UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Unlocking and understanding the demand flexibility in office buildings

Miguel Coelho Correia Vargues

Mestrado Integrado em Engenharia da Energia e do Ambiente

Dissertação orientada por:
Prof. Dr. Eng. Guilherme Carrilho da Graça

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Abstract

The rising integration of variable, uncontrollable and hardly predictable renewable energy sources into the energy generation mix of many countries around the world has been increasing the need for solutions that could help the electric power grids maintain the supply and demand balance, at any time. In recent years, demand flexibility in buildings has been studied and presented in different forms, mainly through mathematical formulations. On a demand flexibility event, the goal is not only to change consumption towards helping the grid, but also maintain comfort uninterrupted. Therefore, the grid's side and the users' comfort side were two areas that had to be fully studied. Recent studies have started testing these events through simulation in different buildings and climates, but few have empirically tested them. This thesis intended to study the effect of different constructions in a more rudimentary demand flexibility event, but its main goal was to test a demand flexibility event on a real office building, during working hours and without compromising the comfort and the workability of the people in the space. From the proposed methodology of how to study and present a demand flexibility event, five units were stated and used to characterize the event. As a result, the ramp duration of the main event was 94 min and the recovery time 60 min. Both ramp-rate were the same with an increase or a decrease of 335 W/min, and 670 W of actual power decrease was reached. An extrapolation regarding the actual power decrease and the power ramp-rates determined values more close to reality around 9 kW and 4.5 kW/min, respectively. Regarding the comfort side, thermal comfort was mostly assured on average throughout the open space, with two zones being over 0.4 ºC and the average of the space being 0.1 ºC (for a very short period of time) over the operative temperature upper limit of 26 ºC. In the end a simulation of the event was done to validate the empirical results.

K**eywords:** Demand Flexibility; Office buildings; Indoor comfort; Building energy simulations; Energy plus; Real case study experiment.

Resumo

Os combustíveis fósseis representam mais de 80% de todo o consumo de energia primária em todo o mundo. A sua utilização leva à emissão de diferentes gases para a atmosfera. Os gases de efeito de estufa são esses gases emitidos por essas fontes e ao se acomularem na atmosfera causam o efeito de estufa e contribuiem para o aquecimento global. A preocupação mundial sobre este tema tem se notado no investimento crescente em energias renováveis e/ou não poluentes. O problema está associado com a natureza de muitas destas fontes renováveis e com a sua integração, que ao serem variáveis no tempo, incontroláveis e de ainda difícil previsão, pode levar ao desiquilibrio do balanço energético. Para remediar essa situação é necessário que a rede eléctrica sofra algumas alterações por forma a torná-la mais atenta e reactiva a qualquer desiquilibro que nela ocorra. Essa busca é então de uma rede electrica mais robusta, mais inteligente na reacção a esses eventos desiquilibradores, mais eficiente, comunicativa e segura. Por forma a garantir este balanço, as redes electricas têm procurado aumentar a flexibilidade operacional através de várias soluções. Entre elas, o corte parcial da produção de energias renováveis como a energia eólica ou o *economic load dispatch* em centrais de reserva. A gestão do lado do consumo é outra solução que tem vindo a ser estudada por forma a resolver esses problemas crescentes do lado da produção. Entre as soluções existe a resposta de consumo (*demand response*), eficiência energética e mais recentemente a flexibilidade do lado do consumo (*demand flexibility*). Quando for possível comunicar bi-direcionalmente na rede eléctrica (solução ainda em desenvolvimento), vai ser possivel estabelecer contacto instantâneo e em tempo real entre o sistema produtor e os diferentes tipos de consumidores. A utilização dos edifícios é cada vez mais vista como uma solução integrada e muito significante, já que representam em média na europa 40% do consumo de energia final. Se o objectivo é assegurar a segurança e o controlo inteligente da rede electrica, então o estudo da flexibilidade em edifícios tem que ser uma solução prioritária. Mais especificamente, os edifícios comerciais representam 40% do consumo total nos edificios, e dentro dos edifícios comerciais, os edifícios educacionais e de escritórios representam 40% do consumo de energia. Alem destes valores, os edifícios de escritórios e os educacionais apresentam semelhanças muito significativas ao nível das fontes de consumo, organização dos espaços e utilização. Mesmo dentro destas parecenças entre estes dois grupos, dentro de cada um as semelhanças são claras, com qualquer edifício de escritório apresentar aproximadamente as mesmas caracteristicas referidas atrás. Por isso, nos últimos anos, a flexibilidade do lado do consumo (*demand flexibility*) em edifícios deste tipo tem sido a ser estudada e apresentada de diversas formas, habitualmente através de formulações matemáticas. Esta flexibilidade é a capacidade de um edifício alterar o seu consumo, aumentando ou dimininuindo-o, sempre que a rede electrica precisar. Através de uma comunicação instantânea, a rede conhece o estado de flexbilidade dos edifícios, escolhe os que precisa para a situação em particular e informa os edifícios escolhidos. Dependendo do tipo de flexibilidade de cada um, a sua aglomeração e gestão pode ser fulcral para este tipo que desiquilibrios que as fontes renováveis e variáveis tanto, infortutamente promovem. Porque os edifícios de escritórios têm os seus propósitos e utilizações bem definidos, este tipo de solução tem que ser estudada de uma forma completa e consciente. Por isso, num evento de flexibilidade o objectivo não é só garantir que os edifícios mudem o consumo de acordo com o que a rede precisa, mas também que mantenham os padrões de conforto para que a produtividade dos seus trabalhadores não seja afectada. Esta tese pretende estudar estes dois lados, não só a variação do consumo energético mas também o consumo dos utilizadores do espaço. Como esta solução é bastante complexa e o seu estudo ainda está muito no início, a dispersão é grande e a sua própria definição se confunde com outras soluções como o *demand response*. Além disso, a forma de ser apresentado ainda aparenta não estar definida. Dos estudos que existem, muitos apresentam formulações matemáticas e de programação das conumicações entre o sistema de HVAC, o edifício e a rede eléctrica. Estudos recentes começaram a testar estes eventos de *demand flexibility* através de simulações de differentes edifícios em diferentes climas. Resultados experimentais existem muito poucos.

Esta tese de mestrado pretende não só fazer uma revisão bibliográfica sobre o estado actual das redes eléctricas, mas também apresentar as soluções existentes e futuras para resolver estes problemas de desiquilibrios, nos dois lados da equação. Depois focando-se nos edifícios de escritórios e por fim nos eventos de *demand flexibility*. Como não existe uma definição e apresentação consensual, nesta tesa ambas são propostas. Depois disso é vez de se perceber que tipo de fontes podem ser mais flexíveis e como é que a energia é transferida dentre deste tipo de sistemas que são os edifícios. Antes dos casos de estudo, o conforto é estudado nas variáveis utilizadas para a sua medição. Num primeiro caso prático estudou-se o efeito de diferentes tipos de construções num evento bastante simples de flexibilidade do lado do consumo. O objectivo era perceber o potencial de differentes construções na flexibilidade energética de um edifício. Para isso foram utilizadas duas salas na Faculdade de Ciências da Universidade de Lisboa, uma com isolamento térmica e outra sem e foram comparadas as curvas de temperatura em ambos. Como o objectivo principal da tese era testar um evento real, num edifício real de escritórios, durante o horário de trabalho e sem comprometer o conforto ou a produtividade dos trabalhadores, foi escolhido um edifício que pudesse oferecer essas condições. O segundo caso de estudo foi feito na Camâra municipal do Seixal, num espaço aberto de escritórios. Este tipo de eventos são caracterizados por uma fase em que o edificio aumenta ou diminui o seu consumo do HVAC até que os limites de conforto sejam atingidos e nessa altura volta ao ponto em que estava de consumo no inicio do evento. Neste caso os ventiloconvectores foram desligados durante um periodo e ligados novamente. Várias variáveis foram medidas, entre elas, os consumos dos ventiloconvectores, dos equipamentos e iluminação, a temperatura do ar, das superfícies, humidade relativa e concentrações de CO_2. Assim era possível depois perceber como tinha corrido o evento. Através da proposta de metodologia de estudo e apresentação deste tipo de eventos, cinco unidades foram distinguidas e usadas para characterizar o mesmo. No evento principal, a duração da primeira parte foi de 94 min e o tempo de recuperação foi de 58 min. Tanto a taxa de subida como descida do consumo foi de 335 W/min e a quantidade máximo de potência que foi reduzida foi de 670 W. Uma extrapolação feita sobre estas duas unidades para o sistema AVAC completo determinou valores aproximados para ambas a rondar os 9 kW e os 4.5 kW/min, respectivamente. Em relação ao conforto, este foi maioritariamente assegurado durante a maior parte do evento, sendo que apenas duas zonas ultrapassaram 0.4 ºC acima do limite máximo da temperatura operative, indicada para medir o conforto térmico, e a média dessa temperatura para o espaço todo só ultrapassou, por um curto espaço de tempo, cerca de 0.1 ºC desse limite. No final foi apresentada uma simulção em *EnergyPlus* que valida os valores medicos experimentalmente para a temperatura interior do ar, a temperatura operativa e a concentração de CO_2.

Palavras-Chave: Flexibilidade do lado do consume;, edifícios de escritórios; conforto interior; simulações energéticas em edifícios; Energy plus; Caso de estudo com parte experimental.

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List of Acronyms

IEA – International Energy Agency;

RES – Renewable energy sources;

S&D – Supply and demand;

DSM – Demand side management;

DR – Demand response;

DF – Demand flexibility;

EE – Energy efficiency;

BPIE – Building Performance Institute Europe;

EC – Energy conservation;

TOU tariff – Time-of-use tariff;

SG – Smart grid;

HVAC – Heating, ventilation and air-conditioning;

T&D lines– Transmission and distribution lines;

OECD – Organization for Economic Co-operation and Development;

US or USA – United States of America;

AHU – Air handling unit;

MELs – Miscellaneous electric loads;

OE - office equipment;

ME - miscellaneous equipment;

BMS – Building management system;

BEMS – Building energy management system;

EIA – Energy Information Association of the United States of America;

CBECS – Commercial Buildings Energy Consumption Survey;

DSF – Demand-side flexibility;

CHP - Combined heat and power;

COP – Coefficient of Performance;

JRC – Joint Research Center;

ASHRAE – *American Society of Heating, Refrigerating and Air-conditioning Engineers;*

BR - Big room;

SR - Small Room;

NV - Natural ventilation

List of other symbols

ρ – *Ramp-rate (W/min)*

π – *Total power capacity (W)*

δ – Ramp duration (min)

σ – Recovery time (min)

π_{max}^{+} - Maximum (max) available power (corresponding to the P_{max}) that can be increased (+);

π_{max}^{-} - Maximum (max) available power (corresponding to the P_{min}) that can be reduced (-);

ρ_{max}^{+} - Maximum (max) ramp-rate which can be increased (+);

ρ_{max}^{-} - Maximum (max) ramp-rate which can be decreased (-);

π_{real}^{+} - Actual (real) available power that can be increased (+);

π_{real}^{-} - Actual (real) available power that can be decreased (-);

ρ_{real}^{+} - Actual (real) ramp rate which can be increased (+);

ρ_{real}^{-} - Actual (real) ramp rate which can be decreased (-);

G_I – Internal gains (W);

G_S – Solar gains (W);

G_V – Gains due to ventilation (W);

G_C – Climatization gains (W);

T_i – Indoor air temperature (ºC);

T_s – Surface temperature (ºC);

T_{ins} – Insufflated air temperature (ºC);

T_{out} – Outdoor air temperature (ºC);

k – Thermal Conductivity (W/m.K);

U_n – U-value – Thermal transmittance (W/m2.K);

V_s – Room Volume (m3);

$\dot{V}$ – Air flow (m3/s);

Ach – Air changes per hour (m^3/s);

MAT or T_a- Mean air temperature (ºC);

MRT or T_r- Mean radiant temperature (ºC);

T_{op} - Operative temperature (ºC);

RH - Relative humidity (%);

PMV - Predictive mean vote;

PPD - Predicted percentage dissatisfied (%);

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1. First Chapter – Introduction

1.1. Introduction

Fossil fuels account for more than 80% of the world primary energy consumption and their combustion leads to the emission of different gases to the atmosphere [1]. The Greenhouse Gases (GHG) are these emitted gases that by getting retained in the atmosphere, cause the greenhouse effect, and contribute to the global warming [2]. The anthropogenic increase of these GHG concentrations in the atmosphere are the cause (with 95%-100% certainty) of innumerous climate changes all around the globe (including the one stated before) [3]. For the past few years it is noticeable that all continents are facing diverse climate changes [3], and 2016 was an example of that, as it was the hottest year ever recorded. Throughout the past decades the world has agreed to fight against these problems, exceling some important steps towards the future: The Kyoto Protocol in 1991; the 2020 goals agreed on 2009 by the European Union (EU); among others. The later development in the world's joint action against climate change was COP21 Paris 2015. All 195 nations attending agreed to reduce GHG emissions in order to prevent a global warming above 2ºC [4]. Even though, there's a claim that this agreement was just based on promises and aims, and not on specific policies, it was a proof that the world acknowledges that this threat is real and global. By now, two thirds of global GHG emissions and more than 80% of total emitted CO_2 result from the energy sector [1]. Considering the natural growth on global energy demand, if no opposition is offered, the increase of fossil fuels consumption and their following emissions will be a reality. To secure a more sustainable and non-fossil fuel dependent future, new alternatives to the current energy sector must be stablished, and these alternatives must cover all areas: waste recycling, energy production from renewable and cleaner energy sources, demand-side management, energy efficiency, smart buildings and grid, etc.

Mostly after 2009, many countries have created and implemented laws and policies, which year by year increase the investments made in these areas. For example, the IEA World Energy Outlook 2014 reported that, in 2013, the European Union was responsible for 57% of the world's subsidies to renewable energy, with a total value of EUR 52 billion. These national support policies and subsidies towards energy efficiency and renewable energies relegated the conventional power plants, as their operational hours decreased and their share on the electricity mix was reduced. These developments caused a price reduction on the whole renewable energies' sector, resulting on the change of the wholesale electricity market. In 2013, from the total of EUR 52 billion, solar photovoltaic was responsible for over EUR 22 billion and wind power for half of it [5]. All these investments were key to make important advancements in some of the proposed goals in these protocols. An example of that is the increasing renewable energies contribution on the total gross energy generation that, until 2013, rose up to 26% on the EU-28 [6], and the renewable energies share in the global electricity supply was an estimate of 22.1% [7].

Despite the benefits associated with renewable energy sources (RES), uncertainty of supply due to the variable, hardly unpredictable, and so, uncontrollable nature of some of these resources (e.g. sun or wind), is recognized as one of the main issues of these technologies [8]. Because of their uncontrollability, their investment and integration must be fully evaluated and understood, otherwise, high shares of uncontrollable power feed-in will result in problems for the operation of the power system. In addition, there are other problems that can arise and cause a supply and demand (S&D) imbalance, such as, unpredictable variations of demand and uncontrolled supply unit failures. Therefore, the power system must increase its own operational flexibility to overcome any problem and reduce the risk of an abrupt power system collapse [8, 9].

In [10], a definition to operational flexibility of a power system is given, and stands for the technical ability of a power system unit to modulate electrical power feed-in i.e. variations on the energy supply side; and/or power out- feed i.e. variations on the energy demand side; to ensure, over time, the S&D

balance. This operational flexibility can be assured by different mechanisms in two major sides: the generation side and the demand side. On the generation side, there are two mechanisms that are currently being used to increase the supply flexibility: economic load dispatch, or RES power feed-in curtailment [8, 11]. Adding to these two, the Energy market and battery systems also appear as solutions. Before the integration of large shares of renewable energies and their consequent hard predictability problems, the supply side would always follow the demand. Changes in the load would have to be satisfied by flexible generation. With the increase of renewable but variable generation, as the supply became less flexible, the demand sought to become more flexible. For many years, on the demand side, demand-side management (DSM) has been one of the main focus of studies in the area, because of its huge potential in helping control the S&D balance [12]. This help is based in three different tools: demand response (DR), demand flexibility (DF) (the core of this thesis) and energy efficiency (EE). The first two, in different ways, are meant to reshape the load diagram towards the grid instant requirements and the third is to reduce the magnitude of the load diagram [13].

Considering first the generation side, and before explaining the economic load dispatch, there is a characteristic that needs to be introduced. This characteristic is inherent to all energy sources, and it’s called dispatch time. This characteristic defines a source on their response time to generation calls, and it groups sources between the ones that can be consumed when it’s needed, and the ones that can only be produced (and so consumed if there are no storage solutions associated) on uncontrolled periods of the day and night. The sun, as it is only available during the day is, sometimes, “covered” by the clouds [8]. This interrupts its energy production on uncontrolled, and sometimes, hardly predictable big periods. Because of this, it is classified as non-dispatchable. On the contrary, dispatchable sources help increase the operational flexibility. The units that use these sources, can increase or decrease their power output, responding to the RES variable generation or towards demand fluctuations. The ramping up or down by these flexible generating units, e.g. conventional power plants, depends on many characteristics. These characteristics are their generating capacity, operating conditions (whether unit is just starting up or operating at a minimum load hold point) and optional technologies for reducing startup time and increasing ramp rate (usually expressed in MW/min), as mentioned in [14]. They will help the grid organize the best instant solution for a backup power reserve, avoiding excessive fatigue in the plant structure [15]. The overuse of these fast responding mechanisms on conventional power stations could result in a reduction of the expected life of such components, which were mainly designed for base load [16]. Another form of dynamic fast responding are all kinds of stationary capacities: batteries, hydro storage and pumped hydro storage, etc. For instance, in a full battery the electricity is instantaneously available. Another example is a hydro power station, in the case of the water volume being between regulated levels, its production into electricity is also seconds away from the grid generation call [17] [10]. All these examples are viable options (in different scales) for increasing the operational flexibility of the grid. Thus, the objective behind Economic load dispatch is to schedule the output power of committed generating units, in order to meet the required load demand at an optimal operating cost, while satisfying all units and system constraints, and variable characteristics. Doing so, the power system is not only reducing operating costs, but also saving energy and reducing emissions [18, 19]. As said before, this is not an innovative mechanism, as it is a traditional tool in the operation of power systems.

On another side, the RES power feed-in curtailment comes as a solution for the integration of large shares of non-dispatchable and uncontrolled power feed-in RES. This solution is to safely maximize the operational flexibility through their curtailment [17]. Meaning that by setting the power output of a, e.g. wind turbine, to a lower level, the unpredictability that is characteristic to this resource can be prevented from affecting the generation. The difference between the real power output (without curtailment) and the curtailed power output, at a specific instant, will define its provided operational flexibility. In conclusion, through a dynamic but simple, and at a really low cost process, the real-time operation of these resources will turn them more controllable and thus dispatchable [20]. However, this difference will be a power loss for the power system, reducing the generation efficiency of this source. Another, and an easy way to manage the operational flexibility for a power grid is to have other power grids zones interconnected, and use these connections to import or export power capacity [10].

To have complete control over the power system, both sides must always be in near balance, but most importantly, the grid must always seek to increase its own operational flexibility. According to the Buildings Performance Institute Europe (BPIE) [21], "buildings currently (2009) represent almost 40% of total final energy consumption". If a turnabout is required to ensure the safety and smart control of the grid, the focus must be in understanding how can the demand side be fully tapped. Because of this, buildings appear as a huge solution for the grid to recover the control over the power system. As mentioned before, managing the demand side is the solution to overcome the current grid's S&D imbalances, but despite existing three tools (DR, DF and EE), the first two are the only ones that are effective. The other tool (EE) only aims to reduce consumption in total, therefore shortening the possibilities for exploring the system's power flexibility. Nonetheless, energy efficiency measures, as renovating the electrical loads to more efficient ones (short-term action) or changing consumer behavior for a more efficient one (long-term action, energy conservation (EC)), must always be taken first into consideration in any case, in order to eradicate any energy consumption excess [22]. As a result, demand response and demand flexibility emerge, ultimately, as the main solutions to increase operational flexibility on the demand side. On the one hand, the demand response is defined as a way to reshape the load pattern, by adjusting the consumer-end use of electricity, in order to reduce the gap to the generation profiles of the power system [13]. Consumers are encouraged to change their consumption patterns by dynamic pricing (real-time changes in prices based on the current generation) or by an incentive-based program [20, 19]. In such manner, this concept is based on different approaches. In order to shift the main loads, from on-peak to off-peak periods, one approach is to set time of use (TOU) tariffs. Another way is to use smart meters, for consumers to monitor their consumption, not only to reduce their overall values overtime (strategic conservation), but also to adjust their behavior towards the grid current needs, reducing peak loads (peak shaving). On the other hand, demand flexibility is the ability of a building to react (by increasing or decreasing its energy consumption) upon instant signaled requests (surplus or shortage power) from the Smart Grid (SG), without compromising its comfort. This subject has, recently, dedicated many studies, as [21, 25, 26, 27, 28] show. In all these studies, this ability has been described as an ancillary service, but despite some studies may have simulated these events, there is still a lack of real case studies [26, 27].

