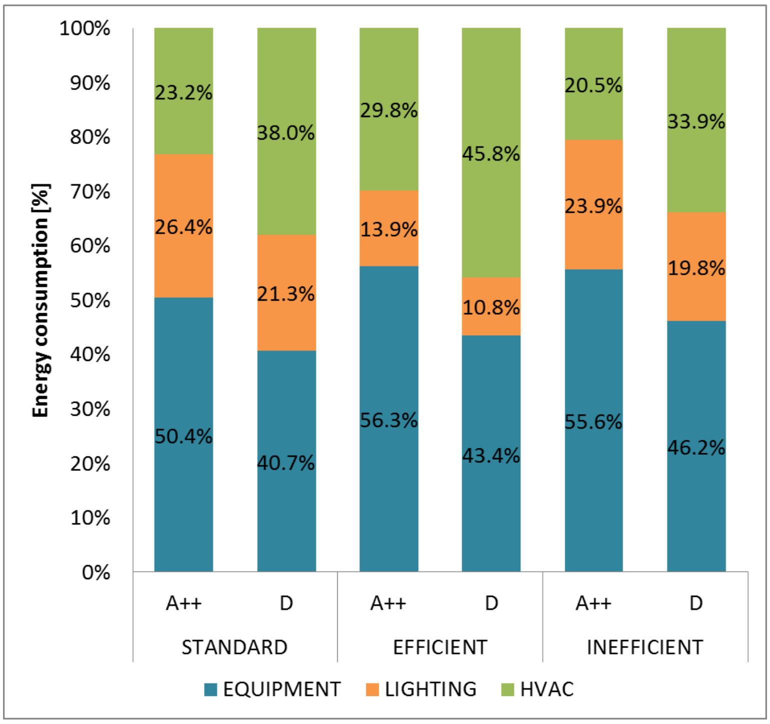


Figure 20: Energy consumption by category, size and occupant profile, in relation to standard occupants.

4.3. Results by category

This section aims to disclose energy consumption results separately for equipment, lighting and HVAC. Occupant profile affected all categories, as well as the size and constructive solution. The magnitude of their influence, however, was different in each scenario, although the size was the most influencing of them all, as detailed in the following subsections.

After all, a more extensive analysis was made in order to evaluate occupancy impact in energy consumption. Comparisons were made between building models with identical characteristics, except for occupancy profile. For example, building models 1, 17 and 33 were compared to each other and so on.

4.3.1. Equipment

Energy consumption due to equipment usage is only affected by three out of the five analysed parameters. Location and energy efficiency class had absolutely no influence over this category.

Energy consumption increased proportionally with the building usage floor area. This outcome was expected as energy consumption by equipment is calculated at DesignBuilder as power per m². Well-insulated LOB consumed 5.66 times more energy than well-insulated SOB. For poorly insulated buildings, this rate was 5.52.

When analysing constructive solution alone, it was found that poorly insulated buildings increase energy consumption by 4.51% in SOB and by 1.90% in LOB, when compared to well-insulated buildings. These results make clear that small buildings are more affected by constructive solutions than large ones.

Occupancy was also an influencing parameter. In relation to standard occupancy, energy consumption due to equipment usage decreased by 26.67% for efficient occupants. Inefficient occupants increased the standard values by 78.04%.

4.3.2. Lighting

Analysing energy consumption due to lighting is more complex than equipment on the grounds that, in this category, efficient occupants' behaviour is influenced by more variables than other occupancy profiles. Nevertheless, for all profiles, energy efficiency class did not affect energy demand by lighting.

In relation to standard occupant results, inefficient occupancy increased energy consumption by 45.73% in all conditions. For standard and inefficient occupants, the increase in energy demand due to size followed the same proportion of equipment demand (5.66 for well-insulated buildings and 5.52 for the poorly insulated ones). Constructive solution influence is also equal to equipment.

On the other hand, efficient occupants demand a more detailed analysis. As energy consumption by lighting depends on natural lighting levels, location is also a parameter that affects consumption. SOB located in Salvador consumed an average of 4.6% less energy than the ones located in Aveiro. For LOB, this rate was 14.7%.

As location began to matter, constructive solution and size affected each building in its own way, as shown in table 19.

Table 19: Increase in energy consumption due to lighting in poorly insulated buildings, when compared to well-insulated buildings.

Aveiro 100 m²	Aveiro 500 m²	Salvador 100 m²	Salvador 500 m²
4,02 %	1,28 %	4,12 %	1,50 %

As Salvador has more natural lighting than Aveiro, energy saving potential regarding lighting consumption was bigger in the tropical location. Table 20 shows the results for each location and building size when compared to standard occupancy.

Table 20: Energy savings potential in relation to standard occupancy.

Aveiro 100 m²	Aveiro 500 m²	Salvador 100 m²	Salvador 500 m²
72.68%	61.04%	73.95%	66.78%

4.3.3. HVAC

Energy consumption by HVAC was affected by all five parameters. The size of the building was the most influential of them all, followed by energy efficiency class and location. The building's constructive solution was the least influential parameter.

Unlike energy demand by equipment, HVAC consumption did not increase proportionally with size. LOB had an average increase ratio of 4.39 for standard occupants, 4.33 for efficient occupants, and 4.46 for inefficient ones.