Although both have the same goal - increase the operational flexibility of the power system - and may look alike, they have different premises, and so, different targets. In the case of demand response the goal is to allocate (by those programs mentioned before) any flexible load that usually is used on peak hours, for the best optimal time period (off peak hours) of the whole day), depending on the interest of the power system [31]. Because of this, the best buildings are the residential ones, as some of their main loads are characterized as so. As the idea for demand flexibility is to be able to change consumption, at any time, either by increasing or decreasing energy, the premise is no longer to allocate loads for different periods of the day but to create a fluid and dynamic consumption. Its target is no longer residential buildings, but commercial, offices and educational buildings, as the HVAC system comes as a substantial flexible load [32]. However, its management can't affect the comfort of its occupants or their activities in the building, protecting always both, the grid and the building's interests. Considering the size of these buildings and that they represent a 40% share of all non-residential buildings [21], the potential agglomerated flexible consumption projects a huge help for the grid. The next chapter will explain and detail these and other characteristics that make these buildings' flexibility an enormous help for the grid. The goal of this thesis is to test this type of event and understand its core characteristics and potentialities.

1.2. Research objectives and scope of the research

This work focuses on the understanding of how the building's energy systems can interact and behave when the goal is the optimization of the building's operation, while offering support to the grid. In order to optimize this interaction, there is a need to turn buildings, grids and their communications smarter. To achieve this, the BEMS must be synchronized with all the control systems: the HVAC system; the self-produced energy control system; and all the loads. The flexibility of each building to react to signals sent from the grid, by increasing or reducing their consumption, would have a huge effect when considered the share of energy consumption that the built environment is responsible for. This responsibility shift by the buildings, from passive into active consumers, will be rewarded on how flexible and supportive of the grid the buildings are. With the increase of variable and uncontrollable renewable energy sources penetration, the demand flexibility appears as one of many solutions to undertake this problem. Although this topic is starting to attract greater and greater researching interest, most of these studies only present simulations to demand flexibility events. This thesis tries to go a step further by testing an event on a real office building in real office working hours, without compromising the thermal comfort of its users.

1.3. Research Questions

The aforementioned raises the following question, which is center to this research work.

How can buildings offer demand flexibility to the electric power grid without compromising the comfort and activities of their users?

Furthermore, the following sub questions can be formulated as well:

1. *Which types of buildings offer the most flexibility potential?*
2. *How can these buildings turn from passive consumers into active consumers?*
3. *What is the effect of the building's construction on its flexibility potential?*
4. *How can these events be tested in a real-time case study?*
5. *How can comfort be assured while on a demand flexibility event?*

1.4. Thesis outline

In the second chapter, the problem is exposed and the different ways to solve it are presented throughout the course of the first subtopic. On the second topic, the proposed solution is presented in all its components. Additionally, the simulation software, EnergyPlus is briefly introduced.

In the third chapter, it's time to understand its potential in a real-time office environment. First, a case study on two rooms with different insulation characteristics (a poorly insulated room and a highly insulated one), will test how air temperature changes during a very rudimental demand flexibility event. This will serve as an introductory example to the real case study done in the Seixal's city hall. In the fourth chapter, the practical results of both experiments will be presented with a brief explanation of the main components in study in the events.

In the fifth chapter, a deeper look will be given regarding the second experiment, where the two sides of a DF event: the users' comfort side and the electric power grid side; will be analyzed. The event itself will be studied in the proposed nomenclature and concept explained in the second chapter.

On the sixth chapter, the results of the second case study will be compared to a simulation made in EnergyPlus. It will be studied its simulation ability in this kind of events and which types of inputs are required for the simulations. On the last chapter, the conclusions assessed in the whole thesis and proved in the case study will be presented, as well as possible future research work.

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2. Second Chapter – Theoretical Background

2.1. The electric power system

The electric power system connects the sources of electricity to the consumers and operates in a constant readjustment, always seeking for the supply and demand balance. There are three main parts that constitute it: the power generation, transmission and distribution lines. The power generation is responsible for producing electricity from different sources (coal, gas, sun, wind, water, etc.) based on different processes (pressure, heat, light, mechanic, etc.). The transmission lines transport bulk quantities of power from the generation, at very high voltages, through very large distances to electric substations. These substations are usually located near big demand centers and are responsible for bridging the transmission lines to the distribution lines. The electricity passes through transformers, stepping down its voltage and is then distributed to every group of consumers at their required voltage. Local low voltage power stations are therefore connected to the distribution lines [33]. The transmission and distribution lines system are commonly defined as the electric power grid, as all the lines form an electrical web. Even though the last two parts are structural in the management of the power system, they have lower importance in this work. A much relevant infrastructure is the control center and it is a fundamental piece of the grid, as it’s responsible for everything that happens in it. This part has many functions: control both the supply and the demand, and prevent any imbalances; optimize energy production costs and reduce environmental consequences; ensure energy supply whenever is requested; and assure electrical quality standards (like constant frequency, voltage between demanded limits, high reliability) [33]. In the 1970s, the term system security appeared as being the ability of these control centers to endure any instantaneous anomaly in the system (disturbances and/or contingencies). This search for a more reliable control system changed them to become more decentralized and flexible. Undoubtedly, any component can fail, and just because of this, the grid must always be able to overcome these situations [11]. Besides component’s unpredictable issues, the demand also changes over the course of the day, month and year. Even though the load diagram can have a predictable shape, it is never possible to predict the exact demand or even that its shape will be the same every day. As detailed before, there are different options for increasing the operational flexibility. The management of all these solutions in respect of their cost and benefits in order to face any problem will reflect the quality of the system and its reliability. As the world seeks for renewable ways to produce energy that won’t release GHG, the shares of renewable sources increase. Globally, in 2014, wind and solar broke, individually, their annual capacity installation records. Hydropower total new capacity was even topped, in 2014, by both of these sources [7].Both represented 90% of 2014 total non-hydropower renewable additions prefacing now 83% of global renewable (non-hydropower) installed capacity [7]. Globally, in the European Union or even in the BRICS (Brazil, Russia, India, China and South Africa), the two biggest non-hydropower renewable sources are, so, wind power and solar power [7]. This increase of non-dispatchable power market share will demand a higher operational flexibility from the grid, and this means a huge renovation in the way how power systems operate.

The traditional way of operating has been to always follow the demand. This is accomplished by understanding and controlling the supply. Now, with more and more variable and hardly predictable generation, the goal has changed. Now the grid must understand better the demand, to be able to control it. This is accomplished by first developing a smarter power system and using it as a platform to apply DSM mechanisms [1]. This smart power system is what it’s called a smart grid. A smart grid is a modern power system with communication and automation skills. The power and information bi-directional system will connect, monitor and help control every component, from power sources to singular electric appliances. By doing so, the SG will be able to: understand better consumer behaviors; reduce generation costs; accommodate higher (variable) renewable shares; enhance energy markets; and increase the overall system’s efficiency and reliability [31, 32]. In order to implement a SG, two aspects must be developed: smart infrastructures and smart technologies.

Current electric transmission and distribution lines (T&D lines) are aging all over OECD Europe and OECD North America [36]. As these lines need to be always updated, replacing them without any SG-based-philosophy update (despite their higher initial cost) would be a non-smart move by these governments, as higher future savings are foreseen [31, 33, 34]. Until now, the only sensing and control made on the power grid was on substations and control centers. These infrastructural updates would turn T&D lines automated, and so, able to read and control themselves at any point. These changes include: automated fault location and restoration (for an automated reaction to instant circuit failures e.g. blackout); dynamically adjusting distribution controls to accommodate variability, power ramping and bidirectional power flow (enabling more renewable energies integration); sensing and optimizing the need for Volt-Ampere Reactive power, frequency control, etc. [35].

More than just revolutionizing the grid infrastructures, new and smarter technologies must be created and implemented in every other component of the power system. As a result, the importance of demand-side management strategies grows, projecting huge changes in every part of the demand. In the US, in 2010, buildings represented 41% of total primary energy consumption, and 7% of the world primary energy consumption. From those 41%, 54% was consumed by residential buildings and 46% by non-residential (or commercial) buildings [38]. Though, considering primary energy consumption shares alone is not conclusive enough. Electricity consumption is the one that must be considered because it’s the source the power system is meant to transport. Thus, in the US, in 2010, buildings were responsible for consuming 74% of total electricity consumption (39% due to residential buildings and 35% due to non-residential buildings) [38]. Because of these shares, buildings in the US represent a huge potential help for the grid, as any change in them can result in huge changes in the overall consumption values, and so in the S&D balance. In 2012, in the EU-28, the buildings energy consumption was about 40%, and their electricity consumption accounted for 55% [39]. From the built floor space, in 2012, 76% were residential buildings and 24% were non-residential. Even though residential buildings floor space was higher, 66% of that was of single family houses, and more area doesn’t mean more energy consumption [39]. To completely understand the full potential of both groups of buildings, the energy consumption must be calculated per square meter (energy intensity), and in this case, non-residential buildings consumed 40% more energy (for all end-uses) than residential buildings in 2009 [21] and 54% more in 2012 [39]. Regarding only the electricity consumption in 2010, residential buildings consumed 29.71% and non-residential buildings consumed 29.41% [40]. This is another proof buildings can have a huge impact in the S&D balance, if they follow the revolution that is going to occur in the power system.

Therefore, when tackling either one of these kinds of buildings, the same two questions must be asked: how can the smart grid take advantage of these types of buildings? And what has to change in them, for them to harness their full potential? First these buildings must be studied and understood, and only then the first question can be answered. The second question will be answered along with the first one, suggesting technologies that must be developed. In the end, one of the main questions of this thesis “how to turn buildings from passive consumers into active consumers?” will also be answered. After this full analysis, the target buildings of this thesis will be exposed, as well as the proposed mechanism to ensure their help to the smart grid.

2.2. Understanding buildings

Buildings differ from each other on the specific construction characteristics, if it's residential or commercial, the purpose/type of that building (household, office, shop, hospital, etc.), the primary and final energy sources, the types of loads inside that building and the users that live and/or work in it. However, to understand their potential to help the grid, some characteristics are more relevant than others. Loads are certainly a very important part of a building with its consumption being the target for any possible help to the grid. Briefly, their description will start with the HVAC systems. These systems cover all combinations of three different subsystems: heating (H), ventilation (V) and cooling (AC). They can be as simple as an oil heater in a residential home, to be as complex as the air conditioning systems found in a space shuttle. Another example is an air handling unit (AHU) found in airports, or in industrial or commercial buildings. The size and features of these systems are, consequently, based on the specific requirements of the building [41]. The water heating systems can be either integrated in a HVAC system, taking advantage of the heat losses of this system to heat the water, or even use the same energy sources as the HVAC system to heat it. A boiler that uses e.g. natural gas; or a solar panel that uses the sun's energy, are both examples of simpler water heating systems. Following, appliances are all devices that need electricity to function [42]. Examples are: electronic devices e.g. information technology and communication devices (ITCs); refrigerators; washing machines; alarm clocks; ATMS; medical equipment; etc. These devices can also be referred, in other literatures, and later on in this thesis, as miscellaneous electric loads (or MELs) [40, 41]. Figure 1 shows the different end-uses in buildings in the US and their respective share, in 2010. As the figure shows, HVAC, water heating made up more than 60% of building's site energy consumption, with lighting representing only 9% [38].

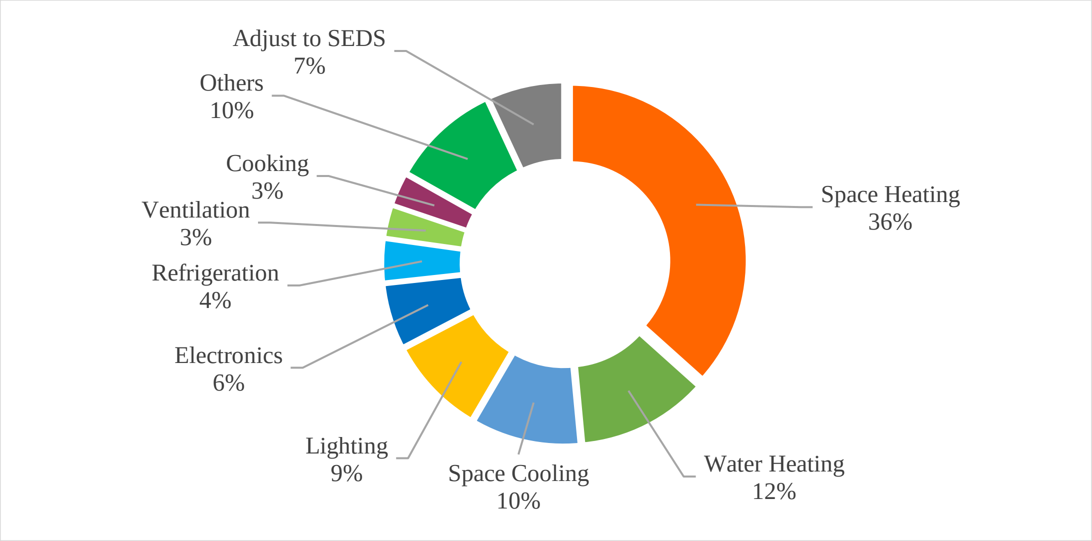

Figure 1 - Buildings site energy consumption by end-use

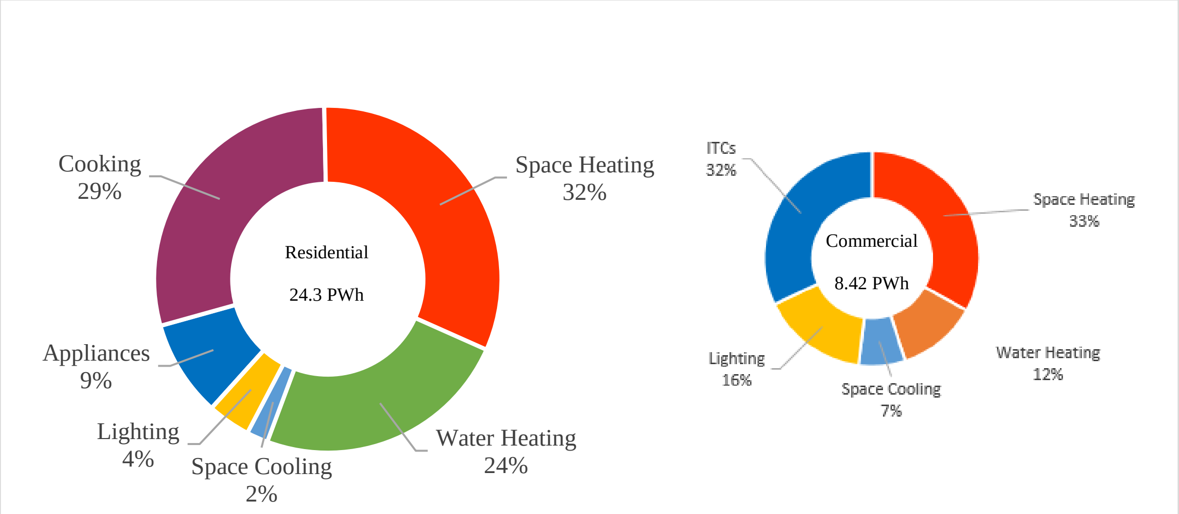

Figure 2 - World building final energy consumption per end-use in 2010. Source IEA (2013)

In the same year, on a report made by IPCC [45] (Figure 2), space and water heating were responsible for huge impacts in the world's final energy consumption. It is reasonable to assume that, because countries that are in the temperate-snow zone of the globe are more developed [46] they can afford higher comfort expenses. The second largest end-use in residential and commercial buildings were, as it is expected, cooking and other (ITCs equipment, etc.), respectively. Finally, and since residential buildings are in a large part used for sleeping or are empty during the day, the lighting does not represent a huge share of the total energy consumption. On the contrary, commercial buildings have a respective lighting share much higher.

To search for a solution for the electric system, only end-uses that require electricity to function are part of that solution. Even though not every end-use is sourced by electricity, they can be, and so the range of loads is wide. Consequently, each one of these loads will be characterized in terms of flexibility of use. What this means is that every load has specific characteristics, in terms of period of usage, availability, if they can be shutdown/turned on instantly, etc. This characterization will group loads into different categories. Consumers will have different combinations of loads, creating different consumer load mixes. The predominant type of load will then define the consumer load mix type. As consumers change habbits, activities or appliances, their load mix will also vary, and the predominant type may also change. According to the report [47], there are 5 types of loads:

1. Storable load;
2. Shiftable load;
3. Curtailable load;
4. Base load;
5. Self-generation.

Firstly, the load must be classified either as storable or non-storable. In this case, if the load can either charge e.g. a room, by thermal inertia (e.g. using heating system to heat a room), or a thermochemical battery (e.g. an electric car can be charged by itself), and only release its energy when it's needed, then the load is classified as storable. If not, then the load must be classified in her ability to be shiftable or not. In other words, if the consumer is able to change the period of the day when is using this load, without being affected by this change (e.g. shifting the time of the day when the washing machine is working), then that load is shiftable. If not, then the next step is to evaluate if the load is curtailable or not. Even though, as mentioned before, the curtailment of RES power feed-in is to reduce the power output of a, e.g. wind turbine, here, a curtailable load is the one that can be turned off completely and instantaneously. Examples of this are in some cases, a television, some lights, or a printer in an office. In the case of not being a curtailable load, it is defined as a base load. In this case, the load cannot be storable, shiftable nor curtailable because it is a core load, as e.g. burglary alarm, some light, any automatic load, temperature sensors or even an automatic door or light, an escalator or an elevator. Finally, a device is a self-generator if it can produce energy as a supplier and use it as a backup power (if it's dispatchable). The figure below (Figure 3) resumes all these types of loads. After assessing every load for their type, a consumer load mix can be identified. Later on, when analyzing residential and commercial buildings seperately, examples will be made to fully understand this concept and their load environment [47].

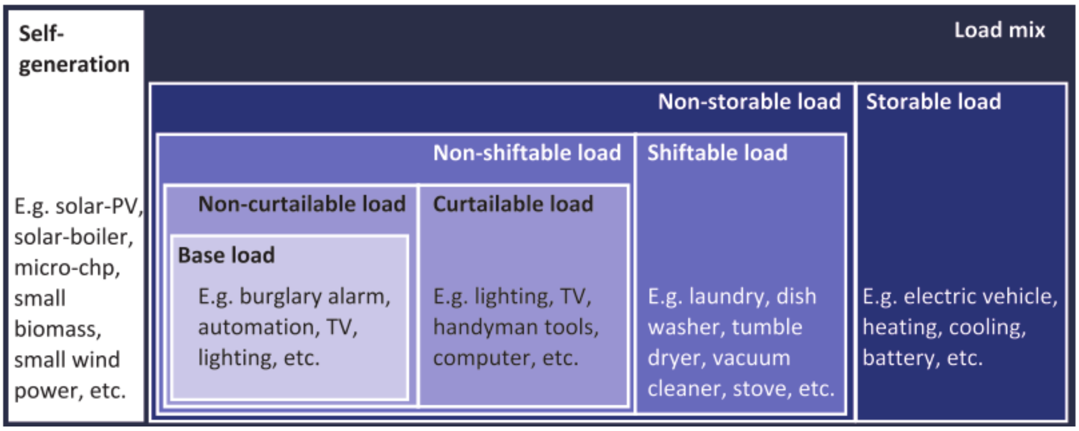

Figure 3 - Consumer load mix. Source [47]

While the supply becomes more uncontrollable and inflexible, the solution has been to invest in expensive backup generating capacity with expensive generating fees [8]. Learning and understanding the demand, buildings specially, will help the power system protect itself from future imbalances. After understanding buildings in general, and before studying how commercial buildings can help, it is crucial to completely grasp how residential buildings are also expected to help and the reasons they are not enough for this concept change. As they are not the point of this thesis their study will be brief. Nevertheless, their complexity, in terms of consumer load mix, demand response programs and consumers themselves will be addressed, as well as problems and barriers to their success, as active consumers.

Demand-side Management is defined as a way to reshape the load diagram, by adjusting the consumer-end use of electricity, in order to reduce the gap to the generation profiles of the power system [12]. This concept is based on different approaches, with the main one being demand response. The idea behind demand response is to promote changes (through incentive based programs/contracts) in the electric consumption of end-use customers, towards fixing S&D imbalances [48]. To capitalize the residential building stock, a set of contracts must exist to satisfy every kind of costumer. Here, in Table 1, five types will be presented. Some of those contracts will be price based (use a tariff for electricity to trigger the consumption on different periods), volume based (constrain the load through a consumption cap/floor) or control based (where the grid has total/partial control over consumption) [47]. In the future, in a smart grid, all consumers will be notified on building energy management system (BEMS) devices, through internet signals or even through the T&D lines. Those signals will be able send coded information to the device and, depending on the contract, can even activate or deactivate different loads. Additionally, the signal volatility can be low (static) or high (dynamic). This characteristic of the signal defines the frequency of the signal (not to be confused with utility frequency). In the case of a static contract, the signals are more spaced from each other and can be notified with longer notice. In a dynamic contract, the signal demands quick changes and through small periods, reflecting the changes on the electricity trading market. There are other characteristics that are shown below (Table 1) that will define the financial compensation. These characteristics translate the type of risk (price risk or volume risk), the complexity for costumers and their autonomy and privacy. The complexity level is determined by the difficulties of learning and understanding the concepts of signal volatility, each appliance's consumption impact, their best management, etc.; The autonomy loss extends for the fact that with, for instance, a direct load control contract, some loads may be controlled by the grid, affecting a lot the lives of the consumers. The privacy loss means that the clients may be forced to record their consumption and release, freely, any detail about their habits and their consumer load mix [47]. Table 1 below shows five contracts and their features:

	Signal form	Signal volatility	Price risk	Volume risk	Complexity	Autonomy/ Privacy loss	Financial compensation
Time of use pricing	Price based	Static	Low	None	Low	None	Limited
Dynamic pricing	Price based	Dynamic	High	None	High	None	High potential
Fixed load capping	Volume based	Static	None	Low	High	Limited	Limited
Dynamic load capping	Volume based	Dynamic	None	High	High	Limited	High potential
Direct load control	Control based	Predefined	None	None	None	High	Limited/ High potential

Table 1 - Range of contract types

Even though, on a direct load control contract, the consumer doesn't need to know about signal volatility (and so the complexity appears as none), the contract will be much more legally complex because of the privacy and autonomy issues that come with, both consumer and service provider rights [47].

All these problematic features cause high resistance and discomfort to non-educated consumers (in the energy sector), but are the only way for the service provider to ensure the desired demand response. Depending on the current system conditions and the best solution for the grid, that regarding contract will potentiate higher financial compensations. Although costumers would of course select the best contract for themselves, many times this compensation system may not even be that attractive for the common consumer. This can be from being merely unknown or confusing, to being too risky, intrusive and/or complex. Apart from these problems, there are others that also have to be made clear: contracts that preview a loss of privacy (even limited) require metering devices with data recording abilities, increasing the costs for the costumers [47]; these energy related matters are not common knowledge, and so there is an absolute need for consumer education; the little help that households singularly represent (in terms of total power); and a possible difficult growth to all households or to a considerable percentage of them. Concluding, even though there is a huge potential regarding demand response programs in residential buildings, there is still a long way for them to reach a slightly reasonable use.

2.2.1. Commercial buildings

Inside the non-residential sector, variety is huge, as they represent all other categories of buildings from hospitals, schools, shops, offices, government buildings, service buildings, malls, sport centers, hotels, restaurants, etc. All these types form a heterogeneous mix, but for an easier characterization, instead of doing it individually, they can be grouped together. Even though this separation can be done in many different ways, this work will follow the one presented in the Buildings Performance Institute Europe (BPIE) survey [21]. While the separation in groups is based in the BPIE survey, both the floor space and its correspondent energy consumption percentages are extracted from both (2003 and 2012) Commercial Buildings Energy Consumption Survey (CBECS) from the US Energy Information Administration (EIA) [35, 48]. This data is all resumed in the next table (Table 2). The first group is constituted with all kinds of retail and wholesale shops (e.g. food and non-food shops, gas stations, malls, hair dressers, congress buildings, laundries, mechanics, etc.) and is defined by a complete mix of characteristics such as size, construction type, purpose, activities, and energy consumption. Because of these imparities, it is hard to find a common way to manage their demand. In 2003, they represented 20% of the whole non-residential floor space and 20% of the total energy consumption of non-residential buildings. Their total energy consumption decreased to 27% in 2012 as their floor space also decreased to 16%. In the second largest group, all office buildings, call centers, administrative and municipal buildings are included and they represented 28% of total area of non-residential buildings (29% in 2012). On the contrary to the first group: the type of loads; their weight in the building's energy consumption mix; and the building's load diagram are very alike between office buildings. Another aspect of these buildings is that their heating and cooling demands are similar to residential buildings (except offices usually have less hours of consumption comparably). When in 2003 they represented 28% of total energy consumption (in non-residential buildings), in 2012 their consumption rose to 29%. Another group of buildings is the one that aggregates all educational buildings, from libraries to research labs, universities and schools (all kinds). These buildings have similar load patterns to office buildings, as they are most active during the same time periods. On that same survey, they accounted for 14% of all floor space of non-residential buildings and toped 11% of total consumed energy in 2012, less 1% than in 2003 (12%). Moreover, restaurants, cafés, pubs, discos, and hotels represented, in 2003, 7% of total floor area of commercial buildings (the same in 2012) and make another category. In 2003, in the US, these buildings in consumed around 7% of total non-residential buildings energy consumption. In 2012 it was 8%. With 4% of total floor space, in 2003, there are all medical buildings: with continuous usage patterns, such as, public and private hospitals; and 24h care centers, etc. In 2003 in the US these buildings consumed 8% of total and 10% in 2012. These buildings are characterized by their very low priority to reduce or smart manage their consumption, as their priority is to focus on the patients. The last category represents all other buildings, from warehouses, garage buildings, garden and agricultural buildings, empty lots, etc. Even though the last category is the second biggest (27% in 2003 and 28% in 2012), it groups completely different buildings with unique characteristics (unique loads and specific working hours) and little influence separately, making them hard to manage. As it shows below in Table 3, they represented the same energy consumption in 2003 and 2012 of 15%.

Year		Wholesale and retail	Offices	Educational	Hotels and restaurants	Hospitals	Others
2003	Floor space	20%	28%	14%	7%	4%	27%
	Total energy consumption	29%	28%	12%	7%	8%	15%
2012	Floor space	16%	30%	14%	7%	5%	28%
	Total energy consumption	27%	29%	11%	8%	10%	15%

Table 2 - Floor space and total energy consumption in commercial buildings in the US in 2003 and 2012. Source CBECS

As stated before, the energy density (kWh/m^2) in commercial buildings in the EU was, in 2012, 55% higher than in households (286 kWh/m^2 to 185 kWh/m^2) [39]. Regarding only the electricity consumption in 2010, residential buildings consumed 29.71% and non-residential buildings consumed 29.41% (39% and 35% respectively in the US in the same year) [37, 35]. Despite existing demand response programs for residential buildings, there are some arguments that prove that a bigger impact can be achieved by creating programs targeting commercial buildings [50]. For starters, these buildings are usually used by Small and Medium Enterprises (SMEs), large businesses, government entities, or organizations of any kind, etc. and a common ground for these entities is their interest in reducing costs and increasing revenue stream. Another aspect is that, more than 30% of commercial buildings in the US have any kind of BEMS, which can communicate with the grid and be helpful towards it in real time. Even buildings without these systems are usually more familiarized (than the average residential user) with outsourcing/contracting experts or teams of experts for those matters. Specialized contracts/programs that take advantage of their demand and can be financially rewarding to commercial building users, appearing as a win-win situation for both the grid and the building. Residential users, on the other hand, might not understand the value of their help, might not know how to apply, and which benefits there are for both the grid and them. The challenges grow even more as residents may not even understand any of the contracts presented before for simple reasons of lack of information, poor education, lack of skills/knowledge to execute the contracts or even to select the appropriate contract [47]. Demand flexibility appears as an alternative solution to demand response, for its premise of very fast demand response programs, turning commercial buildings from passive into active consumers [50, 23, 7].

2.3. Demand Flexibility

As stated before, demand flexibility is a building's capability to react (by increasing or decreasing its energy consumption) upon instant signaled requests (surplus or shortage power) from the smart grid, without compromising the comfort or the activity of its users[51, 52, 53]. On different studies a similar definition has been made for a building's ancillary service, as its ability to react to the smart grid requests to alter the consumption without affecting the comfort of its users [21, 53, 25]. The term flexibility evolves from the real and predictable need from the grid to accommodate different variations in the system [8, 17]. This chapter will capture all the components of this concept for its complete understanding as a whole. There is little literature regarding this topic, as it's still a very recent one and so, although following it, some of the definitions and the way the DF event is presented graphically are proposed as a new way of approach.

By now, the grid has already flexibility profiles for each supplier, defining their instant state and characteristics towards helping the grid, as it was introduced before as operational flexibility. These profiles have four main characteristics that help the grid decide which supplier offers the best solution for the problem aimed to fix. These characteristics are illustrated in Figure 4 and are the total power production capacity, the power ramp-rate, the ramp duration and the cost. Considering an initial time t_0, the total power production capacity (MW), π, is the maximum power that this supplier can increase or decrease from the power generation that it was at t_0. The power ramp-rate (MW/min), ρ, is the rate at which this supplier can increase or decrease its power to the required level. The ramp duration (min), δ, is the time during which the supplier can produce energy or reduce its generation at that requested power (between points 2 and 1). The cost (€/MWh) is the price paid by the grid for that amount of energy produced. Although the available energy produced by this dispatchable supplier is the area inside the trapeze [8, 54], after point 2 the supplier is already decreasing its supply to the power at which it started at t_0, and so it doesn't count anymore as help to the grid.

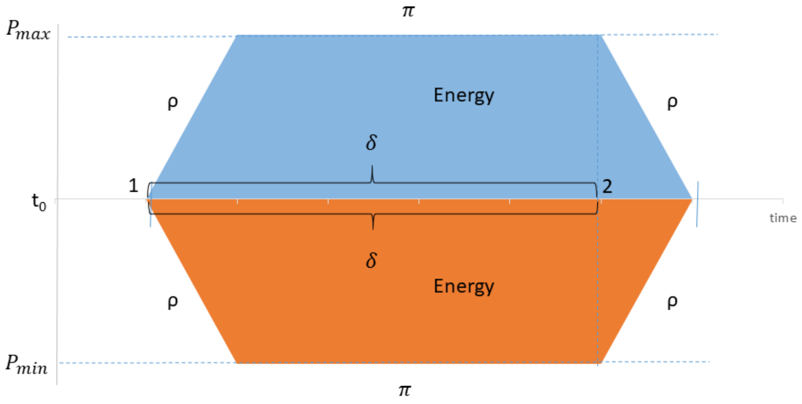

Figure 4 – Theoretical operational flexibility

As it's shown in Figure 4, each supplier of operational flexibility can be described with only three characteristics (if the price is excluded). Although, depending on the specific situation, they can have different meanings. For the grid to know the nominal operational flexibility (Figure 5), these first six indexes must be created:

π^{+}_{max} - This represents the maximum (max) available power (corresponding to the P_{max}) that can be increased (+) by the supplier;

π^{-}_{max} - This represents the maximum (max) available power (corresponding to the P_{min}) that can be reduced (-) by the supplier;

ρ^{+}_{max} - This represents the maximum (max) ramp-rate in which the supplier can increase (+) from 0 to the π^{+}_{max} or from the π^{-}_{max} to 0;

ρ_{max}^{-} - This represents the maximum (max) ramp-rate in which the supplier can decrease (-) from the π_{max}^{+} to 0 or from 0 to the π_{max}^{-};

δ^{+} - This represents the ramp duration on the case the supplier increases (+) its power generation;

δ^{-} - This represents the ramp duration on the case the supplier decreases (-) its power generation.

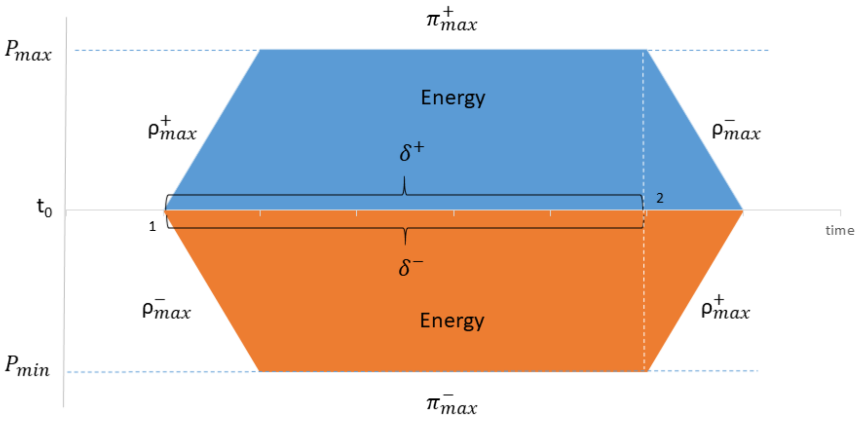

Figure 5 – Nominal operational flexibility

Nevertheless, for different reasons, the actual operational flexibility may be lower than the nominal operation point. Figure 6, represents two separate scenarios. A scenario where the supplier decreases its generation (the first yellow region) from the value at t_0, bringing it back to the power value at t_0. And a scenario where the supplier increases its generation (the second yellow region) from point 3 until is requested to reduce its generation and comeback to the initial value at 3. Because of all these situations, a representation (through the next four indexes) must be done (Figure 6) for the grid to know what the actual flexibility is.

π_{real}^{+} - This represents the actual (real) available power that can be increased (+) at that time;

π_{real}^{-} - This represents the actual (real) available power that can be decreased (-) at that time;

ρ_{real}^{+} - This represents the actual (real) ramp rate in which the supplier can increase (+) from 0 to π_{real}^{+}or from π_{real}^{-} to 0;

ρ_{real}^{-} - This represents the actual (real) ramp rate in which the supplier can decrease (-) from π_{real}^{+} to 0 or from 0 to π_{real}^{-}.

Again, the ramp duration, is only defined as the real time, having just that the same two meanings from before: on a power decrease scenario is δ^{-};on a power increase scenario is δ^{+}. Its value can be computed, depending on the event, subtracting the time between points 2 and 1, or between points 4 and 3, respectively. The amount of actual/real energy being diverted to the grid is represented by the area in yellow in Figure 6. The white line represents how the supplier would behave, decreasing in the first yellow trapeze, and increasing its power generation, on the second yellow trapeze.

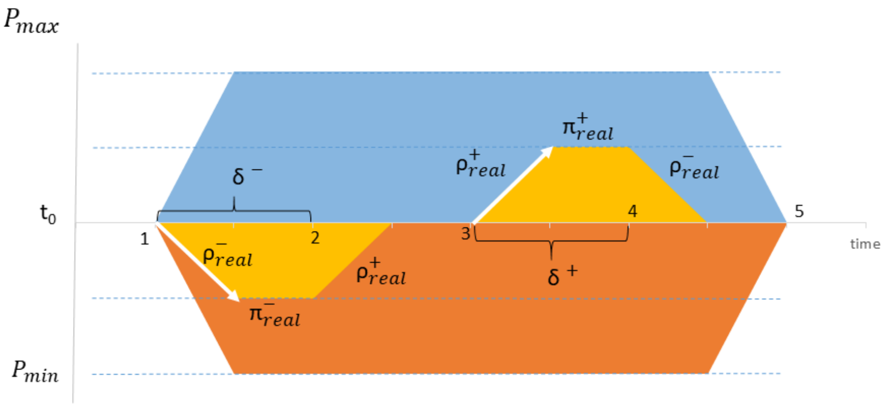

Figure 6 – Actual operational flexibility

The same can be applied to the demand-side with some adjustments. These characteristics can be defined in another way as it follows: The total power capacity (MW), π, is the maximum power that a building can ensure to reduce or increase. The power ramp-rate (MW/min), ρ, is the rate at which this building can increase or decrease its power to the required level. The ramp duration (min), δ, is the time that the building can provide help at that requested power. The Cost won't be studied in this thesis, but it's the price paid by the grid for the energy that was allocated by that building [55,10,52]. This way, each building has its own two maximums of demand flexibility (as explained above), one regarding the increase of power, and the other one its decrease. Depending on the time of day, on the users' needs, the availability of each load, etc., each building can have its version of the Figure 6, representing its own demand flexibility. Before entering in much detail regarding how to represent a demand flexibility event on a building, first the type of buildings that are most suitable for these events must be assessed and explained, and second, which loads will be the most effective helping the grid.

Even though every building can have some level of flexibility, not all buildings fill every requisite to be interesting for the grid. To find the best target building type(s) to extract the most flexibility possible, a criteria list must be created. The proposed criteria are down below:

Similarities between buildings of the same type: even though commercial buildings were already grouped in types of buildings, that doesn't mean that there is only one type of building per group. The higher the similarities inside a group, the easier it is to study them, leading to higher potential of research and later investment. E.g. wholesale and retail buildings have the higher discrepancies between them, as it was described before. On the contrary, offices and educational buildings tend to have similar characteristics between them.

Must have a high share of flexible power: high consumption doesn't necessarily mean high flexible load. What differentiates buildings that have the same energy demands is the type of loads and their shares. As the smart grid seeks to control the demand side (in this case non-residential buildings) by requesting increase or decrease of power at any time, the building's flexible loads must be attractive and helpful for the grid. E.g. buildings that have high HVAC demands have there a huge potential of flexible power (later explained) [28].

The entity must be open and available to help the smart grid (voluntarily or with financial compensation) at any time. E.g. in this case, hospitals, hotels and even restaurants have bigger goals than helping the grid, even if that meant being financially compensated. Because of their own purpose and the conditions they offer (or must offer), being flexible towards clients/users is way more important than towards the grid. As the cost of being flexible is very low, buildings that can be flexible towards the grid, can make profit with even very low financial compensations [28].

From these criteria, it's clear that from all types of commercial buildings, the ones that prevail are offices and educational buildings. Any other building misses always any criterion, and in terms of research focus, the proximity of load mixes (energy densities and activities) between these two, as proved in [56], makes them a good starting point to study and understand demand flexibility [30].

Before studying how to extract the flexibility from these it is crucial to understand how they are constituted. Office buildings are on their essence a place of businesses or services. An office is the area or set of areas in a building that are meant for administrative work, such as reading, writing and/or working on the computer, for meetings between workers and for storage. As for the working areas, these can range from open spaces for all workers to individual offices for each worker. The storage areas can be open or enclosed, as file or office supplies rooms, libraries, etc. Additionally, these buildings have bathrooms or lockers, common areas for multiple uses, kitchens and bars. The common areas can vary from printing and copying areas, to break areas, smoking rooms, reception areas, corridors, etc. In small cases, kitchens and bars aren’t required, as commercial refrigeration areas and eating areas with microwaves and other cooking equipment are enough for the office workers’ needs. The organization of these spaces is usually different considering: the company’s philosophy; the designated work developed there; and the relationships between departments and team groups. Always aiming for the most efficient work flow, communication and supervision.

Between all buildings, educational buildings are the ones which most resemble offices, as their spaces, loads and user’s activities are very similar. As offices, educational buildings are also places for reading, writing, working on the computer and working in groups. Most of times, the users in both types of buildings tend to be seated and working or walking between rooms. All the spaces for offices (described before) tend to be the same for educational buildings except for characteristics as the area of the room, number of rooms and their arrangement inside the building. Despite existing many other differences between these two buildings, the focus of this thesis is not to assess those differences but to understand which loads exist and which are interesting in terms of their flexibility towards the grid. To achieve that, the same load mix characterization that was previously introduced will be done to offices and educational buildings (all together). These loads can be divided in different groups as they are presented below.

2.3.1. Loads inside offices and educational buildings

Loads can be divided in many groups but the main ones are: HVAC, lighting, miscellaneous electric loads (MELs), water heating, food preparation, commercial refrigeration and others. Table 3 presents, for each end-use, their share on the whole energy consumption of an office building, on three different locations: USA UK and Spain. What it shows is that even in opposite climate regions (UK as being a colder region, and Spain as being a warmer one) and so very different HVAC systems (as UK has higher heating needs, Spain has more cooling needs from air conditioning) [57], the seek for comfort is always significant. Another aspect that can be retained is the fact that the first three group loads are also a huge cut on the energy consumption. These three group loads are HVAC, lighting and appliances and sum up to 95% in Spain, 77% in the UK and 83% in the USA. In the UK the top three is not the same as in the other countries, because of the cold climate and the need for water heating (DHW). Lighting appears as second energy end-use in these kinds of buildings, as appliances appears as third, both in the USA and Spain [56]. To understand the whole consumption spectrum in offices, it’s best to understand the main groups of loads: HVAC systems, lighting, MELS, commercial refrigeration and others.

	HVAC	Lighting	Miscellaneous electric loads (MELs)	Water heating	Food preparation	Refrigeration	Others
USA (%)	48	22	13	4	1	3	10
UK (%)	55	17	5	10	5	5	4
Spain (%)	52	33	10	-	-	-	5

Table 3 - Energy consumption in offices by end use. Source [56]

HVAC systems

HVAC systems are responsible for maintaining a comfortable environment in terms of temperature, humidity, and air quality and renovation indexes. Depending on those indexes, different parts of the system are set to work together to achieve the costumers' requirements. A complete system is constituted by three different parts: The heating system (H in HVAC) is responsible for heating the air inside the room or the exterior air used to renovate the inside air. Integrated to these air heating systems can be also a water heating system. The ventilation system (V in HVAC) is responsible for mechanically bringing the exterior air into to the rooms, or extracting the interior air outside. This air if needed, is also treated according to the desired inside temperature, relative humidity and air quality. Finally, the Cooling system or air conditioning system (AC in HVAC) is responsible for cooling the air inside the room or the air that is brought by the ventilation system to the inside of the room [57, 58, 38].