Energy efficiency class had practically the same effect on all occupancy profiles: lower class systems (D) increased energy consumption by an average of 2.01 times for standard occupants and by 1.99 for efficient and inefficient ones. Regardless of the occupancy profile, the energy efficiency class had more impact on buildings located in Salvador.

Salvador also increased energy demand from HVAC systems when compared to Aveiro. In fact, for buildings located in a tropical climate, energy demand grown on a ratio of 1.78 for standard occupants, 1.84 for efficient occupants, and 1.81 for inefficient ones. Also, the impact of the constructive solution is higher in Salvador.

In summary, size has a bigger impact on energy consumption by inefficient occupants than by efficient ones. On the other hand, efficient occupants are more influenced by the building's location and constructive solution. Energy efficiency class affects both occupancy profiles equally.

4.4. Discussion

Energy efficiency stands out as a cost-effective way to help several nations to achieve their goals towards the global warming fight. BPS tools are therefore indispensable since they allow the prediction of energy use in buildings. As all software, however, BPS tools have limitations, such as the consideration of occupants' behaviours in energy consumption. This thesis aimed to study specifically this limitation and quantify the impact of behaviour on energy consumption in service buildings.

Another goal was to evaluate the major contributing parameters to the overall energy saving potential. For that matter, forty-eight building models were created with different characteristics regarding occupancy, location, size, constructive solution and the building's energy efficiency.

The first research question refers to the quantification of energy saving potential associated with consumer behaviour. As expected, occupant behaviour had a significant influence on energy consumption in service buildings. In all scenarios, efficient occupant behaviours were able to reduce energy consumption while inefficient behaviours increased energy demand when compared to standard ones. The energy saving potential varied depending on the building typology, constructive features and climate. It also varied depending on the energy final use (equipment, lighting, or HVAC).

A general result was calculated as averaged values of total energy consumption for all forty-eight building models, considering only the difference between occupancy profile. Standard occupants are represented in building models 1 to 16, efficient occupants, 17 to 32, and inefficient ones, 33 to 48. It can be observed (figure 21) that efficient occupants were able to reduce consumption by 32.64% when compared to standard occupants. Inefficient behaviours increased energy consumption by 58.64%.

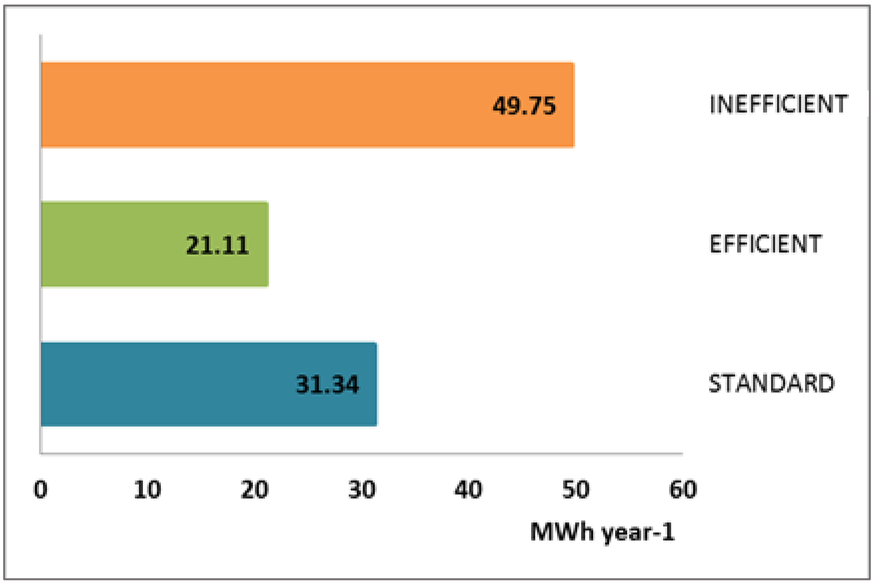


Figure 21: Average values for annual energy consumption according to occupant profile.

Table 21 shows the energy consumption breakdown by each category regarding occupancy profile. Note that lighting is the category with higher energy saving potential by efficient occupants (65.3%). The higher energy waste potential by inefficient occupants is on equipment (78.0%).

Table 21: Annual energy consumption breakdown regarding end-use category and occupancy profile.

Category	Standard Occupant [MWh year^{-1}]	Efficient Occupant [MWh year^{-1}]	Inefficient Occupant [MWh year^{-1}]
Equipment	14.11	10.35	25.13
Lighting	7.40	2.56	10.78
HVAC	9.83	8.20	13.84

The importance of energy consumption by each of the end uses considered also varied depending on occupancy profile, as shown in figure 22. For all occupants, equipment is the category that most demand energy, followed by HVAC and then lighting.