To tackle all these needs, there are a lot of different technologies on the market. These technologies include: combined heat and power (CHP), active solar thermal (AST), heat pumps, thermal energy storage (TES), chillers, boilers etc. Combined heat and power plants are responsible for producing both heat and electricity and use those for water and air heating, and for cooling (using thermally driven chillers). Because these plants produce electricity and heat for the building, their contribution is not interesting for a demand flexibility program. For this reason, their study in this thesis is not so important. AST are systems that use heat from the sun to heat air and water or even, as it was mentioned before, for cooling with thermally driven chillers. As this technology exonerates the electric power grid from providing electricity for heating and cooling the building, its study is also irrelevant for this thesis. To clarify, this doesn't mean that these systems are totally responsible for all electricity consumption, but because they don't require the electric power system to work, their study in this thesis is irrelevant. A technology that requires electricity from the grid and so of huge relevance for this thesis is the heat pump. The heat pump uses energy from the surroundings (air, water or ground) and electricity (or natural gas), to raise (for heating) or lower (for cooling) the temperature of water or air. This can be done separately using a different heat pump cycle for heating and cooling, or it can be done simultaneously by a hybrid system [57]. Heat pumps usually have efficiencies higher than 100%, where the output heating/cooling power is higher than the input electric power. Depending on the output, this efficiency has different names: COP (Coefficient Of Performance) is assigned for heating heat pumps; EER (Energy Efficiency Ratio) is for cooling heat pumps. The technology used for cooling can be used on air-conditioners, on reversible/hybrid air-conditioners and on chillers. Even though these systems can be used for heating and/or cooling, they are predominantly used for cooling [60]. Another solution for heating or cooling is through Thermal Energy Storage (TES). As the name implies this is not a way of producing heat or cold, but to store it over time, and so not a solution for DF events. A type of TES that can be useful is sensible heat storage (e.g. using the building's envelope to store thermal energy of the rooms and open spaces for short but critical periods of time), etc. The last one can be a very important strategy for increasing the demand flexibility of buildings. Despite this, this thesis will not cover this topic. When it comes to the ventilation system, this system basis itself on the premise of keeping a healthy environment to its users, free of pollutants, bacteria and with attention to the CO_2 concentrations [60, 61]. The humidification or des-humidification, the heating or cooling of the air, depends on the complexity of the HVAC system. There are two main types of ventilation systems: constant-air-volume; variable-air-volume. The difference between both lies with the name. In the first, the volume of air entering the space is always constant, and the temperature either rises or lowers depending on the users' needs [59]. In the second, the volume fluctuates according with difference between the desired temperature, and its actual value. This way, the volume of e.g. cooled air starts high and as the room temperature gets closer to the desired one, the volume gets lower until it reaches the minimum required [61, [41]. The ventilation has always to meet the minimum air quality requirements values per person, thus, a demand-controlled system is always a better solution, as it can analyze the occupancy of the room and act like it. This way, instead of assuming the occupancy of a room stays true to the occupancy patterns, carbon dioxide sensors can help detect the room current minimum requirements, save energy and prevent health problems [62, 63]. An example for a whole HVAC system is the one present on the second case study. The building is equipped with a AHU, which uses outdoor air and recirculated air to renovate the air inside and maintain indoor air quality. This air is pre-heated (using boilers) or pre-cooled (using chillers) and distributed through air ducts throughout the building. The same boilers and chillers heat and cool water (in this case), respectively, which is sent into the heating and cooling coils of the system. These coils serve the fan-coils, which by circulating the air from the AHU into the building rooms, heat or cool them [64].

Apart from these technologies, every system, to be the most efficient must have a complete set of sensors to control, continuously, the values of inside and outside temperature, inside and outside humidity, air quality, air mass flow, occupation, and much more. These sensors will receive these values and send that information to the HVAC managing system or any other building energy management system [58, 62]. This way, these HVAC systems can be programmed to, instantly and continuously, control, cross-reference and manage these parameters between different predefined users' comfort levels. Exploring these comfort levels is the key to take the most out of the building's demand flexibility. As mentioned before, the envelope's characteristics of a specific room(s), space(s), floors or even the whole office will also be very critical for the HVAC system design and management, resulting on different and unique system configurations per building [62]. An example of a building energy management system is when there are smart meters interconnected and smart electric appliances which incorporated into the BEMS help manage and control the electric loads in a building [34, 35, 65].

Lighting systems

The second most important load in the list above is lighting. According to the statistics of the Joint Research Center (JRC) from the European commission, office lighting in the UE-27 was responsible for 21.6 % of total energy consumption in the tertiary sector, in 2007 [66]. This means, it was one of the biggest electricity consumers with similar shares as electric space and water heating systems with 19.7 % in all commercial buildings [66]. In the US, lighting systems are responsible for 30%-50% of total annual electricity consumption in office buildings. Even without statistics, the importance of lighting systems in any building, with more focus in offices and educational buildings, is clear. Efficient buildings are usually designed to take the most out of daylight, by adjusting the light consumption to save the most energy, without disturbing any lighting levels requirements. Depending on the type of space, function and occupancy, the electrical lighting types and their levels will vary. Therefore, there are 4 different types of electrical lighting: ambient lighting, task lighting, accent lighting and emergency lighting. Ambient lighting works usually as a lighting baseline for any room, just to fill the room with light (give a "sense of space"). After that, task lighting comes as a more specific source of light. In this case, their location, range, intensity and other characteristics have pre-established requirements. These are destined to specific types of detailed work, as of reading, writing, working on the computer, etc. Accent lighting is used on other situations where there is no need for work purposes (e.g. to highlight a display). In the end, emergency lighting is used, as the name implies, in emergency situations, usually to highlight an evacuation path for example. Although, designing the lighting system is not only choosing the types of lights. Any room or space has its own characteristics, use and occupancy schedules. For this reason, there are different options to take when designing the lighting system. These options are based on the type of light control system required for each room and what functions does it has. There are two types of light control systems: manual and automatic. Manual controls are designed for rooms where the staying period can't be predicted and so can't be controlled, e.g. equipment/storage rooms. It is a less desirable option because the BEMS loses the control over to the user. Automatic controls are the opposite, and so they can be programmed to change the light depending on different situations. This type of option is usually associated with two types of sensors: the one that uses a movement sensor is called on-off control or step-function control and lights the space when it detects movement; the one that uses a daylight sensor is called dimming control and adjusts the electric lighting accordingly to the current daylight. Rooms, where sudden changes on lighting don't affect the users' activities, or where the use period is small (e.g. corridors, restrooms, etc.), usually, tend to have automatic on-off/step-function control systems. Rooms where sudden changes on lighting do affect users' activities and/or rooms that have great daylight integration (work spaces, private or non-private offices, etc.), tend to use automatic dimming. When these rooms have no daylight interferences, manual dimming is the solution (e.g. conference rooms, interior rooms, etc.), which, as it was justified behind, is always a bad solution for increasing the efficiency or the demand flexibility. Continuous automatic dimming is always the best option as there are no jumps in the lighting levels and so users are not interrupted by these changes [62]. This kind of technology is best suited for increasing the operational flexibility and so promoting the demand flexibility, as it allows the BEMS to change the lighting without causing discomfort on the users, either as a distraction or as a light imbalance (too much light or too low).

Miscellaneous Electric Loads (MELs):

As it was briefly introduced before, MELs are Miscellaneous Equipment Loads and they can represent almost any plug-load equipment. In order to analyze this vast list of loads, they can be divided on two different groups: office equipment (OE) and miscellaneous equipment (ME) [67]. The first group is represented by all Information and Communication Technologies (ICTs) equipment. In this group can be included desktops, monitors, laptops, printers, scanners, copiers, fax machines, multi-functions, rooters and wireless LANs (WLANs), data centers (although offices usually don't have their own data centers) [68], video displays (for commercial displays, and for official presentations), internet security systems and burglary alarms, etc. In the second group, the miscellaneous equipment represents any other plug-load equipment, such as, coffee makers, personal fans, heaters, radios, mobile phone chargers, phones, microwaves, etc. [67]. Since the beginning of the ICTs development until now, the past decades have proven a substantial and continuous growth for this type of loads [66]. As productivity in buildings can be linked to electricity consumption increments, loads as ITCs, HVAC systems, and other ME can increase in order to create a better working environment [69, 68]. While the research has been mainly focused on ways to reduce energy consumption on HVAC and lighting systems, turning them more efficient, MELs consumption is expected to increase. This will end-up countering the overall savings that have been accomplished [44]. Because of this rapid growth, accounting every plug-load consumption profile, separately, can be quite difficult, and so accurate data can be difficult to be obtained [66, 68]. Despite this, many studies report that OE has usually the highest share in electricity in offices ranging from 70 % in [70] to 83% in [67]. In 2011, in the US, 70% of all desktops, monitors and laptops installed in all commercial buildings were installed in offices and educational buildings [68]. As explained before, it is hard to assess which loads (if any) could help increase demand flexibility, because of the lack of studies on these types of loads, and the lack of control and predictability of their use by the BEMS.

Refrigeration:

The next load group of the Table 3 is the refrigeration. Despite commercial refrigeration is commonly associated with every refrigeration unit which is meant to display and sell food or beverages [40], in offices and educational buildings, the most common ones are cold vending machines and beverage and food coolers. These two make up almost 30% of total commercial refrigeration energy consumption in the EU-27 in 2007, with other machines being ice cream freezers, open frozen island and open chilled vertical multi-deck, usually placed at food or beverage stores. As present on the Table 3, the share of energy consumption in offices, due to commercial refrigeration, is 3% in the US and 5% in the UK [56]. Although these machines are placed in offices sometimes their operation, and so energy consumption, is not even controlled by the office. In these cases, they cannot increase the demand flexibility. On the contrary, if controlled by the office, the energy consumption can be balanced between the required inside temperature of the machine, and so promote an increment on the demand flexibility.

Other Loads:

When it comes to other loads as escalators, automatic doors and lifts the information is even narrower, with the share of lifts in offices being 14% of all buildings in the EU in 2011, with over 600 thousand lifts installed. The expectations in the Energy Efficiency Status Report 2012 were that the search for a better work environment and the need for convenience would also help increase its numbers in the EU in the years to come [40]. Because of the nature (un-predictable and uncontrollable use) of these loads, it can also be expected that their impact on the demand flexibility of a building can be unnoticeable.

Offices and educational buildings' consumer load mix:

After describing the whole spectrum of loads inside an office or educational building, it is time to aggregate the loads, individually, into the consumer load mix configuration presented before at Figure 3 and applied already to residential buildings. The focus, now, is to understand which loads can effectively help increase the demand flexibility. The taken approach will be to organize all the loads in a common consumer load mix and then recognize which can really be helpful. Thus, a typical load mix of an office or educational building would be like this:

1. Storable loads: thermal energy storage with water tanks, latent heat storage, and/or sensible heat storage; commercial refrigeration; etc.
2. Shiftable loads: printers, scanners, copiers, faxes, multi-functions, when is not urgent; HVAC system; etc.
3. Curtailable loads: accent lighting; video displays for commercial displays; continuous dimming; personal items chargers; laptops etc.
4. Base load: burglary alarm; emergency, task and ambient lights; desktops; monitors; rooters and WLANs; data centers; internet security systems; printers, scanners, copiers, faxes, multi-functions, radios, microwaves, phones, coffee makers, personal fans and heaters, when are being used; other loads as lifts, automatic doors and escalators; etc.
5. Self-generation: combined heat and power; active solar thermal; photovoltaic solar panels; wind turbines; etc.

As explained before the only group that cannot offer any demand flexibility is the base load. Apart from that, all groups can offer some flexibility. The deciding factors of when to use each kind of group will vary with their impact on the consumption of the building (π) and their actual availability. This availability will unfold in two characteristics: the time that this kind of load takes from its consumption to the most it can offer (ρ); and the time it can offer this demand flexibility until it needs to retreat to its original state (δ). Although curtailable loads can help increase demand flexibility, they also can be used as a EC measure, and may not be so relevant. Regarding self-generation and storable loads, their help can also be relevant but they're not the focus of this thesis. The focus will be on the study of the HVAC system potential on DF events, because of its large influence on building's load diagram and its management availability through BEMS. Even though, thermal comfort was not yet introduced, the HVAC usage for demand flexibility makes thermal comfort management a priority when determining the availability of these systems. This way, it's important to analyze main comfort conditions during these events. By being able to offer its flexibility, the building renews its trait in a step closer of becoming an active consumer [71, 72].

Now that the HVAC system is proven to be the best option for office buildings, Figure 6, needs to be updated to this context. Firstly, a new variable needs to be introduced, which is the recovery time (min), σ, i.e. the time from the point (point 2 or 4 depending) the building can no longer offer demand flexibility and is recovering to its initial state. On a standard DF event, only one yellow region (Figure

7) would represent a whole event. The building would receive a signal from the electric power system to, in the first scenario, decrease its consumption. The building and the grid would know in advance the building's DF profile, as well as its ramp duration and its recovery time. In the case of a building decreasing its cooling loads, temperature would rise until the comfort temperature upper limit would be reached. The ramp duration would've ended and the building would've returned to its initial stage, increasing its consumption again and bringing the temperature back to its initial value, before the next event started. The reason why the two yellow regions are separated is because, usually, temperature takes a longer time to arrive to its initial value, than it takes power to be re-set to its initial stage. As comfort should never be interrupted, the recovery time is defined by the time it's required to bring temperature back to its initial value and never just because the building's power consumption has returned to its initial stage. The same can be applied to the increasing consumption scenario between points 5 and 4 [52, 10]. Figure 7 presents the updated proposed way to how buildings can present their demand flexibility. Therefore, the recovery time has also two indexes:

σ^+ - This represents the recovery time on the case the building increases (+) its consumption;

σ^- - This represents the recovery time on the case the supplier decreases (-) its consumption.

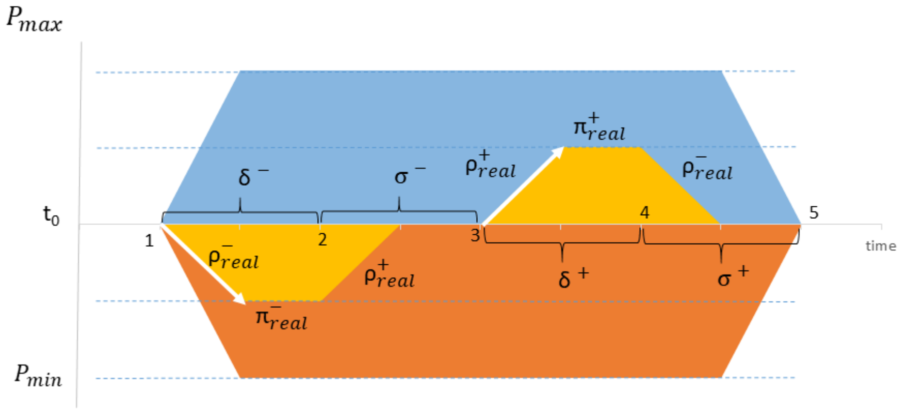

Figure 7 – Building's demand flexibility

Although a lot of studies focus on demand-side flexibility (DSF) opportunities and how to capitalize on them, considering specifically demand flexibility events as just described, the list is shorter. Table 19 shows a state-of-the-art regarding some demand flexibility studies with or without simulations, with or without real case studies, thus better understanding the research done so far.

2.3.2. The thermal behavior of a building

Describing buildings statistically and on their loads its important but to really comprehend them, the laws that define their thermal and rate behavior must be understood. In thermodynamics, a system is a quantity of matter of a defined identity which is being studied or analyzed. It can be anything from a building, a room or a set of rooms, a part or a whole heating or cooling system, or any other material volume under study. The system is also characterized by its boundaries, its surroundings and the way how it interacts with both, transferring mass and energy in the form of work or heat. This interaction will determine what kind of system it is, varying from an open system, closed system to an isolated building. To begin with, an open system is one that can have transfer of mass and energy over its boundaries. An example of an open system is a room with its windows open because air (mass) and heat can be transferred from the outside to the inside, or vice-versa, through the walls and windows of that room. When there is only transfer of energy and no mass it means we are in the presence of a closed system, and the same room without any openings is a perfect example of it. An isolated system, in the limit, can be the same room with an adiabatic envelope, where no mass nor energy are virtually transferred in or outside its boundaries. Apart from the latter systems, different systems lead to different types of energy transfer, but always obeying the first law of thermodynamics

(Conservation of Energy). According to the first law, the increase of energy stored in a control volume or close system must be equal to the amount of energy that enters the system, minus the amount of energy that leaves it. The changes that happen inside the system characterize its internal energy (E_{int}), and there are different ways for the system to use or consume this energy. For a closed system, there are two ways of energy transmission: heat transfer through the boundaries, and work done to or by the system. As for an open system, the term energy advection represents the mass exchanges that can occur over the same boundaries. The changes inside the system are accounted by its internal energy, and a represented by the equation (1) under:

$$\Delta E_{int} = E_{int,f} - E_{int,i} = Q - W \quad (1)$$

In the first law, the variation of energy includes different kinds of energies that amount to the total energy. The total energy consists of kinetic, potential (mechanical), and internal energy. Inside the internal energy there can be chemical, nuclear and thermal energy. In this thesis, some forms of energy will be more important than others, but by stablishing that the major system will be a building unit, or a room or a floor, then the two more important ones are thermal and mechanical energies. As the equation (1) above represents the variation of energy on a determined time interval, the one below (2) is at an instant t. Because energy (joule - J) over time (second – s) is power (watt – W), this becomes defined as a rate.

$$dE_{int} = dQ - dW \quad (2)$$

In another words, the variation of total energy over an interval of 1 second, is the rate at which its stored energy increases or decreases (dE_{int}), depending on the other terms of this equation. The other terms of the equation, include the inflow rate (dE_{in}) and outflow rate (dE_{out}) through the borders and the generated rate (dE_g) inside the system, as shown in (3). On a steady-state, where the inflow and generated thermal and mechanical rate level the outflow, and the total stored rate is 0, we can convert the (3) into (4).

$$dE_{int} = dE_{int} - dE_{out} + dE_g \quad (3)$$

$$dE_{int} = dE_{int} - dE_{out} + dE_g = 0 \quad (4)$$

$$G_I + G_S + G_C + G_V = L \quad (5)$$

In buildings, this equation is organized in a different way with a whole different thermology for each variable. In order for a better understanding of buildings as system, the first step is to isolate the gains to one side, and the losses for the other (6). On the side of the gains, there can be many kinds of it: internal gains (G_I), solar gains (G_S), climatization gains (G_V), and gains due to the ventilation (G_C). On the side of the losses, these are due to the heat transfer through the walls from the inside to the outside, represented by L. Before going into detail about gains and losses, it is crucial to understand how heat travels inside the system and how it can be exchanged with the surroundings. Heat is transferred between points in a system when there is a difference of temperature, on the direction of lower temperatures. If this transfer occurs in the same body or throughout bodies that are connected to each other it is called conduction. In an atomic and molecular level, these particles have their own energy and are in constant activity. The transfer occurs spontaneously from a higher temperature (and so higher energy) particle to one with lower temperature, through the collision of these microscopic particles along the material(s). The amount of energy that is transferred per unit time, q_x (W) is a function of the temperature gradient, dT/dx (K /m), the area, A (m^2), and the thermal conductivity, k (W/m K) of this material. It can be translated into the rate equation (6)$q_x = -k.A.\frac{(T_2-T_1)}{l}$ that is a simplification from the Fourier's law. The temperature gradient is exchanged for the difference of temperature between point 2 and 1 in a material, with a thickness, l (m). The thermal conductivity describes how heat conducts through a material, and can also be linked to the thermal resistivity, R, in (7), which is a property attributed to a material with a specified thickness and defines its resistance to transfer heat. The negative sign is required because as heat travels from the higher temperatures to the lower temperatures, the temperature difference is always decreasing. Although, in these equations temperature is expressed in kelvin (K), its use in this thesis will be always done in degrees Celsius (ºC).

$$q_x = -k.A.\frac{(T_2-T_1)}{l} \tag{6}$$

$$R = \frac{l}{k} \tag{7}$$

Convection occurs when the air comes into contact with a surface or another fluid, at a higher temperature than the former. The heat warms up the air, expands it, decreasing its density and making it rise due to the buoyancy effect. On the opposite direction, the surrounding colder and denser air lowers, taking place of the risen air and gets heated, eventually creating a convection current. As in conduction the convective heat rate (W) depends directly on the difference of temperature (K), in this case between the air (T) and the surface (T_S), the area of the surface, A (m^2) and, also in this case, on a convection heat transfer coefficient that characterizes the fluid motion of the latter. Equation (8) translates this process.

$$q_h = h.A.(T_s - T) \tag{8}$$

Yet, heat transfer doesn't happen only through a material or through two connecting objects, it can happen as well through two bodies separated spatially. Thermal radiation is the name process from which electromagnetic waves (or otherwise called photons) transport heat between two bodies or between one body and its environment. It depends on the Boltzman constant, σ (W/(m^2.K^4)), on the emissivity of the body, ε, the area, A (m^2) and the absolute temperature of the target surface, T_s^4, and the other surfaces, T_{nei}^4 both in (K^4), as it is shown in the equation (9).

$$q_{rad} = \sigma.\varepsilon.A.F_{s,nei}.(T_s^4 - T_{nei}^4) \tag{9}$$

Where σ has the value of 5.67x10^{-8} W/(m^2.K^4), and the emissivity takes values from 0 to 1.

After this brief introduction of heat transfer, it's time to return to equation (5), and understand how each part works in a building. The internal heat gains come often from electric equipment, people, lights and are an important piece of the whole thermal balance of the room in study. Occupation and activity influence the use of these equipment and the rates of convective and radiative heating that come from them. Secondly, the solar gains represent another source of heat, this one arriving at the non-opaque fraction of the façade, directly or indirectly from the sun, and crossing them into the rooms of the building. The solar gains are so dependent on the non-opaque fraction of the façade, A (m^2), e.g. the windows, the solar factor, SF (%), or, as commonly known, the g-value, which is the fraction of solar gains that come into the surface, the horizontal direct radiation and the horizontal indirect radiation (W/m^2). Furthermore, the EA is the elevation angle and the AZ is the azimuth angles, both in degrees (º). The equation (10) assembles these very important heat gains.

$$G_S = A_w.SF.(R_{DIR}.\cos(EA).\cos(AZ) + R_{DIF}) \tag{10}$$

In order to compensate all these previous gains, buildings sometimes need an HVAC system that can climatize the spaces, heating or cooling the air inside and/or brought from the outside. Equation (11) simply describes how heat gains can be added to the energy balance of a space. By multiplying the flow of the insufflated air, ρ.$\dot{V}$ (kg/s), its specific heat, C_p (1005 kJ/(kg.K)) and the difference of temperature between its temperature, T_{ins} (K) and the room's air temperature, T_i (K), the heat rate gain , G_C (W) due to the climatization will be achieved. If the insulated air temperature is lower than the air temperature inside, the gains will have a negative sign, and will help decrease the temperature inside.

$$G_C = \rho.\dot{V}.\ C_p.(\ T_{ins} - T_i) \qquad \begin{array}{l} \text{If } T_{ins} > T_i,\ G_C > 0, \text{and } T_i \text{ will increase} \\ \text{If } T_{ins} < T_i,\ G_C < 0, \text{and } T_i \text{ will decrease} \end{array} \tag{11}$$

Mechanical exchanges of air with the outside, through ventilation are viewed as heat gains because of the energy spent in moving the air in and out of the building. This is usually done for two reasons: to use the difference of temperatures to raise or lower the inside air temperature; and/or to improve indoor air quality. If an increase of temperature is experienced, this heat rate will be added up to the left side of (5). When temperature outside is used to cooldown the building, then this term will be negative and will be accounted as a loss on the energy balance. Equation (12) describes this process where C_p (kJ/(kg.K) is the specific heat of the incoming air, $\rho.\dot{V}$ in this case is the mass flow of air (kg/s) that is being ventilated inside the room, T_{out} is the air temperature outside and T_i is the air temperature inside, both in (K). There is also the possibility that without mechanical nor natural ventilation, the room has only infiltration. Instead, $\dot{V}$ is Ach i.e. air changes per hour, and is the number of times the total air volume of the room is exchanged with outside air. Its unit is also m^3/s.

$$G_V = \rho.\dot{V}.\ C_p.(\ T_{out} - T_i) \qquad \begin{array}{l} \text{If } T_{out} > T_i,\ G_V > 0, \text{and } T_i \text{ will increase} \\ \text{If } T_{out} < T_i,\ G_V < 0, \text{and } T_i \text{ will decrease} \end{array} \tag{12}$$

On the other side of the heat rate balance are the losses through the building envelope and exterior openings and any other inside wall or door. The building envelope is the physical barrier that protects the building from the outside environment, noise and weather. Its materials and structure design determine how isolated the inside is, how it loses energy through the walls and how temperature and humidity behaves inside the room. Aside from the envelope, interior walls and any openings also influence the losses of one room to another and are also important for the energy balance. As explained before, each system has its own boundaries and so the losses for the energy balance have to be accounted on the walls, doors and windows that delimit that system. The heat travels by conduction through layers of one or more connected materials, making the losses equation (13) similar to the one explained before for this heat transfer mechanism. The L is the sum of all heat rate conducted through each material on the walls, windows and doors. In this case, the losses are calculated per surface (a set of different layers of materials connected in series) with the global heat transfer coefficient, U-value, of that surface. This value is translated into (14). The minus sign is no longer required because this represents the real amount of losses and its already on the right-hand side of the energy balance (equation (13)).

$$\mathrm{L} = \sum_n^k U_n.\ A_n.(\ T_i - T_{out}) \qquad \begin{array}{l} \text{If } T_{out} > T_i,\ L < 0, \text{and } T_i \text{ will increase} \\ \text{If } T_{out} < T_i,\ L > 0, \text{and } T_i \text{ will decrease} \end{array} \tag{1}$$

$$U_n = \frac{1}{\sum_m^j R_m} = \frac{1}{(R_i + \frac{l}{k} + \frac{l}{k} + \cdots + R_{out})} \tag{2}$$

As explained before, the rate balance equation (5) describes the steady-state of a room at a certain moment. However, to better understand how a building functions, it’s crucial to study its transient model. Because any gradient grows on the decrease of temperature, it requires a negative sign, therefore it appears on the right-hand side of equation (15). As a result, equation (5), must be rewritten to include the stored energy variance per unit time. Apart from the temperature gradient, V_r is the volume of the room (m^3) and ρ and C_p remain the same as on the other terms. As a demand flexibility event is characterized by the time it takes for the temperature in a room to rise (if the cooling load has just been turned off) or to lower (if the heating load has just been turned off) until the comfort temperature upper or lower limit, respectively, it’s required to add this stored energy variation term into the energy conservation equation. This way, understanding the energy balances in a building, more specifically, how temperature changes over time will be essential when trying to harvest their full potential, by transforming them from passive consumers to active ones.

$$G_I + Gs + \rho.\dot{V}.\ C_p.(\ T_{ins} - \ T_i) + \rho.\dot{V}.\ C_p.(\ T_{out} - \ T_i) = \sum_n^k U_n.\ A_n.(\ T_i - \ T_{sn}) + \rho.\ V_r.\ C_p\frac{dT}{dt} \tag{15}$$

As a demand flexibility event has always two steps: when the HVAC system is on and when the HVAC system is off; both stages have their own energy transient equations. Despite the case studies are yet to be explained, these theoretical demonstrations have to be done now. For both equations, and because of the type of HVAC system used in the main case study of this thesis is a fan-coil, there is no separation between the mechanical ventilation and the heating or cooling loads. The fan-coil heats or cools the ventilated air, prior from arriving to the space. Thus, the climatization rate englobes these three loads. Additionally, the ventilation gains will be only considered due to the infiltration rate through the surfaces that contain the space, as there is no natural ventilation.

Starting with the stage when the HVAC system is off, the $G_C = 0$. Thus, equation (15) can be translated into equation (16). At this point the room's transient state sees its mean air temperature rise as long as the internal gains (G_I) and solar gains (G_S) are greater than the losses (L) through the frontiers (walls, roof, floor and windows) of the open space system and the infiltration energy rate.

The differential equation (17) expresses the inside temperature change rate and from there, the function that expresses the inside temperature can be extracted. To simplify this analysis, the changes over time in T_{out}, G_I and G_S are going to be considered constant. After integrating it, where $G = G_I + G_S$ and $h = \sum_n^k U_n.A_n$, two variables can be withdrawn: the time (t) which the interior temperature takes to arrive to a certain value (18); and the value that the interior temperature (T_i) takes after a certain time (t) (19). A simpler type of system analysis can be seen on other examples as the lumped method [73]. In the case, in equation (19), the time constant (τ) is responsible for how fast the dynamic change occurs, and so, how steep the curve is, where $\tau = \frac{\rho.C_p.V_r}{h+\rho.C_p.V_r.Ach}$, as shown in Figure 8. In the latter figure, it's shown that the higher the $b = \frac{1}{\tau}$, the steeper is the curve. Because there are changes in the outside temperature, internal and solar gains, the time constant will vary and an analytical solution can no longer be achieved. For this reason, a software of energy analysis (Energy Plus) will be used to simulate this curve. Later will be explain how the software works and a comparison from theory to the practical data will be made. Figure 12 represents this curve analyzed here.

$$\mathrm{G_I + Gs\ + \rho.\ V_r.\ C_p.Ach.(\ T_{out} - \ T_i)\ = \sum_n^k U_n.\ A_n.(\ T_i - \ T_{sn}) + \rho.\ V_r.\ C_p\frac{dT}{dt}} \tag{16}$$

$$\mathrm{\frac{dT}{dt} = \frac{G_I + Gs + \rho.\ V_s.\ C_p.ACH.(\ T_{out} - T_i) - \sum_n^k\ U_n.\ A_n.(\ T_i - T_{sn})}{\rho.\ V_r.\ C_p}} \tag{17}$$

$$t = -\frac{\ln\left(\mathrm{T_i} - \frac{(h\times \mathrm{T_{sn}} + G + \rho\times \mathrm{V_r}\times\ \mathrm{C_p}\times \mathrm{Ach}\times \mathrm{T_{out}})}{\rho\times \mathrm{V_r}\times\ \mathrm{C_p}\times \mathrm{Ach+h})}\right)}{Ach} - \frac{h}{\rho\times \mathrm{V_r}\times \mathrm{C_p}\times \mathrm{Ach}} \tag{18}$$

$$T_i = k1.e^{(-\frac{t}{\tau})} + \frac{(h\times \mathrm{T_{sn}} + G + \rho\times \mathrm{V_r}\times\ \mathrm{C_p}\times \mathrm{Ach}\times \mathrm{T_{out}})}{(\rho\times \mathrm{V_r}\times\ \mathrm{C_p}\times \mathrm{Ach+h})} \tag{19}$$

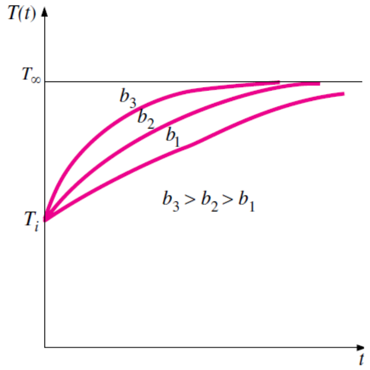

Figure 8 – Effect of the time constant, τ, in the dynamic change of temperature

The same can be done to the second stage of a DF event. When the HVAC system is turned on, this increase of consumption adds another component to the previous equations. This component is the climatization energy rate, in this case, representing the cooling load. This load acts as a loss of heat, and so G_C gets a negative value and as long as T_{ins} is lower than T_i, T_i will decrease. As this happens, with the decrease of this difference of temperature, the cooling load will also reduce its effect on the room. To describe this decrease in temperature, equation (16) changes to accommodate the G_C. Equation (20) expresses the energy balance on the second half of the event. (21) results in the extraction of the temperature gradient on this half of the event. From there equations (22) and (23) show the t in function of T_i and the T_i in function of t, respectively. The same associations regarding G and h can be made right now, and so, $\tau = \frac{\rho.C_p.V_r}{h + \rho.C_p.V_r + \rho.C_p.V_r.Ach}$. Energy Plus will use these equations to assemble a result curve, and its result will be pared with the curve from above (for the first part of the event), to form the simulation curve. This will be all presented on the 6th chapter.

$$\mathrm{G_I} + \mathrm{Gs} + \rho.\ \mathrm{V_r}.\ \mathrm{C_p}.\mathrm{Ach}.(\mathrm{T_{out}} - \mathrm{T_i}) + \rho.\dot{V}.\ C_p.(\ T_{ins} - T_i) = \textstyle\sum_{\mathrm{n}}^{\mathrm{k}} \mathrm{U_n}.\ \mathrm{A_n}.(\mathrm{T_i} - \mathrm{T_{sn}}) + \rho.\ \mathrm{V_s}.\ \mathrm{C_p}\frac{\mathrm{dT}}{\mathrm{dt}} \tag{20}$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \frac{\mathrm{G_I}+\mathrm{Gs}+\rho.\mathrm{V_s}.\mathrm{C_p}.\mathrm{ACH}.(\mathrm{T_{out}}-\mathrm{T_i})-\sum_{\mathrm{n}}^{\mathrm{k}}\mathrm{U_n}.\mathrm{A_n}.(\mathrm{T_i}-\mathrm{T_{sn}})}{\rho.\mathrm{V_r}.\mathrm{C_p}}$$

(21)

$$t = -\frac{\ln\left(\mathrm{T_i}-\frac{(\rho\times\dot{V}\times C_p\times T_{ins}+h\times\mathrm{T_{sn}}+G+\rho\times\mathrm{V_r}\times\mathrm{C_p}\times\mathrm{Ach}\times\mathrm{T_{out}})}{(\rho\times\dot{V}\times C_p+\rho\times\mathrm{V_r}\times\mathrm{C_p}\times\mathrm{Ach}+\mathrm{h})}\right)}{Ach} - \frac{h}{(\rho\times\dot{V}\times C_p+\rho\times\mathrm{V_r}\times\mathrm{C_p}\times\mathrm{Ach})} \tag{22}$$

$$T_i = k1.e^{(-\frac{t}{\tau})} + \frac{(h\times\mathrm{T_{sn}}+G+\rho\times\mathrm{V_r}\times\mathrm{C_p}\times\mathrm{Ach}\times\mathrm{T_{out}}+\rho\times\dot{V}\times C_p\times T_{ins})}{(\rho\times\mathrm{V_r}\times\mathrm{C_p}\times\mathrm{Ach}+\mathrm{h}+\rho\times\dot{V}\times C_p)} \tag{23}$$

2.3.3. Thermal comfort

Thermal comfort is defined as a state of mind at which the user is satisfied with the thermal characteristics of the space at that given time [74, 75]. Therefore, this user’s experience is based on its body characteristics and how its body reacts to the room’s environment it’s in, but also on the latter itself and the heat and mass equations and energy balances that help describe it. If the energy balances and heat and mass equations of a space have been already explained, there is still a need to, briefly, introduce the human body energy equations that are critical to understanding its perspective on comfort, (24) shows what types of heat losses and gains impact the human body and the heat storage (S) reflects how the body is responding to the thermal environment. The other variables that help describe this balance are the metabolism (M) (how the body manages its energy), the external work (W), heat exchanges from radiation (R), convection (C), conduction (K), heat loss by evaporation (E) and heat exchange by respiration (RES). If the storage is 0 it means balance is achieved. As the body has a thermo-regulatory system that is in constant search to keep this balance, some of these variables can vary from gains or losses [76, 77]. Because it depends on the perception of the user, it can follow unpredicted patterns and deviate from the theoretical energy balances of the room or of the human body and from the heat and mass equations described before. Despite that, there are a group of variables that can help describe how comfort works. Those are mean air temperature (MAT), mean radiant temperature (MRT), relative humidity (RH), air velocity, activity level/metabolic rate of the users and the thermal resistance of their clothes [76, 77]. Firstly, air temperature is, as the name implies, the air temperature of the room in study. The mean radiant temperature is the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space [75]. An estimation can be made by computing the area averaged temperature of the surfaces surrounding a person, and their effect by their angle factor [76]. Thirdly, relative humidity (%) is the ratio between the partial pressure of water vapor and the maximum pressure of that same water vapor at the same temperature and total pressure [75]. Moreover, the air velocity is simply the wind speed at the location of the user in the room. The activity level, related to the metabolic rate of the person and what the user is doing at that moment will determine how much heat he/she produces. The metabolic rate is measured in met and the activity level is in W. Finally, different clothes offer different resistance to sensible heat transfer (measured in clo) and so the heat sent by the person to the room. The last two are important because can affect the sensibility of the user to perceive if the room is thermally balanced [75, 77, 76].

To determine thermal comfort there are various methods that use these variables in their calculations. These methods are the predictive mean vote (PMV) and the predicted percentage dissatisfied (PPD). Both developed by Fanger, the PMV is method that predicts the mean value of votes from a large group of people, regarding how they feel towards the thermal characteristics of the room between 7 values from -3 (cold) to +3 (hot) (when using the ASHRAE thermal sensation scale, in Table 6), where comfort is assured when the PMV is between -1 and 1. Because the mean value just states the average between all the people in the study, and doesn't show how many people are uncomfortable, the PPD gives the percentage of people that are dissatisfied. In this case comfort is granted if a maximum of 10% of the individual votes are lower than -1 or higher than 1. As these methods can be very complex and require a lot of measurements (that are neither feasible in the terms of this thesis nor its focus), the operative temperature (Top) was used (as it can be) as a substitution. An optimum operative temperature corresponds to a PMV value of zero. Table A.5 from the EN ISO 7730 (Table 4) shows how the ranges for this temperature can vary, for different kinds of buildings and different seasons. Table A.1 from the same European norm and international standard (Table 5) the category of comfort precision. The category selected for this thesis is B, and, regarding a landscape office (open space) and in summer (cooling season), the operative temperature varies from 23 ºC and 26 ºC [78, 77, 79]. In this category, less than 10% of occupants would feel thermal discomfort if the upper and lower operative temperature limits were overstepped. In category C, the upper limit would rise to 27ºC and the lower limit would decrease to 22ºC. In this case, less than 15 % of occupants would feel thermal discomfort. The operative temperature (Top) can be calculated from (25) and requires measurements of mean air temperature (T_a) and mean radiant temperature (T_r) and the air velocity (w). The mean radiant temperature can be calculated from (26) and is a steady-state area weighted average of the surface's radiant temperatures around users. Therefore, it's a simplified version that doesn't take into consideration the user's geometric position nor its orientation regarding the surface, and so its angle factor. Only after assessing the MRT of the room, (26) can be computed. The A index is related to the air velocity of the room in (27). If the air velocity is lower than 0.2 m/s and the difference of temperature $|T_a - T_r|$ is small, the operative temperature can be calculated from (28), below [80, 81].

$$S = M \pm W \pm R \pm C \pm K - E - RES \tag{24}$$

$$T_{op} = T_a + (1 - A)(T_r - T_a) \tag{25}$$

$$T_r = \frac{T_1 \times A_1 + T_2 \times A_2 + \cdots + T_N \times A_N}{(A_1 + A_2 + \cdots + A_N)} \quad (26)$$

$$A = 0.73 \times w^{0.2} \quad (27)$$

$$T_{op} = \frac{1}{2} \times (T_a + T_r) \quad (28)$$

Regarding the CO_2 concentrations and as long there is people and no ventilation, its values are in a constant increment. In the pursuit of comfort in a demand flexibility event, CO_2 concentrations must be evaluated and its comfort limits must be respected. In terms of discomfort, the problems that arise with poor ventilation are usually due to user's body odors, and concentrations between 1000 and 1200 ppm or higher can reflect that. Apart from that, only concentrations greater than e.g. 5000 ppm can be a risk to the health of the users, and so the recommendations are always to apply ventilation to at least maintain a lower level than 1000 ppm [82, 83]. When it comes to relative humidity, there are many hazards caused by low and high RH. Relative humidity levels lower than 30% can cause the drying of the skin, eyes, throat, nose, mucous membranes, aggravation of allergic rhinitis, asthma and even the survival and spread of some viruses. On the other hand, higher than 60% RH can take to mold, mites and fungi growth. This way, the recommended values for RH are between 30-60 % [84, 85].

Type of building/space	Activity W/m^2	Category	Operative temperatures °C		Maximum mean air velocity m/s	
			Summer (cooling season)	Winter (heating season)	Summer (cooling season)	Winter (heating season)
Single office	70	A	24,5 ± 1,0	22,0 ± 1,9	0,12	0,10
Landscape office						
Conference room		B	24,5 ± 1,5	22,0 ± 2,0	0,19	0,16
Auditorium						
Cafeteria/restaurant		C	24,5 ± 2,5	22,0 ± 3,0	0,24	0,21
Classroom						

Table 4 – Table A.5 – Example design criteria for spaces in various types of building. Source [78]

Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR %	vertical air temperature difference	caused by warm or cool floor	radiant assymmetry
A	< 6	- 0,2 < PMV < + 0,2	< 10	< 3	< 10	< 5
B	< 10	- 0,5 < PMV < + 0,5	< 20	< 5	< 10	< 5
C	< 15	- 0,7 < PMV < + 0,7	< 30	< 10	< 15	< 10

Table 5 – Table A.1 – Categories of thermal environment. Source [78]

Sensation	Value
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	+0
Slightly cool	-1
Cool	-2
Cold	-3

Table 6 – Seven-point thermal sensation scale

2.4. Dynamic simulation- EnergyPlus

Energy Plus is a simulation software that uses general heat transfer and energy balance equations to analyze energy and thermal loads in a building. Its goal is to serve as a tool for engineers and architects in the study and development of real and exact energy systems in buildings. It's organized in a manager structure, where three main managers (surface heat balance manager, air heat balance manager and building system's simulation manager) organize different sets of modules, individually, in order to simplify the overall communications inside the software and reduce the complexity of the simulation process [86, 87], as it can be seen in Figure 9 . Firstly, it is necessary to design the building's thermal zones and possible shading groups that are going to be studied in the model. During this thesis, the tool used to design the simulated spaces was Sketchup with a plugin called Legacy Open Studio (Figure 10). Secondly, the user must enter all kinds of inputs, from occupancy or lighting schedules, to HVAC system's equipment, number of people, materials for walls, windows and doors, the way they are layered in the building, etc. Furthermore, another type of input must be given and that is an hourly yearlong weather file which the software will use during the simulation. This file usually contains outside air temperatures, relative humidity, wind speed, wind direction, and values for direct and diffuse radiation. After the building's characteristics and its operating conditions are described in and out of it, the user must choose from a wide list of outputs, varying from heating and cooling rate loads, to surface temperatures, zone mean air temperatures, mechanic ventilation mass or flow rates, outside weather characteristics, used schedules, internal or any other gains associated outputs, zone operative temperatures, etc.; throughout the selected simulation period and on the specific timestep [86, 87, 88]. This software will be better explained in the sixth chapter, with all the inputs used, how and why.