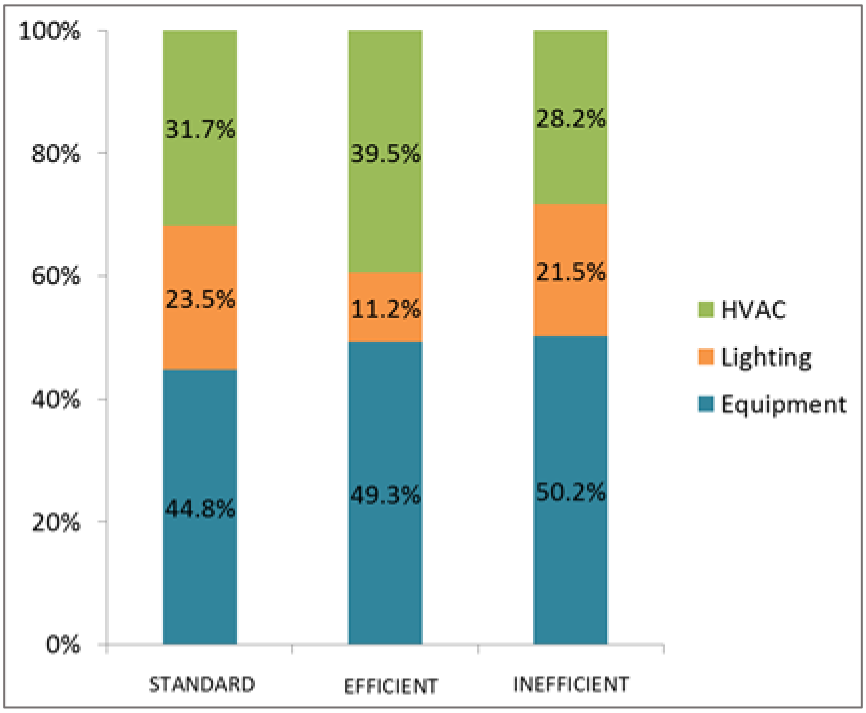


Figure 22: Impact of occupancy profile on energy consumption by each category.

Although efficient occupants were able to reduce energy consumption in all three categories, energy demand by lighting showed substantial reduction when compared to standard results. Therefore equipment and HVAC gained importance as energy demand by these two categories did not decrease at the same rate as lighting. The same happened with inefficient occupants regarding the increase of energy demand by equipment, which reduced the importance of lighting and HVAC.

This thesis' second research question regards the major contributing parameters to the overall reduction of energy consumption. Section 3.2 disclosed general results in that matter. The higher rates for both energy saving and waste potentials were due to energy efficiency class: when compared to standard results for A++ buildings, efficient occupants can reduce energy consumption by 34.7%, while inefficient behaviours can increase consumption by 60.6%. That result can explain as energy efficiency class has a high impact on energy demand by HVAC system, which has a big importance in energy consumption for all occupancy profiles.

Concerning gross values for energy saving and waste, energy efficiency class was the parameter that most affected energy consumption. HVAC systems with a class equivalent to D demanded an average of 24.6% more energy than the ones with class A++.

Secondly, different locations were liable for a diversion of 18.9% in energy consumption. Buildings situated in Salvador had higher energy demand by HVAC systems. Although there is no need for heating, the energy needed for cooling throughout the entire year ended up being significantly higher than energy demand by HVAC in Aveiro, where both heating and cooling are needed.

Regarding the building’s size, it was observed that energy demand increases in a higher rate than the gross building area, however, energy demand increase in a lower rate than the useful floor area. Considering the gross area, LOB demand 7,2% more energy per square meter than SOB. When only the useful floor area is taken into account, this rate drops to -3.1%.

Finally, poorly insulated buildings were responsible for an increase of 6.1% in energy consumption when compared to well-insulated ones. Constructive solutions influenced energy consumption of all end-use categories, although in a very slight manner.

At last, it is inevitable to notice that regardless the rigorousness of efficient behaviours, waste potential by inefficient occupants was always higher than saving potential. This result shows the danger of unconcerned energy behaviours and the threat they can be to the progress of energy efficiency.

5. CONCLUSION

5.1. Summary

This chapter aims to summarise the main conclusion of this dissertation in order to evaluate if all proposed objectives have been achieved. It also discloses on the main obstacles and, finally, some future research prospects are indicated.

5.2. General conclusions

Understanding energy behaviour is a multifaceted task, which makes it a challenge to be rightfully represented in dynamic simulation tools. Although several studies support the great energy saving potential through behavioural changes, there is still little knowledge regarding occupant behaviours. Therefore, it represents a significant limitation of dynamic simulation tools and is one of the reasons why results often differ from reality.

This thesis aimed to propose a quantitative methodology to analyse occupants' behaviours and their impact on energy consumption in service buildings. It was also a goal to acknowledge which parameters have a greater impact on energy consumption in service buildings and therefore should be the focus of potential interventions.

The proposed methodology was based on the building dynamics simulation considering extreme operation profiles, representing limit energy behaviours of service buildings occupants using DesignBuilder software. Five main factors were considered and combined to acquire a large variability of results: occupant profile, location, the size of the building, constructive solution, and energy efficiency class of HVAC system.

Before analysing the results, it is important to consider this thesis' limitations. As energy behaviour is a complex and recent theme, there is a great variety of studies with different results. It has not yet been elaborated an uncontestable teory about human behaviour, and therefore behavioural modelling approaches are not yet unblemished. Another limitation concerns service buildings data acquisition, as information varies between countries regarding building typology and energy consumption breakdown.

Two research questions were initially formulated and appropriately addressed in the previous chapter of this thesis. The first goal was to quantify the potential of energy consumption reduction associated with consumer behaviour in service buildings. To that end, average values of total energy consumption for all building models were considered. The potential of energy reduction due to efficient behaviours was 32.64% when compared to standard behaviours. On the other hand, inefficient behaviours increased energy consumption by 58.64%.

Energy saving and waste potential were different for each of the three energy end-uses. Efficient behaviours have a higher impact on lighting, while inefficient behaviours have a higher influence on equipment. The least affected category, for both, was HVAC system. For all occupancy profiles, equipment was the category responsible for most of the energy consumption, followed by HVAC and lighting. Their importance, however, varied from one occupancy profile to another.

The second research question aimed to define the major contributing parameters to the overall reduction of energy consumption. Energy efficiency class was the parameter with higher energy saving and waste potential. When compared to standard results for A++ HVAC systems, efficient behaviours reduced energy consumption by 34.7%, while inefficient behaviours increased consumption by 60.6%. At the same time, the lower results for energy saving and waste potential were for HVAC systems equivalent to energy efficiency class D. Efficient occupants demanded 31.31% less energy than standard ones, while inefficient occupants consumed an extra 56.26%.

Note that energy saving and waste potential had little variation regardless the analysed parameter. However, concerning gross values for energy consumption, some parameters, namely the building size, had a major contribution to the increase of energy consumption. Results showed that energy demand increases in a higher rate than the gross building size; however, it increases at a lower rate than the useful floor area.

As expected, the lower the efficiency class, the higher the energy consumption. HVAC systems with a class equivalent to D demanded an average of 24.6% more energy than the A++ systems. The location also influenced total energy consumption: Salvador has a higher energy demand due to cooling necessity, increasing energy consumption by 18.9% when compared to buildings situated in Aveiro. Finally, poorly insulated buildings are accountable for an increase of 6.1% in total energy consumption in comparison to well-insulated buildings.

Regarding climate influence, occupant actions have a more significant impact on buildings located at warmer climates, as previously stated by Bonte et al. [38]. Climate strongly influences heating and cooling behaviour: while cold climates induce a greater use of heating and have less cooling demand, warm cilmates increases cooling needs. Also, warmer climates represent locations closer to Ecuador, which have a higher solar insolation and therefore affects natural lighting and ventilation.

In conclusion, it is essential to have a deep knowledge of all outward factors in order to combine the building's physical characteristics, its energy end-uses and systems as they can affect the building's energy consumption. However, it was demonstrated that occupant behaviour can positively affect energy consumption, as well as it can have a negative influence. Results showed that in all scenarios waste potential by inefficient occupants was always higher than saving potentials. It, therefore, highlights the importance of understanding and rightfully considering energy behaviour in order to achieve accurate results in dynamic simulations.

5.3. Future research

As behaviour is a complex topic, efficient and inefficient occupants and their interactions with energy end-uses were representative and established based mainly on other studies. Therefore, for more accurate results, it is important to fully understand energy behaviours, its variations due to contextual, psychological and physiological factors. For instance, same occupancy profiles were considered both in Aveiro and Salvador; however, occupants do not necessarily act the same way in both places due to cultural differences. As modelling process is based in quantitative modelling technics, the use of social techniques such as interviews and surveys may help understand and develop more realistic occupancy profiles.

Further attention must be paid when considering different locations. For comparison purposes, the variations of decree-laws between Portugal and Brazil were not considered. However, it is known that both countries have different legal requirements regarding constructive solutions and energy efficiency class definitions.

As occupant behaviour has a great impact on energy consumption in service buildings, it may also be suggested a more thorough investigation on possible motivational manners for occupants to rethink and modify their energy behaviours.

REFERENCES

[1] EIA, 2016. *International Energy Outlook 2016*. U.S. Energy Information Administration, Washington, USA, 276 pp.

[2] IPCC, 2014. *Climate Change 2014: Synthesis Report*. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 151 pp.

[3] EUROPEAN COMMISSION. *2020 Climate and Energy Package*. Available at: http://ec.europa.eu/clima/policies/strategies/2020_en. Accessed 01 December 2016.

[4] NRDC, 2017. *The Paris agreement on climate change*. Natural Resources Defence Council, New York, USA, 4 pp.

[5] THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION, 2012. *Directive 2012/27/EU of the European Parliament and of the Council of the European Union on energy efficiency*. Official Journal of the European Union, 56 pp.

[6] LOPES, M.A.R., 2015. *Modelling energy behaviours as promoters of energy efficiency: an integrative approach* (PhD Thesis). Coimbra: Universidade de Coimbra, 134 pp.

[7] UNEP, 2009. *Buildings and Climate Change: Summary for Decision-Makers*. United Nations Environment Programme, France, Paris, 62 pp.

[8] MASOSO, O.T., GROBLER, L.J., 2010. *The dark side of occupants' behaviour on building energy use*. In: Energy and Buildings, v. 42, pp. 173-177.

[9] BPIE, 2011. *Europe's buildings under the microscope – A country-by-country review of the energy performance of buildings*. Buildings Performance Institute Europe, Brussel, Belgium, 132 pp.

[10] REIS, A.L., 2013. *Influência dos comportamentos no consumo energético de edifícios* (MSc Thesis). Aveiro: Universidade de Aveiro, 93 pp.