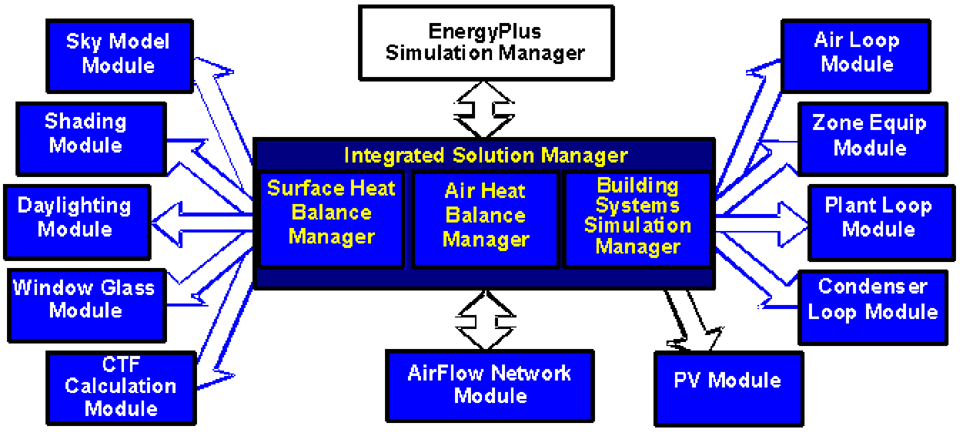

Figure 9 - EnergyPlus program schematic. Source [87]

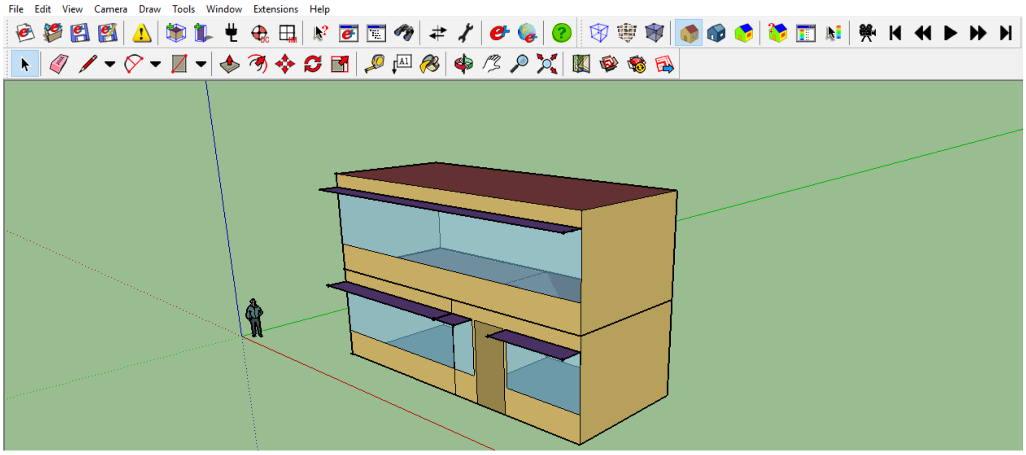

Figure 10 – Illustration of a possible building, designed with Sketchup 2015 and the Legacy Open Studio plugin

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3. Third Chapter – Case studies of demand flexibility events

The idea for the practical part of this work was to test a demand flexibility event in a real office building. As explained before, the HVAC system is a shiftable load that represents a huge share of an office building's power load, being also very manageable when integrated in a BEMS. To prepare for this main case study, a previous one was made to understand how the construction of a buildings would affect a DF event, and what would be required for that real test ahead. Some of these conclusions would help prepare and select the space which the real DF event would be tested. As these case studies were done in Portugal on 9 of May and on 6 of June of 2017, and heating was never used, the cooling and ventilation loads were the ones in study. This way, there were only two possible scenarios: increasing consumption (Figure 11) - start at higher temperatures, turn on the cooling to the maximum power until the comfort temperature lower limit is reached and then turn-off the cooling again and let the building heat up until the maximum temperature of comfort, using only the internal gains (before the event, the temperature could rise either by turning off all HVAC systems, or by using heating); or decreasing consumption (Figure 12) - start at the comfort temperature lower limit using the cooling load, turn-off the cooling load until the internal gains heat up the room to the comfort temperature upper limit, and then turn-on the cooling load until the temperature at the start of the event is established. Although a demand flexibility event can either be increasing or decreasing the consumption, in this thesis, the chosen scenario was the latter one, on Figure 12. This type of event can have the two stages (increasing temperature by turning off the cooling system, and decreasing temperature by turning it back in again after) proven by the previous equations (16) and (20) and by their resulting integrations.

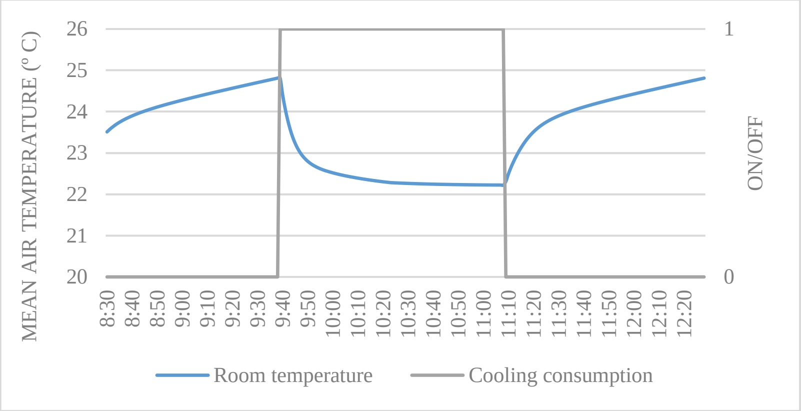


Figure 11 – Demand flexibility event. Cooling load. Increasing consumption

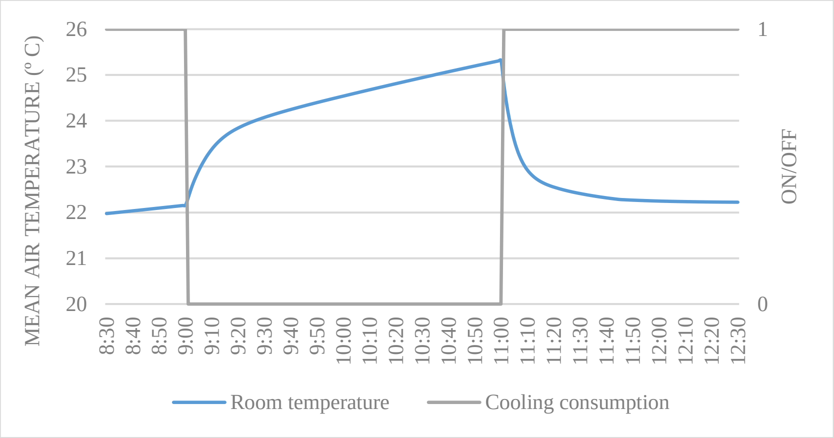


Figure 12 – Demand flexibility event. Cooling load. Decreasing consumption.

3.1. C1 Laboratory rooms

3.1.1. Building description

The first case study is in two adjacent rooms, in the east wing, of C1 building’s fourth floor, in the Faculdade de Ciências da Universidade de Lisboa (FCUL). Throughout the 5 floors, all with similar areas and design, the building has mainly classrooms, offices, laboratories and some workshops, as it can be seen on the architectural plan on Figure 13. The two rooms are delimited with the red line and they serve as the Building Energy Group laboratory. Both rooms are different in terms of area, façade width and design, construction and surface boundaries. Both rooms are in the south southeast (158º) side of the building, as its windows are only facing that same side. In Figure 13, the bottom of the building is facing north northwest (the opposite side), and so the eastside is on the left side of the figure, and the two rooms of the case study are on the top left corner. In blue are the laboratories of this floor, in green the offices, in yellow the classrooms and in white the common areas and the balcony.

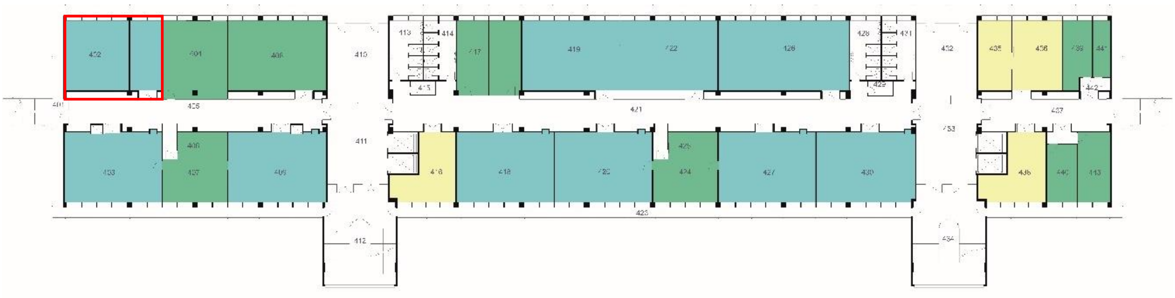


Figure 13 – Architectural plan of the fourth floor of C1 building at FCUL

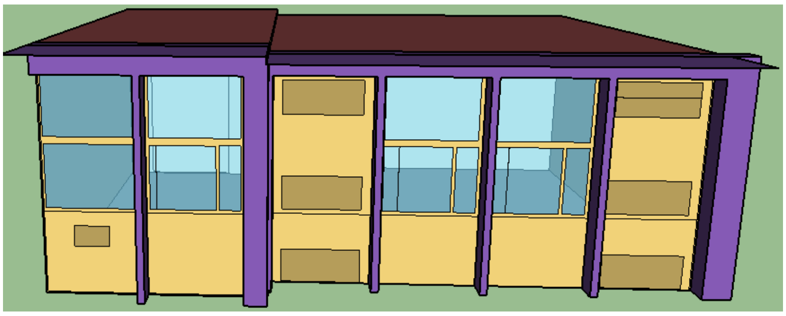


Figure 14 – Sketchup design of both laboratory rooms

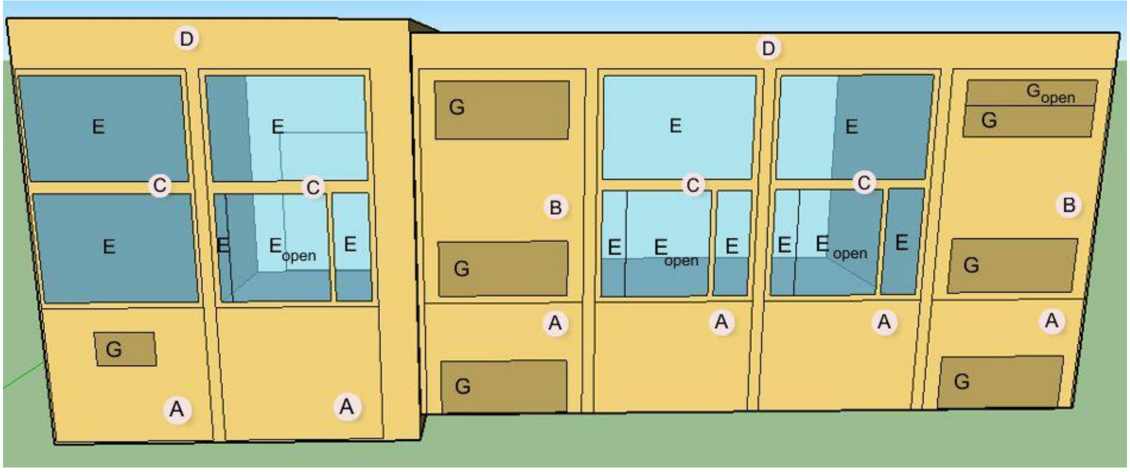


Figure 15 – Surface names for each surface in the facade

As said before there are many differences between the two rooms. The left room is the smaller one with a total area of 21.22 m^2 and will be identified as “Small Room” (SR). The left room has an area of 37.2 m^2 and because of that is called “Big room” (BR). These acronyms will be very useful for naming the wall surfaces and identifying which room they belong to. Table 14 and Table 15 resume everything about both rooms, in terms of their construction and U-values, with the names of each surface always following the same method: “acronym of the room”_”facing side”_”type of surface. The only surfaces that don’t share this naming method are the floors and ceilings of each room and the door that connects both rooms. In front of each name, the thickness of the layer is inside parenthesis. Figure 15 shows the name of each type of surface. The openable windows are the ones with the word “open” in their name in Figure 15. As it’s possible to understand from Table 14 and Table 15, the bigger room has one to two layers of extruded polystyrene (XPS) on each surface. This material is a typical insulator, with 0.036 W/m.K of thermal conductivity, which increases the room’s resistance to conduction heat transfer when comparing to the other room, which has none (XPS). The differences in construction will result in different U-values, which will prompt different thermal effects. The U-values were already introduced, in theory, before and will be used to explain the event on the next chapter. Another difference between the two rooms are the wood panels (BR_South_B) on each side of the façade and the 6 wood openings (BR_South_G). The rest is similar, except from the fact that the bigger room has two glass openings compared to the smaller room. Although both rooms in the picture don’t seem to have the same height, they both have. When designing the thermal zones only the interior height must be used, and because the insulation was installed on the inside of the room, the bigger room appears in Figure 14 as being smaller than in reality. Both rooms have a connected surface with a door, which was closed during the event, and only the SR has a door to the corridor as on Figure 13.

3.1.2. Measurement setup

For this experiment, the goal was to simulate a demand flexibility event, as showed on Figure 12, and test the effect of the mean air temperature in different rooms with different construction materials. The idea was, not only to use this laboratory as a first test for a future demand flexibility event, but also to test and understand the impact of the distinct constructions in an event like this. Despite there was no HVAC system in both rooms, the intention was to get a mean air temperature diagram and for that no mechanical cooling load was needed. By opening the windows, on a single sided display, the inside air would be exchanged with the outside air. This exchange would happen based on a pressure drop between the inside and outside, which would be the result of two mechanisms: wind; and temperature differences between the inside air and the outside. These mechanisms and how they affected the experiments will be later explained on the 4th chapter. To guarantee that this temperature difference was enough to cool down the rooms once high temperatures were satisfied, the event happened during the night with outside temperatures close to 15ºC. The two openable glass windows in the BR and the one in the SR were open with the same ratio open-area/floor-area. This way, the windows could have a similar effect on both rooms. This ratio is presented on the Table 8 down below. To simplify the dimensioning of the windows, assuring always the same ratio between rooms, they were setup with the dimensions presented on Table 7 and with similar configurations to the ones in Picture 1 (the example has smaller areas than those in the event).

	BR window left	BR window right	SR window
Opening width (m)	0.685	0.685	0.784
Opening height (m)	0.940	0.940	0.936
Opening area (m^2)	0,644	0.644	0.734

Table 7 – Dimensions of each openable window on each room

	Big Room	Small Room
Total opening area (m^2)	1.288	0.734
Area of the room (m^2)	37.20	21.22
Ratio	3.46%	3.46%

Table 8 – Opening area ratio with the floor area of each room

To simulate the internal gains due to the people, equipment and lighting that are characteristic from office buildings during work hours, ten cylinders with a lamp inside were used: 6 in the BR and 4 in the SR. These gains were calculated so that each room would have the same power density (W/m^2), as it's shown in Table 9 and Table 10. Because each lamp had an average power of about 440W, their current and voltage were measured and 6 were assembled on the BR. As the heat density (W/m^2) had to be the same, the power needed on the SR was calculated for the other four lamps. Their power was adjusted with a power regulator, so that each could have approximately the same power (the error difference between both room's power density was 0.16%). Their positioning in each room was made to be the most uniform, as it's shown with circles, in Figure 16. Because no HVAC system and a noted response was sought, the power density was way higher than in a normal office building.

Lamp number	Voltage (V)	Current (A)	Power (W)	Average power (W)	Total power (W)	Power density (W/m^2)
1	214	1.743	373	376	1505	70.92
2	210	1.777	377			
3	210	1.804	379			
4	217	1.746	376			

Table 9 – Internal gains per lamp in the small room.

Lamp number	Voltage (V)	Current (A)	Power (W)	Average power (W)	Total power (W)	Power density (W/m^2)
5	235	1.901	447	440	2643	71.04
6	238	1.883	448			
7	238	1.784	425			
8	238	1.785	425			
9	238	1.844	439			
10	239	1.922	459			

Table 10 - Internal gains per lamp in the big room.

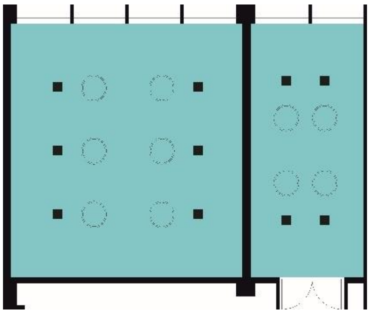


Figure 16 – Internal loads (lamps) positioning in each room

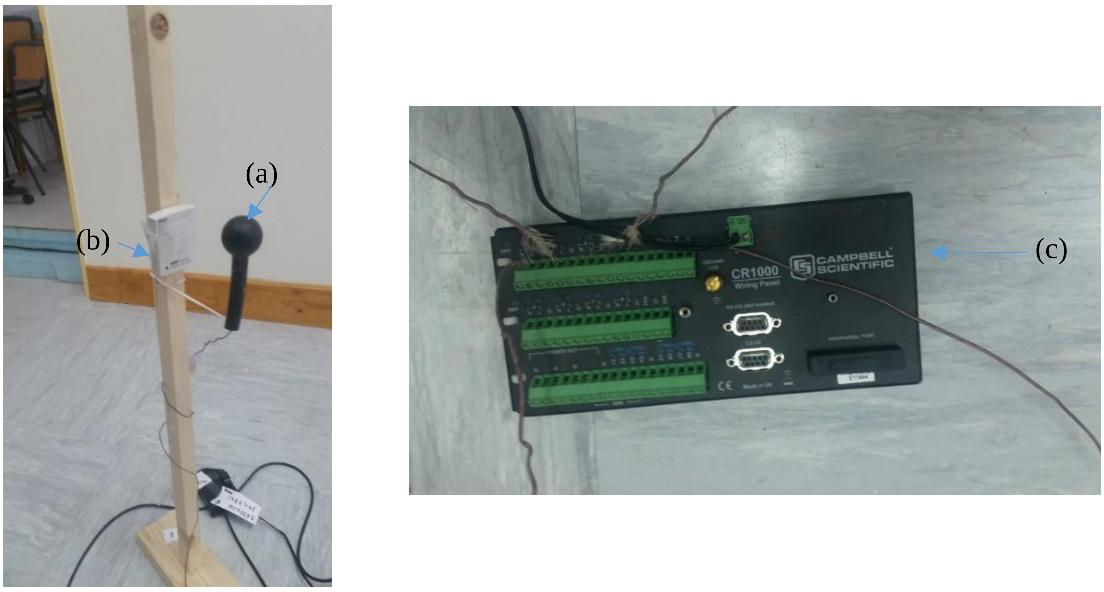
One layer of expanded polystyrene (EPS) was attached to each window of both rooms in order to the solar gains to be blocked. This was done to prevent the solar gains, or its variability, to affect the results and add another variable to the system. Because the experiment was done during the night and dawn, those gains can be neglected.

For a correct comparison between the two mean air temperature diagrams, both rooms had to start the event at the same mean air temperature. In order for this to happen, the preparation for the event included a period of time where the internal gains were turned on and the opening area per room was being changed (always maintaining the same open-area/floor-area ratio). When both rooms stabilized at the same mean air temperature, the windows were closed and the event started. The windows were opened again at the end of the first stage of the event (when both rooms had risen over 28 ºC).

Regarding the measurement itself, at 50 cm from each lamp, 10 HOBO data logging sensors (model U12-012) measuring air temperature (6 for the BR and 4 for the SR) were positioned on wooden poles (Picture 3). The height at which the HOBOs were positioned was 70cm, as it's the standard height for measuring thermal comfort. Attached to each of these poles, there were also 10 globe thermometers measuring globe temperatures, used to later compute the operative temperature [80]. Those globe thermometers were connected in each room to a CR1000 data logger as in Picture 3. At that time, one other HOBO data logging sensor (model UX100-011) connected with two thermocouples (one to each room) was also measuring the air temperatures of each room. Because the internal loads were produced solely by lamps, the CO_2 concentration didn't change, as it would in a normal occupied office, and so they were not recorded. Picture 1, 2 and 3 below show how the measurement was setup.