[11] ZEBRA2020. *Data Tool – Energy efficiency trends in buildings*. Available at: http://www.zebra-monitoring.enerdata.eu/overall-building-activities/share-of-non-residential-buildings-with-epc-labels-a-or-b.html. Accessed at 15 June 2017.

[12] DIKMEN, Ç. B., GULTEKIN, A. B., 2011. *Usage of renewable energy resources in buildings in the context of sustainability*. Journal of Engineering, Science and Design, v. 1, pp. 96-100.

[13] SHARAFI, M., ELMEKKAWY, T. Y., BIBEAU, E. L., 2015. *Optimal design of hybrid renewable energy systems in buildings with low to high renewable energy ratio*. Renewable Energy, v. 83, pp. 1026-1042.

[14] ASHRAE, 2009. *Sustaining our future by rebuilding our past – Presidential Address*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 6 pp.

[15] JUDD, K.S., SANQUIST, T., ZALESNY, M., FERNANDEZ, N., 2013. *The role of occupant behaviour in achieving net zero energy: a demonstration project at Fort Carson*. Pacific Northwest National Laboratory, 101 pp.

[16] MILLER, D.J., 2013. *Behavioral opportunities for energy savings in office buildings: a London field experiment* (MSc Thesis). London: Imperial College of London, 100 pp.

[17] WBCSD, 2009. *Transforming the Market: Energy Efficiency in Buildings*. World Business Council for Sustainable Development, 72 pp.

[18] HOES, P., HENSEN, J., LOOMANS, M., VRIES, B., BOURGEOIS, D., 2009. *User behaviour in whole building simulation*. Energy and Buildings, v. 41, pp. 295-302.

[19] DIETZ, T, GARDNER, G.T., GILLIGAN, J., STERN, P.C., VANDENBERGH, M.P., 2009. *Household actions can provide behavioral wedge to rapidly reduce US carbon emissions*. Proceedings of the National Academy of Sciences of the United States of America, v. 106, pp. 18452-18456.

[20] NGUYEN, T. & AIELLO, M., 2013. *Energy intelligent buildings based on user activity: a survey*. Energy and Buildings, v. 56, pP. 244-257.

[21] EUROPEAN COMMISSION, 2012. *Energy Efficiency Status Report 2012 – electricity consumption and efficiency trends in the EU-27*. Luxembourg: Publications Office of the European Union, 143 pp.

[22] EIA, 2016. *Electricity consumption intensities (kWh) by end use, 2012*. Table E6. Available at: https://www.eia.gov/consumption/commercial/data/2012/index.php?view=consumption#e1-e11. Accessed 24 November 2016.

[23] SHANKS, K., 2009. *State of the art review: energy use behaviour in business organizations*. Heriot-Watt University, 13 pp.

[24] FABI, V., CORGNATI, S., FILLIPI, M., OLESEN, B., 2011. *Effect of occupant behaviour related influencing factors on final energy end uses in buildings*. Climamed 11 Conference, Madrid, Spain, 17 pp.

[25] YU, Z., FUNG, B.C.M., HAGHIGHAT, F., YOSHINO, H., MOROFSKY, E., 2011. *A systematic procedure to study the influence of occupant behaviour on building energy consumption*. Energy and Buildings, v. 43, pp. 1409-1417.

[26] AL-ZUBAIDY, S. N., TOKBOLAT, S., TOKPATAYEVA, R., 2013. *Passive design of buildings for extreme weather environment*. International Journal of Renewable Energy Development, v. 2, pp. 1-11.

[27] ALLEGRINI, J., 2012. *Urban climate and energy demand in buildings* (MSc. Thesis). Zurich: Swiss Federal Institute of Technology, 166 pp.

[28] IEA, 2013. *Technology Roadmap – Energy efficient building envelopes*. International Energy Agency, Paris, France, 64 pp.

[29] CLAIR, P. *Low-energy design in the United Arab Emirates – Building design principles*. BEDP Environment Design Guide, 10 pp.

[30] CHENARI, B., CARRILHO, J., SILVA, M., 2016. *Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review*. Renewable and Sustainable Energy Reviews, v. 59, pp. 1426-1447.

[31] WANG, L., MATHEW, P., PANG, W., 2012. *Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building*. Energy and Buildings, v. 53, pp. 152-158.

[32] TABULA Project Team, 2012. *Typology approaches for non-residential buildings in five European countries – Existing information, concepts and outlook*. TABULA Thematic Report Nº 3, 39 pp. Available at: http://episcope.eu/fileadmin/tabula/public/docs/report/TABULA_TR3_D9_NonResidentialBuildings.pdf. Accessed on 20 February 2017.

[33] WOLFE, A.K, MALONE, E.L., HEEWAGEN, J., DION, J., 2014. *Behavioral change and building performance: strategies for significant, persistent, and measurable institutional change*. Pacific Northwest National Laboratory, Richland, Washington, 64 pp.

[34] FABI, V., ANDERSEN, R.V., CORGNATI, S., OLESEN, B.W., 2012. *Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models*. Building and Environment, v. 58, pp. 188-198.

[35] KAHNEMAN, D., 2011. *Thinking, Fast and Slow*. New York, Farrar, Straus and Giroux.

[36] YOUNG, R., 1993. *Changing behavior and making it stick: the conceptualization and management of conservation behavior*. Environment and Behavior, v. 25, pp. 485-505.

[37] SHOVE, E., GUY, S., 2000. *The Sociology of Energy, Buildings and the Environment: Constructing knowledge, designing practice*. Routledge, London.

[38] BONTE, M., THELLIER, F., LARTIGUE, B., 2014. *Impact of occupants' actions on energy building performance and thermal sensation*. Energy and Buildings, v. 76, pp. 219-227.

[39] SANTIN, O. G., ITARD, L., VISSCHER, H., 2009. *The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock*. Energy and Buildings, v. 41, pp. 1223-1232.

[40] GUL, M. S., PATIDAR, S., 2015. *Understanding the energy consumption and occupancy of a multi-purpose academic building*. Energy and Buildings, v. 87, pp. 155-165.

[41] MAIER, T., KRZACZEK, M., TEJCHMAN, J., 2009. *Comparison of physical performances of the ventilation systems in low-energy residential houses*. Energy and Buildings, v. 41, pp. 337-353.

[42] HONG, T., LIN, H. W., 2012. *Occupant behavior: impact on energy use of private offices*. In: 1st Asia conference of International Building Performance Simulation Association, Shanghai, 25-27 November, 12 pp.

[43] CLEVENGER, C. M., HAYMAKER, J., 2006. *The impact of the building occupant on energy modelling simulations*. In: Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada, 10 pp.

[44] VAKILOROAYA, V., SAMALI, B., FAKHAR, A., PISHGHADAM, K., 2014. *A review of different strategies for HVAC energy saving*. Energy Conversion and Management, v. 77, pp. 738-754.

[45] POLINDER, H., SCHWEIKER, M., AA, A., SCHAKIB-EKBATAN, K., FABI, V., ANDERSEN, R., et. al, 2013. *Occupant behaviour and modelling*. Institute for Building Environment and Energy Conservation, Tokyo, Japan, 151 pp.

[46] REIS, A., LOPES, M., MARTINS, N., 2015. *Estimating the impact of occupant behaviours on energy consumption of small commercial and service buildings*. In: Energy for Sustainability, 10 pp.

[47] BROWN, Z., JOHNSTONE, N., HASCIC, I., VONG, L., BARASCUD, F., 2012. *Testing the effect of defaults on the thermostat settings of OECD employees*. OECD Environmental Working Papers, n. 51, OECD Publishing, 17 pp.

[48] WARREN, P. R., PARKINS, L. M. *Window-opening behaviour in office buildings*. ASHRAE Trans 1984, 90 (IB):1056-76.

[49] NICOL, J., 2001. *Characterizing occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans*. In: Proceedings of the 7th International IBPSA Conference, Rio de Janeiro, 13-15 August, 6 pp.

[50] ROETZEL, A., TSANGRASSOULIS, A., DIETRICH, U., BUSHING, S., 2010. *A review of occupant control on natural ventilation*. Renewable and Sustainable Energy Reviews, v. 14, pp. 1001-1013.

[51] WILLIAMS, A., ATKINSON, B., GARBESI, K., PAGE, E., RUBINSTEIN, F., 2012. *Lighting controls in commercial buildings*. LEUKOS, v. 8, pp. 161-180.

[52] TZEMPELIKOS, A., 2010. *The impact of manual light switching on lighting energy consumption for a typical office building.* In: International High Performance Buildings Conference. Paper 32, 9 pp.

[53] HUNT, D., 1979. *The use of artificial lighting in relation to daylight levels and occupancy*. Building and Environment, v. 14, pp. 21-33.

[54] PIGG, S., EILERS, M., REED, J., 1996. *Behavioral aspects of lighting and occupancy sensors in private office: a case study of a university office building*. In: American Council for an Energy Efficient Economy, 10 pp.

[55] MAHDAVI, A., PROGLHOF, C., 2008. *Observation-based models of user control actions in buildings*. In: 25th Conference on Passive and Low Energy Architecture, Dublin, 22-24 October, 7 pp.

[56] HEYDARIAN, A., PANTAZIS, E., CARNEIRO, J., GERBER, D., BECERIK-GEBER, B., 2016. *Lights, building, actions: Impact of default lighting settings on occupant behaviour*. Journal of Environmental Psychology, v. 16, pp. 212-223.

[57] BOYCE, P.R., BEITCH, J.A., NEWSHAM, G.R., JONES, C.C., HEERWAGEN, J., MYER, M., HUNTER, C.M., 2006. *Occupant use of switching and dimming controls in offices*. Lighting Research and Technology, v. 38, pp. 358-376.

[58] METZGER, I., KANDT, A., VANGEET, O., 2011. *Plug load behavioral change demonstration project*. National Renewable Energy Laboratory, Colorado, USA, 55 pp.

[59] LASTERNAS, B., ZHAO, J., YUN, R., ZHANG, C., WANG, H., AZIZ, A., LAM, K.P., LOFNESS, V., 2014. *Behavior oriented metrics for plug load energy savings in office environment*. In: ACEEE Summer Study on Energy Efficiency Buildings, pp. 160-172.

[60] NBI, 2012. *Plug Load Best Practice Guide*. New Buildings Institute, 8 pp.

[61] WEBBER, C., ROBERSON, J.A., MCWHINNEY, M.C., BROWN, R.E., PINCKARD, M.J., BUSCH, J.F., 2006. *After-hours power status of office equipment in the USA*. Energy, v. 31, pp. 2823-2838.