Picture 1 – Example of the two openable windows in BR (left); Example of openable window in SR (right)

Picture 2 – Lamps and sensors in BR (left); Lamps and sensors in SR (right)



Picture 3 – Wooden pole with sensors: (a) – globe thermocouple; (b) – HOBO data logger sensor; (c) – Data Logger for globe thermocouples in the SR

3.2. Seixal's City Hall – open space

3.2.1. Building description

In this case study, the target building is the Câmara Municipal do Seixal (Seixal's City Hall) Figure 17), in the city of Seixal, 10 km south from Lisbon, on the other side of the river Tejo. The building has two main wings in rectangular shape, with four floors each (floors -1, 0, 1 and 2), one facing 185º South with its lengthwise façade, and the other facing 5º North (Figure 17 - left). However, they are separated between each other by a middle block, which plays as the welcoming area for citizens, as well as the public services area. Yet, the case study didn't happen on the whole building, but on an open space used for administrative work. This office space is located on the ground floor of the building's north façade block and apart from three small private office rooms, it's an open space type of office. Figure 18 shows the architectural plan of this office space with each zone being identified with specific colors. In white are all the areas that were not part of the study (the rooms in the top part of the figure and the small private offices inside the colored space. In the middle the central area is the open space and the black dashed line represents the corridor. The whole space was divided in 4 zones (Zone 1 divides in A and B) for easier planning of the event. The zone numbers are identified in Figure 18. This open space has different surfaces with different construction layouts. Table 18 organizes the construction characteristics for each surface with detail to each layer of material. The names of each column refer intuitively to each type of surface: interior floor/ceiling, exterior wall, interior wall, raised floor, drop ceiling, exterior windows and metal frames. The drop ceiling represents the layer between the plenum and the open space, and the raised floor is the layer between the open space and the air space underneath the floor. In front of each material name, the thickness of the layer is inside parenthesis. Figure 19 shows the building model north façade in Sketchup and Figure 20 shows only the open space model (and the three private offices) in Sketchup. Although these private offices were not a part of the study had to be drawn to improve the preciseness of the simulation. The detailed explanation of how these models were created is in the sixth chapter.

The building has a building management system (BMS), which is a centralized station for providing supervision, control and management services for the HVAC system (as a BEMS would), for the artificial interior and exterior lighting, for the mechanical systems (automatic windows, elevators, water pumping etc.) and for the security department (surveillance cameras, fire detection, etc.). Although the building has a complex HVAC system, as it was introduced before, the focus will be the components that constitute the office space in study. Each two floors of office space, from each of the wings (north and south) have a dedicated air handling unit (AHU). Because of this, the ground north floor shares one with the underground floor. This type of unit conditions outside air and recirculated air. The system has two modular boilers for heating, two chillers with two independent cold circuits for cooling, and a desiccant dehumidifier wheel for indoor air quality. Both floors have a maximum heating power of 59 kW and a maximum sensible cooling load of 31 kW. Additionally, the open space has associated a four-pipe fan coil unit that can be controlled by the BEMS to control the speed of the fan, the supply air temperature, the starting delay, etc. The four-pipe is a measure from an EE project that changed the two-pipe unit for the four-pipe unit, to increase the flexibility of the service. The supply air arrives from the AHU by specific air ducts that arrive to the fan-coils and are then sent by the diffusers to the space. The return air is extracted from the extracting grilles and a part is channeled back into the AHU and the other part to the outside. This ducting system is hided from sight inside the plenum. The supply air has a maximum inflow of 7890 m^3/h, where 2390 m^3/h goes directly to the -1 floor, 1300 m^3/h goes to the datacenter, and 800 m^3/h goes to 5 rooms facing the atrium. 450 m^3/h goes for the private office rooms and the rest (2950 m^3/h) for the space in study. In the EE project 600 m^3/h were extracted from the whole first floor north wing to the -1 floor of the same wing, bringing the total for the open space to 2635 m^3/h. The same space has an extraction flow of 4100 m^3/h, with an extraction air fan nominal power is of 3 kW. The insufflated air fan nominal power is of 5.5 kW and there is still a chance of free cooling and a second speed mode that increases the nominal flow 1.5 times. This way, the nominal inflow would be 3953 m^3/h or 1.098 m^3/s [89, 64].

Since this is a real office space, there are internal gains that need to be described, as they are an integral part of it. As internal gains there are office equipment, lighting and heat gains derived from people's activity. Starting with OE, in the office space there are 79 computers, there are also 52 desk telephones and two printers, these two along the corridor. Along the open space there are five lines of 23 double parabolic closed lighting sets (making 7 W/m^2), which the first two layers from the glazed façade, are connected to photoelectric sensors, and have its usage limited to the solar gains available at the time. The rest of theses lamps are always used at full illuminance. There are also, on zone 1B 8 sets of these lights, fully turned on. In the corridor, there are 27 circular lights. Although, these internal gains are always being used or at least consuming, internal gains due to users' activity are dependable on the occupancy.

Figure 17 – Seixal's City Hall

Figure 18 – Architectural plan of the north-side open space office, within whole building's ground floor

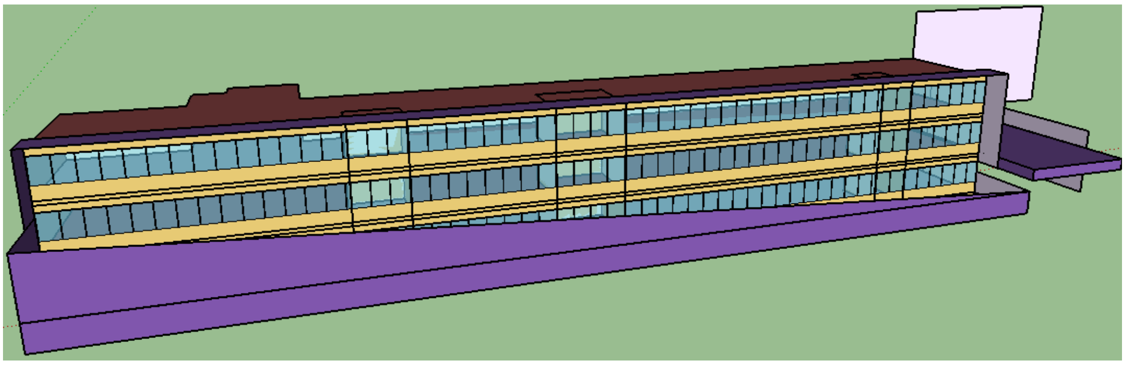


Figure 19 – Sketchup model of the Seixal City Hall (north wing)

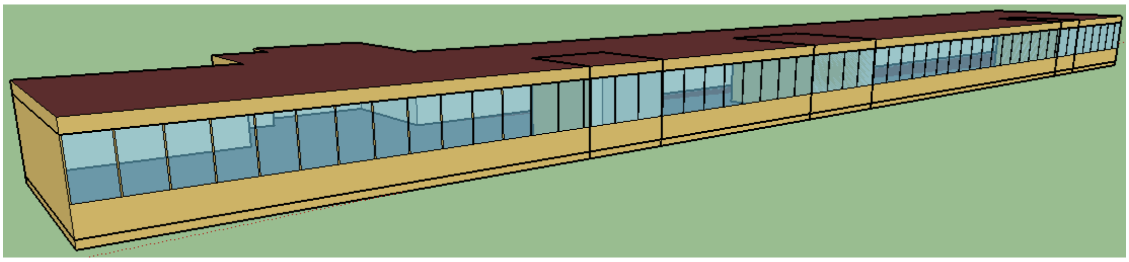


Figure 20 – Sketchup model of only the open space office

3.2.2. Measurement setup

The purpose of this measurement was to use a real office room, in a real office building, with real users and during working hours, assess the ramp duration (δ) and the recovery time (σ) of this room and how comfort plays out on a demand flexibility event (Figure 12). After the building description, the way the DF event was thought and prepared must be clarified. The building was cooled during the night and at the start of the event the room's mean air temperature was 23.5 ºC. The reason for the night cooling was to set the same temperature for every surface, and so any change of either surface or air temperature would be a result sole from the event. At 10h33 the event started, by turning off the fan coils of this room until a temperature close to 26 ºC was reached. At that time, the fan coils would be switched on again with the previous setpoint.

Although there are other variables that can better describe comfort (as explained on the thermal comfort subchapter), the mean air temperature was the deciding one to choose when to turn on the fan coils, as it was the one measured by the BEMS. To post-analyze completely how the event happened, a set of characteristics were measured. As the room was 705 m^2, it was divided into smaller zones and sensors were spread in each one to a better space characterization. Table 11 presents in a summarized way which characteristics were measured, how they were measured (with what instrument) and with what timestep. Figure 21 shows the exact position for each type of measurement and how these zones were defined. To compute the operative temperature, there was a HOBO sensor attached (Picture 4 (a)) to a wooden pole, at 0.7 m from the ground measuring mean air temperature and relative humidity. On the same pole, there was a K-33 sensor measuring CO_2 concentration (Picture 4 (b)). These wooden poles were placed at least one per zone. To measure the surface temperature of each zone a thermographic camera was used and the temperatures were obtained at 18 surfaces in total. An HOBO sensor with screen measuring air temperature, relative humidity and CO_2 concentration was placed on a zone 1 inlet diffuser to help control the experiment and to help describe the conditions in which the air was supplied to the space (Picture 4 (c)). To analyze how the CO_2 concentration and the mean air temperature preformed at three different heights (0.7 m; 1.5 m; 2.2 m) a stratification measurement was also made (Picture 4 (d)). Near the stratification cable there was a wooden pole that was used to measure the mean air temperature (by a HOBO sensor) and CO_2 concentration (by a K33 sensor). The CO_2 concentrations at 1.5 m and 2.2 m were measured by two K-33 data logging sensors. Outside measurements were also made in two different locations: on the west side of the building, a weather station was installed, and it was measuring the total and diffuse average radiation, and the wind speed and direction; on an HOBO placed on the north façade of the building, outside air temperature, CO_2 concentrations and relative humidity were also measured. As the former measurements were made to understand the solar gains, the latter were done to understand the characteristics of the outside supplied air. Both together were used to create a weather file to later be used in the simulation of the event.

To prove that the fan coils were switched off during the first part of the event and to assess their consumption on the other part, a power energy logger was used to measure the three-phase power of those loads. Another power energy logger was used to measure the same data for the whole consumption of the open space (without the fan-coils), to understand how much internal gains were due to the lighting, ITCs and OE in total, and how they operated during the event. The occupancy was measured by counting the people in every zone at a timestep of 5 min, to understand how it could affect the event and its results. The number of opened and closed blinds during the event was also counted to later approximate the simulation to the real solar gains arriving to the room during the event. The pictures below (Picture 5) show how the event and its measurement tools were setup across the four zones.

Figure 21 – Positioning of every type of measurement across the four zones

	Measuring tools	Measured variable	Timestep (min)
Wooden pole	K-33 sensor	CO_2 concentration	1
	HOBO sensor	Mean air temperature	0,5
		Relative humidity	0,5
HOBO with screen	HOBO sensor	Mean air temperature	5
		Relative humidity	5
		CO_2 concentration	5
Stratification cable	K-33 sensor	CO_2 concentration	1
Thermographic camera	Thermographic camera	Surface temperature	At 10:45, 11:15, 12:10, 12:40 and 14:10

Table 11 – Types of measurements, measuring tools, measured variable and timestep

Picture 4 - (a) – HOBO data logger sensor on wooden pole; (b) – K-33 sensor on wooden pole; (c) – Hobo with screen near the inlet; (d) – CO_2 measurements stratification cable

Picture 5 – (a) – Zone 1 position 2 stratification cable and wooden pole; (b) – Zone 2 position 3 wooden pole; (c) – Zone 3 position 6; (d) – Zone 4 position 7;

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4. Forth Chapter – Practical Results

4.1. C1 Laboratory rooms

Because of the rudimentary nature of this experiment, its analysis will be brief. In this experiment, the goal was to compare how the two rooms would behave on a demand flexibility event. The method used to analyze this behavior was by measuring the mean air temperature at the points close to the internal gains, making an average for each room, and plotting these two room mean air temperatures in a figure like the one below (Figure 22). To begin with, the initial temperature of the small room was 25.5 ºC and 25.8 ºC for the big room. As there was no cooling load to bring room temperature to a good starting point for the event and there were no occupants in the rooms during the event, thermal comfort was neither a requirement or an aim. Because of this, the temperatures were always higher than usual in office buildings, during the whole event. This way, the temperature curves would be emphasized by the high temperatures and a clear comparison between the rooms could be made. Another aspect of this measurement was the internal heat gains density. It was 71.04 W/m^2. This density can only be seen in offices that have occupancy densities of 4 m^2/person [90]. Because the windows were closed at the start of the event, no negative gains through natural ventilation (NV) were obtained. In the first stage, the energy balance (15) would only be described by three terms: internal gains, losses and the temperature gradient. Since the target here, was not to study comfort on a demand flexibility event but to get the temperature diagram, the time at which the windows would open was arbitrary and selected when a temperature curve on each room could already be drawn. As before the event the windows were open at a certain ratio, when at 8 am the windows were opened again at the same ratio, the expected result would be that temperature in both rooms would come back to the same initial value. This didn't happen in Figure 22 because of an experiment mistake. Nevertheless, the behavior of the rooms was as expected, with this decrease in T_{in} being explained with equation (12). Outside air temperatures lower than inside ones led to a negative natural ventilation gain (or a loss of heat through NV), and so the result is a decrease of inside air temperature.

The opening of the windows resulted in pressure differences, between in and outside air, by the wind and the difference of air temperature (thermal buoyancy). Although this thesis is not focused on this type of ventilation, the thermal process is due to different densities in warm and cold air, and so differences of pressure. Every window when it's open has a point in its opening height that the difference of pressure is zero. Above which the overpressure makes the air flow out of the room, and under that the under-pressure makes the air flow into the room. The wind has an effect on the NV with a pressure difference created by the wind speed and it's direction [91].

More importantly, the different construction of both rooms played a huge role on how the two rooms behaved during the event. Despite both rooms in their core construction are very similar, the BR has two layers of XPS on the floor, roof and connecting wall between the two rooms, and 1 layer of XPS on all the other walls. This increase of insulation, gives this room the ability to retain heat much longer inside the room, as equations (14) and (13) show. Specifically, (14) shows that by increasing the resistivity of that same surface, in this case with increasing insulation, the U-value will decrease. In addition, equation (14) and (13) show that, for the same surface, losses decrease when the global heat transfer coefficient (U-value) also decreases. The U-values of each surface are presented on Table 15 and Table 16. Table 17 compares the U-values of opposite surfaces to a better understanding of the effect of different constructions (and so U-values) on the heat transfer losses of each surface. This way, the SR without the insulation of the BR, loses heat at a much faster rate than the latter. Because of this, the SR takes more time to heat up and reaches lower temperatures than the BR. Figure 22 demonstrates how the same heat density, in both rooms, takes the SR 3h26min to reach 28.41 ºC, when the BR reaches that temperature after 54 min. For the 3h26min, the BR reaches a mean air temperature of 38.51 ºC. After that, the windows were opened and the temperature dropped in both rooms. Although the mean air temperature captured by the individual HOBOs (model U12-

012) was the unit used to regulate the beginning of the event, at the end of the event this temperature was read by the HOBO (UX100-011). There was also a problem with the calibration of the globe thermometers and that's why its plot is not shown. Lack of time to repeat this experiment made it impossible to retrieve better data from this event. Despite this, this event was meant to show how a demand flexibility event can affect the temperature inside a room, and that different constructions can alter the behavior of a room in a very different way. It can be concluded that the expected results for this event were accomplished, as well these two goals were also tested successfully. The "closed windows" portion of the event can be correlated to the scenario of decreasing consumption, presented before in Figure 12, when the cooling is turned off. The second part of the event could reveal the recovery time of each room, as it's the equivalent part where the cooling consumption would be turned on again on a DF event.

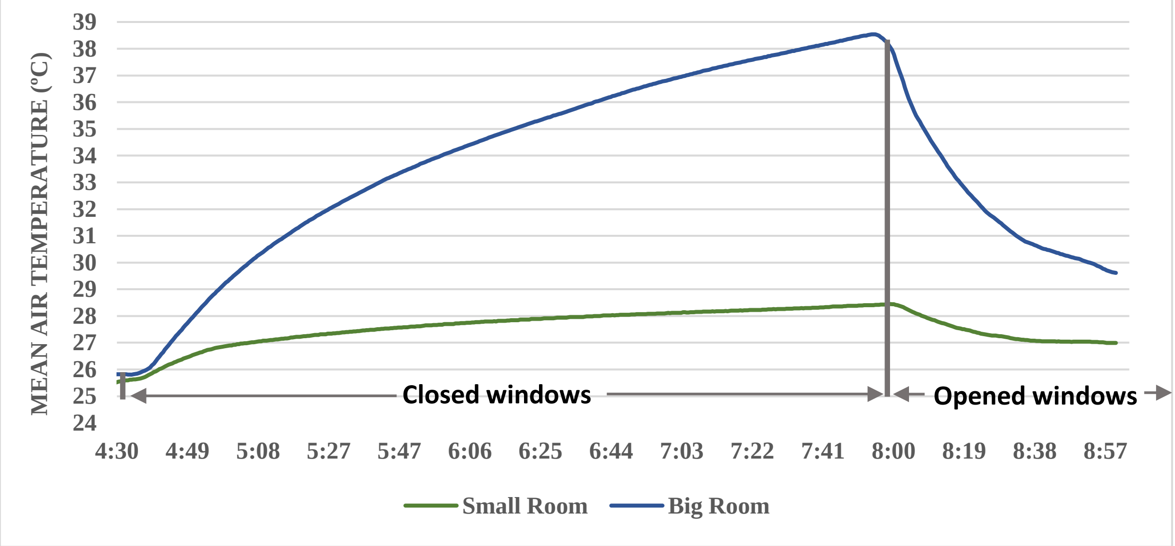

Figure 22 – Mean Air Temperature (ºC) during event for each room

4.2. Seixal City Hall – open space

This experiment attempted to perform a demand flexibility event in an office open space. On a real demand flexibility event, there are two sides required: the electric power grid side and the building side. The electric power grid is only interested in the increase or decrease (in this case) of consumption from the building. The building, apart from the contract monetary compensations (that won't be addressed here), it's only interested in not disturbing the comfort of its users. Therefore, in this experiment both sides must be analyzed: the decrease of consumption followed by the increase of consumption on the second part of the event; and the comfort side.

4.2.1. Electric power grid side

Starting with the consumption side (or the electric power grid side), two power energy loggers were used during the event: one to measure the three-phase power of the fan-coils and the other the three-phase power of the office ITCs, OE loads and lighting. Figure 23 shows how the fan-coils' consumption rate evolves during the event. As the goal was to test one room and not the entire building, the whole HVAC system couldn't be completely turned off and so this room's fan-coils were the only ones being turned off. Since the event started at 10:33, took around two minutes for the fan coils to reduce their consumption rate from 670 W to 0 W. At 10:35 the fan-coils were no longer consuming, as the event had just started. Until 12:09, because of this cease, the inside room temperature rose until the room's temperature (read in the BEMS) was 26 ºC. From 12:10 to 12:11 the consumption rate rose to 825 W, when the fan coils were turned on again. Figure 24 shows the energy consumption of the lighting, ITCs and OE loads, varying with accordance to the occupation. As this event covered the lunch period, users left the room to have lunch, with the consumption following this variance. Also relevant is Figure 25 for the overall consumption rate density (W/m^2) in the office by lighting, ITCs and OE loads. According to CIBSE Handbook [90], a guide for practicing building engineers, depending on the density of occupation (m2/person) in an office space, different sensible heat gains are to be expected from people but also from lighting and equipment. In order to give some substance to what Figure 25 shows, Table 20 indicates a guideline value for the lighting and equipment sensible heat gain densities. In the case of lighting this value is in the 8 to 12 W/m^2 range, depending on the characteristics of the room. The minimum value is indicated for situations where lighting may be switched off near window areas, the case in this office open space as described in the building description of the third chapter. Although occupancy changes during the event, the average occupancy density in the whole open space is 19.45 m^2/person, and so the correspondent value for equipment heat density is 12 W/m^2. This brings a total value of 20W/m^2 on average during the event, which is represented in Figure 25 by the green line.