[62] AUGENBROE, G., 2002. *Trends in building simulation*. Building and environment, v. 37, pp. 891-902.

[63] RYAN, E. M., SANQUIST, T. F., 2012. *Validation of building energy modelling tools under idealized and realistic conditions*. Energy and Buildings, v. 47, pp. 375-382.

[64] SOUZA, J., 2012. *Energy simulation software for buildings: review and comparison*. IT4ENERGY – Information Technology for Energy applications, v. 923, pp. 57-68.

[65] FABI, V., ANDERSEN, R.V., CORGNATI, S.P., OLESEN, B.W., FILIPPI, M., 2011. *Description of occupant behaviour in building energy simulation: state-of-art and concepts for improvements*. In: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November 2011, 8 pp.

[66] YAN, D., O'BRIAN, W., HONG, T., FENG, X., GUNAY, H.B., TAHMASEBI, F., MAHDAVI, A., 2015. *Occupant behavior modelling for building performance simulation: Current state and future challenges*. Energy and Buildings, v. 107, pp. 264-278.

[67] O'BRIAN, W., GUNAY, H. B., 2014. *The contextual factors contributing to occupants' adaptive comfort behaviors in offices – A review and proposed modelling framework*. Building and Environment, v. 77, pp.77-87.

[68] TABAK, V., 2009. *User simulation of space utilization* (PhD Thesis). Eindhoven: Technische Universiteit Eindhoven, 277 pp.

[69] Decreto-Lei nº 79/2006. Diário da República – I Série A. Nº 67, p. 2416-2468, 2006.

[70] ASHRAE, 2007. *ASHRAE Standard – Ventilation for acceptable indoor air quality*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 48 pp.

[71] Portaria 349-B/2013. Diário da República n.º 232/2013, 1º Suplemento, Série I de 2013-11-29.

[72] Commission Delegated Regulation (EU) nº 626/2011 of 4 May 2011.

APPENDIX A – Dynamic simulation results

Table A.1: Dynamic simulation results.

Model number	Occupancy Profile	Location	Size [m²]	Constructive Solution	Energy Efficiency Class	Room Electricity [KWh/year]	Lighting [KWh/year]	HVAC [KWh/year]	Fuel Total [KWh/year]
1	Standard	Aveiro	100	Well-Insulated	A++	4,191.06	2,196.71	1,518.25	7,906.02
2	Standard	Aveiro	100	Well-Insulated	D	4,191.06	2,196.71	3,024.07	9,411.84
3	Standard	Aveiro	100	Poorly Insulated	A++	4,380.25	2,295.87	1,994.70	8,670.82
4	Standard	Aveiro	100	Poorly Insulated	D	4,380.25	2,295.87	3,939.76	10,615.88
5	Standard	Aveiro	500	Well-Insulated	A++	23,715.54	12,430.29	6,690.14	42,835.97
6	Standard	Aveiro	500	Well-Insulated	D	23,715.54	12,430.29	13,301.32	49,447.15
7	Standard	Aveiro	500	Poorly Insulated	A++	24,165.76	12,666.26	9,126.93	45,958.95
8	Standard	Aveiro	500	Poorly Insulated	D	24,165.76	12,666.26	18,014.43	54,846.45
9	Standard	Salvador	100	Well-Insulated	A++	4,191.06	2,196.71	3,105.85	9,493.62
10	Standard	Salvador	100	Well-Insulated	D	4,191.06	2,196.71	6,211.70	12,599.47
11	Standard	Salvador	100	Poorly Insulated	A++	4,380.25	2,295.87	3,139.54	9,815.66
12	Standard	Salvador	100	Poorly Insulated	D	4,380.25	2,295.87	6,279.08	12,955.20
13	Standard	Salvador	500	Well-Insulated	A++	23,715.54	12,430.29	12,694.87	48,840.70
14	Standard	Salvador	500	Well-Insulated	D	23,715.54	12,430.29	27,389.74	63,535.57
15	Standard	Salvador	500	Poorly Insulated	A++	24,165.76	12,666.26	13,600.60	50,432.62
16	Standard	Salvador	500	Poorly Insulated	D	24,165.76	12,666.26	27,201.19	64,033.21
17	Efficient	Aveiro	100	Well-Insulated	A++	3,073.44	601.14	1,233.82	4,908.40
18	Efficient	Aveiro	100	Well-Insulated	D	3,073.44	601.14	2,448.57	6,123.15
19	Efficient	Aveiro	100	Poorly Insulated	A++	3,212.18	626.32	1,729.97	5,568.47
20	Efficient	Aveiro	100	Poorly Insulated	D	3,212.18	626.32	3,401.56	7,240.06
21	Efficient	Aveiro	500	Well-Insulated	A++	17,391.40	4,856.77	5,256.11	27,504.28
22	Efficient	Aveiro	500	Well-Insulated	D	17,391.40	4,856.77	10,395.01	32,643.18

23	Efficient	Aveiro	500	Poorly Insulated	A++	17,721.55	4,919.98	7,780.35	30,421.88
24	Efficient	Aveiro	500	Poorly Insulated	D	17,721.55	4,919.98	15,278.73	37,920.26
25	Efficient	Salvador	100	Well-Insulated	A++	3,073.44	572.93	2,661.29	6,307.66
26	Efficient	Salvador	100	Well-Insulated	D	3,073.44	572.93	5,322.58	8,968.95
27	Efficient	Salvador	100	Poorly Insulated	A++	3,212.18	597.53	2,709.82	6,519.53
28	Efficient	Salvador	100	Poorly Insulated	D	3,212.18	597.53	5,419.64	9,229.35
29	Efficient	Salvador	500	Well-Insulated	A++	17,391.40	4,137.16	11,170.71	32,699.27
30	Efficient	Salvador	500	Well-Insulated	D	17,391.40	4,137.16	22,341.43	43,869.99
31	Efficient	Salvador	500	Poorly Insulated	A++	17,721.55	4,199.96	11,327.62	33,249.13
32	Efficient	Salvador	500	Poorly Insulated	D	17,721.55	4,199.96	22,655.25	44,576.76
33	Inefficient	Aveiro	100	Well-Insulated	A++	7,461.85	3,201.22	2,083.33	12,746.40
34	Inefficient	Aveiro	100	Well-Insulated	D	7,461.85	3,201.22	4,155.10	14,818.17
35	Inefficient	Aveiro	100	Poorly Insulated	A++	7,798.69	3,345.72	2,767.63	13,912.04
36	Inefficient	Aveiro	100	Poorly Insulated	D	7,798.69	3,345.72	5,468.62	16,613.03
37	Inefficient	Aveiro	500	Well-Insulated	A++	42,223.66	18,114.42	9,336.62	69,674.70
38	Inefficient	Aveiro	500	Well-Insulated	D	42,223.66	18,114.42	18,607.20	78,945.28
39	Inefficient	Aveiro	500	Poorly Insulated	A++	43,025.22	18,458.30	12,650.19	74,133.71
40	Inefficient	Aveiro	500	Poorly Insulated	D	43,025.22	18,458.30	24,996.22	86,479.74
41	Inefficient	Salvador	100	Well-Insulated	A++	7,461.85	3,201.22	4,347.16	15,010.23
42	Inefficient	Salvador	100	Well-Insulated	D	7,461.85	3,201.22	8,694.32	19,357.39
43	Inefficient	Salvador	100	Poorly Insulated	A++	7,798.69	3,345.72	4,389.47	15,533.88
44	Inefficient	Salvador	100	Poorly Insulated	D	7,798.69	3,345.72	8,778.95	19,923.36
45	Inefficient	Salvador	500	Well-Insulated	A++	42,223.66	18,114.42	18,630.69	78,968.77
46	Inefficient	Salvador	500	Well-Insulated	D	42,223.66	18,114.42	37,261.38	97,599.46
47	Inefficient	Salvador	500	Poorly Insulated	A++	43,025.22	18,458.30	19,776.87	81,260.39
48	Inefficient	Salvador	500	Poorly Insulated	D	43,025.22	18,458.30	39,553.73	101,037.25

APPENDIX B – Building model groups for average calculations

This appendix shows the building models considered for each calculation presented at section 3. Average results of each group were used for discussion.

Table B.1: Location and occupant profile groups (Table 14)

Location	Standard Occupants [Model Numbers]	Efficient Occupants [Model Numbers]	Inefficient Occupans [Model Numbers]
Aveiro	1 to 9	17 to 24	33 to 40
Salvador	10 to 16	25 to 32	41 to 48

Table B.2: Size and occupant profile groups (Table 15)

Building size	Standard Occupants [Model Numbers]	Efficient Occupants [Model Numbers]	Inefficient Occupans [Model Numbers]
SOB	1 to 4 and 9 to 12	17 to 20 and 25 to 28	33 to 36 and 41 to 44
LOB	5 to 8 and 13 to 16	21 to 24 and 29 to 32	37 to 40 and 45 to 48

Table B.3: Constructive solution and occupant profile groups (Table 17)

Constructive Soluticon	Standard Occupants [Model Numbers]	Efficient Occupants [Model Numbers]	Inefficient Occupans [Model Numbers]
Well-Insulated	1, 2, 5, 6, 9, 10, 13, 14	17, 18, 21, 22, 25, 26, 29, 30	33, 34, 37, 38, 41, 42, 45, 46
Poorly Insulated	3, 4, 7, 8, 11, 12, 15, 16	19, 20, 23, 24, 27, 28, 31, 32	35, 36, 39, 40, 43, 44, 47, 48

Table B.4: Energy efficiency class and occupant profile groups (Table 18)

Energy Efficiency Class	Standard Occupants [Model Numbers]	Efficient Occupants [Model Numbers]	Inefficient Occupans [Model Numbers]
A++	1, 3, 5, 7, 9, 11, 13, 15	17, 19, 21, 23, 25, 27, 29, 31	33, 35, 37, 39, 41, 43, 45, 47
D	2, 4, 6, 8, 10, 12, 14, 16	18, 20, 22, 24, 26, 28, 30, 32	34, 36, 38, 40, 42, 44, 46, 48

Table B.5: Annual energy consumption and occupant profile groups (Table 21)

Standard Occupants [Model Numbers]	Efficient Occupants [Model Numbers]	Inefficient Occupans [Model Numbers]
1 to 16	17 to 32	33 to 48