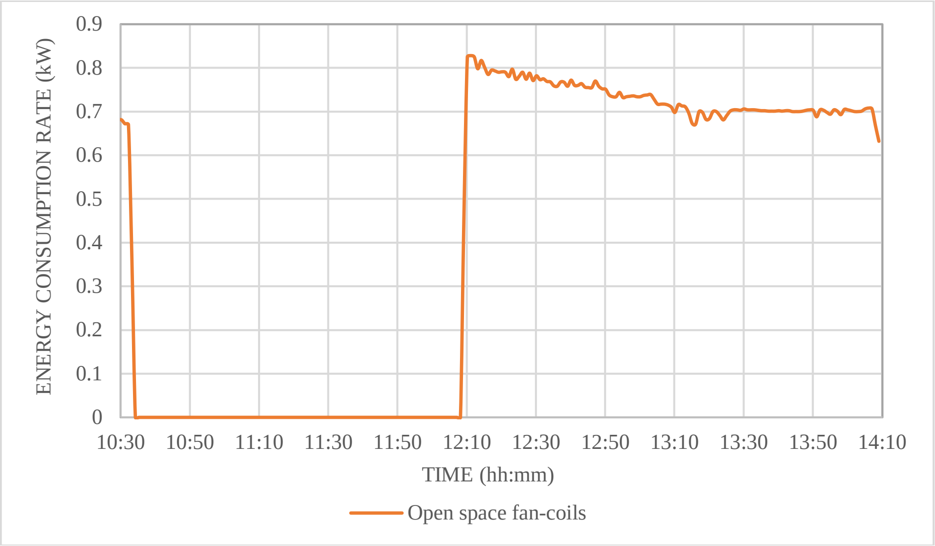

Figure 23 – Fan coils consumption rate during the demand flexibility event

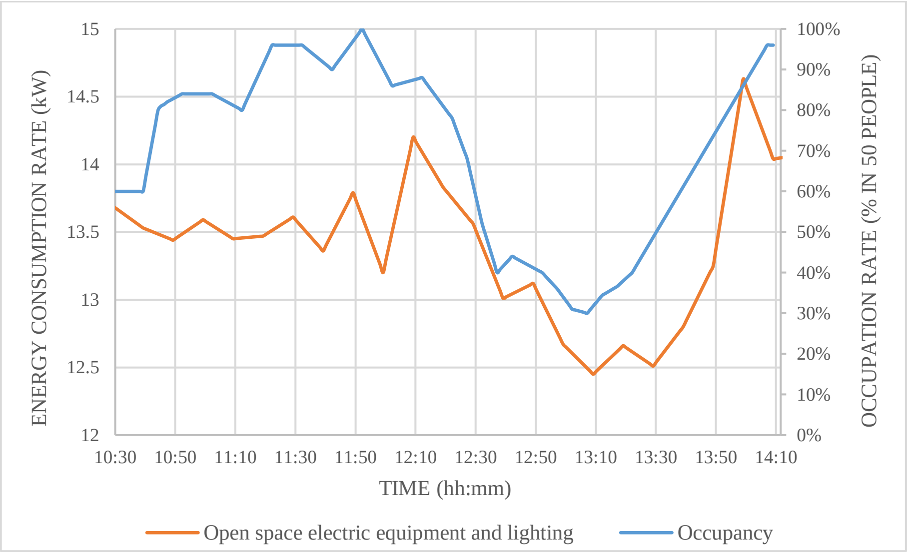

Figure 24 – Lighting, OE and ITCs consumption rate during the demand flexibility event with occupancy

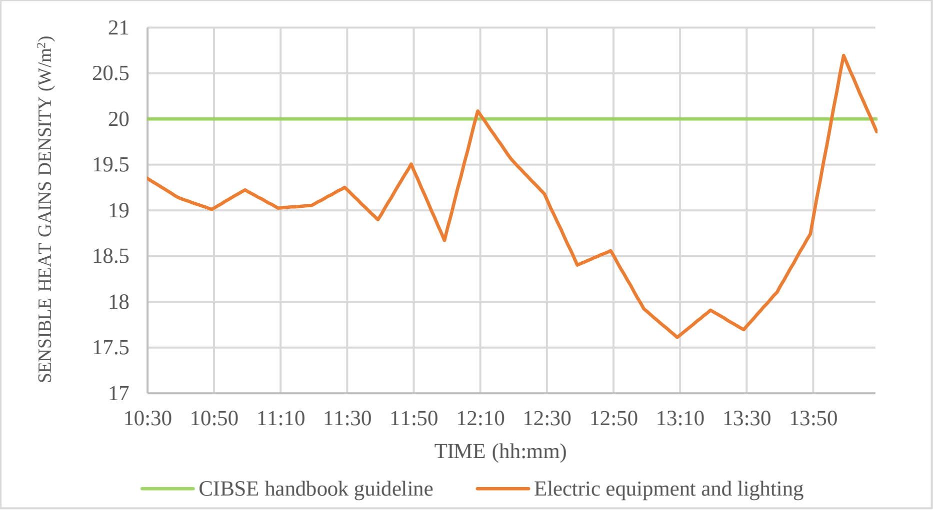

Figure 25 – Lighting, OE and ITCs sensible heat gains density during the demand flexibility event

4.2.2. Thermal comfort side

On the other side, comfort must be ensured at any time and demand flexibility events can't ever disrupt that. To guaranty that the limits of comfort were never crossed, the mean air temperature inside the office was controlled by the BEMS. The results below illustrate how different measured variables changed during the event. As stated before, these variables were: CO_2 concentration, mean air temperature, relative humidity and surface temperature. Regarding the CO_2 concentration in each zone, the Figure 26 reveals how it changed across the four zones. Because there is no ventilation turned on, the CO_2 concentration increases as long as time passes. When the fan-coils are turned on this concentration decreases. When people breath, air is inhaled from the room to their lungs and then exhaled from the lungs to the surrounding environment. Depending on the metabolic rate of the person and because the average internal temperature of the human body is 37 ºC, the air coming out arrives with a higher temperature then when it entered. Because of this, the hot air comes out and heats the surrounding air due to difference of air temperature and difference of water vapor pressures. As the respiration heat losses from an user working, in a sitting position, are very low, the importance of this analysis is rather to explain why the exhaled air rises towards the ceiling [76]. Despite, the stratification measurements of the CO_2 concentrations (Figure 27) were only measured in the zone 1, they can show exactly that higher concentrations occur nearer the ceiling and that even with ventilation (on the second part of the event) there is always more CO_2 concentration in higher places than at the user's level (at 70 cm). The variances on the data are due to sensibility of the K-33 sensor.

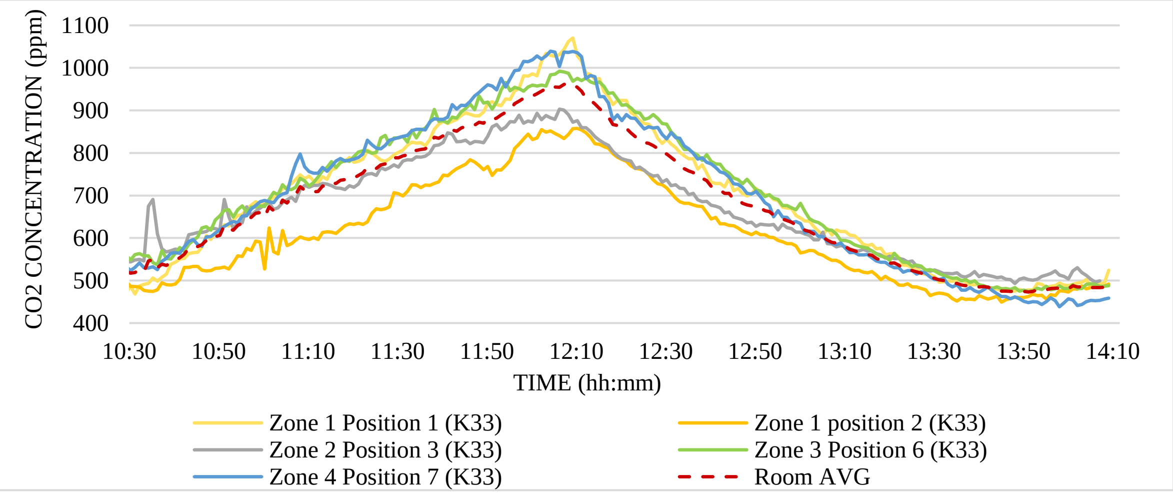

Figure 26 – CO_2 concentration across the four zones, during the event

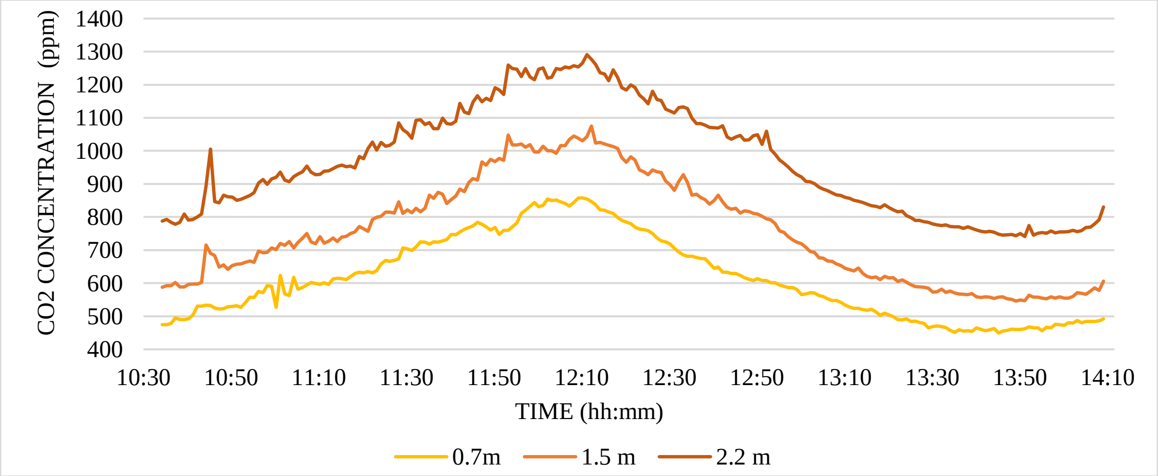

Figure 27 – CO_2 concentration stratification at 0.7 m, 1.5 m and 2.2 m.

With respect to the thermal behavior of the room and the thermal comfort of the users, two temperatures were measured. The mean air temperature was recorded through HOBOs sensors and demonstrated how the air temperature was changing during the event. Figure 28 illustrates that exactly. At the start of the event, the room mean air temperature was 23.5º C. As the time passed the temperature increased only through the heat gains from users, from the lighting and MELS and solar gains, as the fan-coils were turned off. The expected result was that, by convection, these heat gains would heat to the air around them, making the hot air to rise in a buoyance effect Although the mean air temperature is not used as a variable to measure comfort directly, it can demonstrate approximated curves, as the ones presented in Figure 12. Figure 28 shows that the 26º C upper limit was not crossed in any zone. The air temperature was also measured in different heights, using an HOBO sensor (at 0.7 m) and two K-33 sensors (at 1.5 m and 2.2 m), to understand its stratification along the height of the room. Figure 29 illustrates the measured stratification. When the fan-coils were turned off, in the first half of the event, the hotter air would heat up the room and accumulate near the ceiling. When they were turned on the air closer to the outlets in the ceiling was extracted first, and so the temperature decreased with higher intensity in the upper heights. This drop is seen by the darker curves in the figure. After a few minutes, the temperature at the three heights gets almost leveled and then the change rate decreases until the end of the event. The thermal curves are different in aspect because the sensors measuring them were also different. The sensibility of the K-33 sensor can also be noticed in Figure 27 for the CO_2 concentrations, as it's in Figure 29 for the mean air temperature.

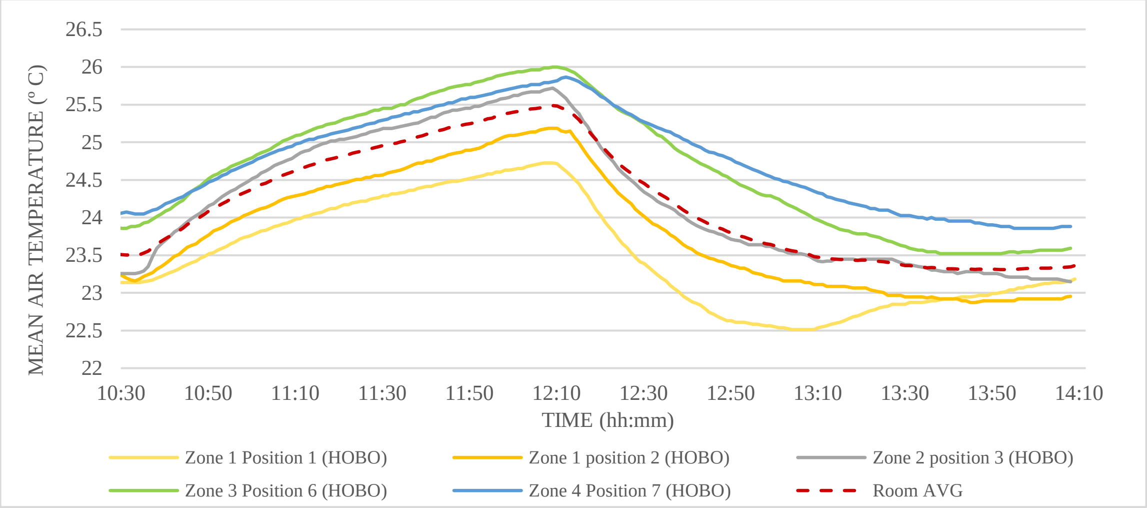

Figure 28 – Mean air temperature across the four zones, during the event

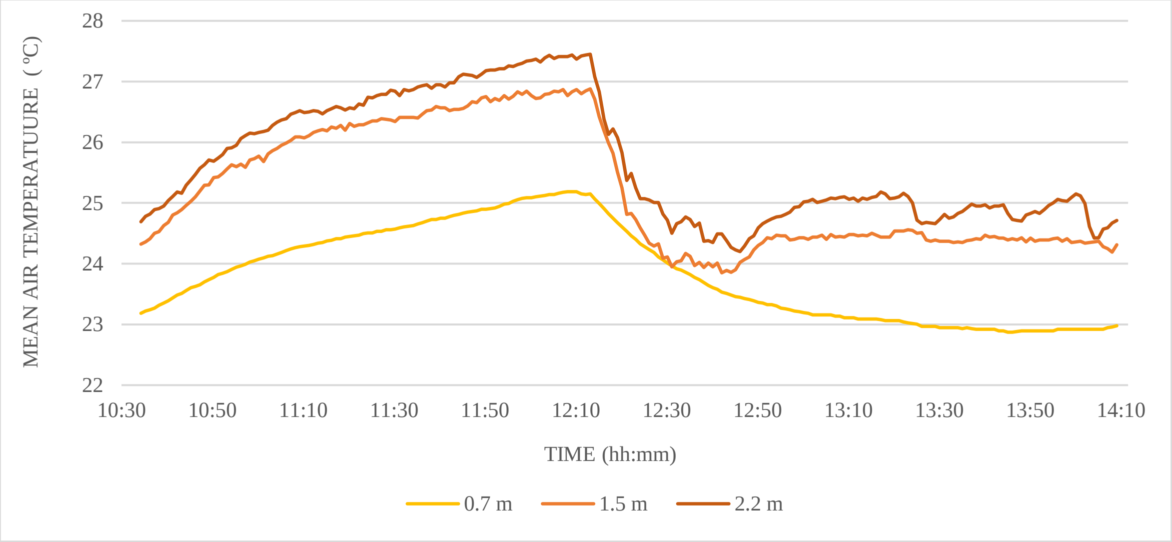

Figure 29 – Mean air temperature stratification at 0.7 m, 1.5 m and 2.2 m

As explained before in the thermal comfort subtopic of the theoretical background chapter, the recommended range for relative humidity in an indoor space is between 30% and 60 %. As the Figure 30 shows, it can be concluded that this range was respected during the whole event, except for a minute in zone 2 position 3. This means that the RH didn't change to levels where it could affect the users, and even that exception can be neglected.

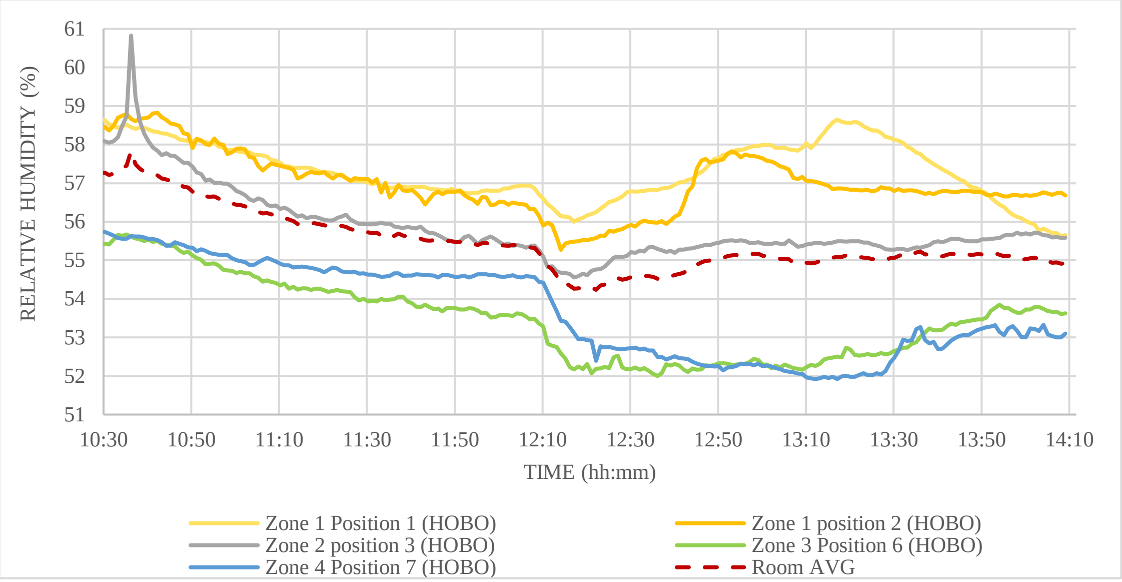

Figure 30 – Evolution of the relative humidity during the event across the four zones

The surface temperature of each zone surface was measured by thermographic camera three times during the event, interpolated and used to calculate the mean radiant temperature of each zone during the event. The open space characteristic architecture and the division of the open space into four zones, led to zones with less surfaces (the middle zones: 2 and 3), and so less impact was felt from the latter, compared to a case where each zone would be separated by walls in every side, as in closed office rooms. On Table 12, each measured surface temperature is presented for each surface of each zone and used to calculate the mean radiant temperature of the same zone, with those results being presented and analyzed on the next chapter. As the building HVAC system was scheduled to be cool down the room, during the night until the event started, the surface temperatures can be assumed to be the same temperature as the air, 23.5 ºC. Because it was not measured at the beginning of the event, this assumption must be made and its associated error must be assumed.

Surface	Area (m^2)	Total area (m^2)	Zone	T (ºC) at 10:45	T (ºC) at 11:15	T (ºC) at 12:10	T (ºC) at 12:40	T (ºC) at 14:10
Floor	232	576	1	25.2	25.9	25.9	21.2	24.4
Wall_West	12.5		1	25.3	26.1	26.3	24.2	24.4
Window_North	57.7		1	25.5	26.6	27.4	26.1	25.1
Roof	232		1	25.4	26.5	27.2	24.8	24.2
Wall_South	16.5		1	25.2	25.6	25.3	23.5	23.3
DataCenter_Door	25.2		1	25.3	25.9	26	23.4	24.2
Wall_South	45.1	224	2	25.3	25.9	26	25	24.9
Wall_East	16.6		2	25.4	26.5	27.2	25.3	24.9
Window_North	32.6		2	25.5	26.7	27.7	25.8	24.6
Floor	130		2	25.3	26.1	26.4	25.1	24.6
Wall_South	69.9	123	3	25.2	25.9	25.9	24.5	25.3
Window_North	53.1		3	25.5	26.7	27.6	26.2	25.4
Floor	148	414	4	25.4	26.3	26.7	25.3	25.1
Roof	148		4	25.5	26.7	27.6	25.7	24.6
Wall_South	50.0		4	25.2	25.9	25.9	25	25
Wall_East	13.5		4	25.3	26.2	26.6	26.2	25.2
Window_North	23.7		4	25.5	26.8	27.9	26.5	24.8
Wall_West	30.2		4	25.4	26.4	27.1	25.9	25.1

Table 12 – Surface temperatures recorded at three different times in 18 different areas

5. Fifth Chapter – Analysis

After presenting the results with a brief explanation, a deeper look must be made into the different components of the demand flexibility event, tested in a real office open space in the Seixal's city hall. Following the same approach on the previous chapter, this analysis will be divided in two parts: the electric consumption side and the users' comfort side. First the demand flexibility event will be defined by the proposed units presented before. With this keen way of analyzing the building's flexibility, it will be easier for the grid to assess which building or set of buildings is the best solution for a specific imbalance situation. After that, the effects on the users' comfort will be studied, as it remains a requirement for this type of events.

5.1. Demand Flexibility units

In the second chapter, Figure 7 showed, in theory, how the grid could know the real-time building's consumption and its demand flexibility profile. It also showed two events, represented by the two yellow trapeze regions. Here, in this case study only the first trapeze must be considered. When paying attention to Figure 31, the first part of the event from point A to D (until 12:10), it has some similarities to the first yellow trapeze from Figure 7. It's also a trapeze and it identifies the real consumption variance as well. Because an event ends when the initial temperature is re-set, the first goal, in this analysis, is to find the variables that define this event. To do that, Figure 31 needs to be shortened to the equivalent of the first yellow trapeze in Figure 7. Figure 32 shows this short version. These variables (in the sequence of the event) are: the actual available power that was decreased (W), π^-_{real}; the actual decreasing power ramp rate (W/min), ρ^-_{real}; the ramp duration (min), δ^-; the increasing power ramp rate (W/min), ρ^+_{real}; and finally, the recovery time (min), σ^-. Considering that the event started just before the fan-coils consumption was cut to zero, point A (in Figure 32 and Figure 31) is this point where the consumption rate was at 670 W. Because the vertical axis doesn't represent the consumption rate, but the decrease or increase of energy consumption, considering that the fan-coil consumption was constant, point A represents the initial position (at 10:33) of the event where the actual decrease of energy consumption was of 0W. After this, and for the next two minutes, the consumption was cut in 670 W and so the actual decreased power (π^-_{real}) was 670 W. Because it took two minutes, the power ramp rate (ρ^-_{real}) in W/min was 335 W/min. At this point B (at 10:35), the cooling load was cut off and temperature was rising. Between 12:09 and 12:11, the fan-coils were turned on again. The ramp duration (δ^-) i.e. the time that takes from points A to C; was 94 min. As it took also 2 minutes to come from 0 W (point C) to 670 W (point D), the increasing power ramp rate (ρ^+_{real}) was 335 W/min.

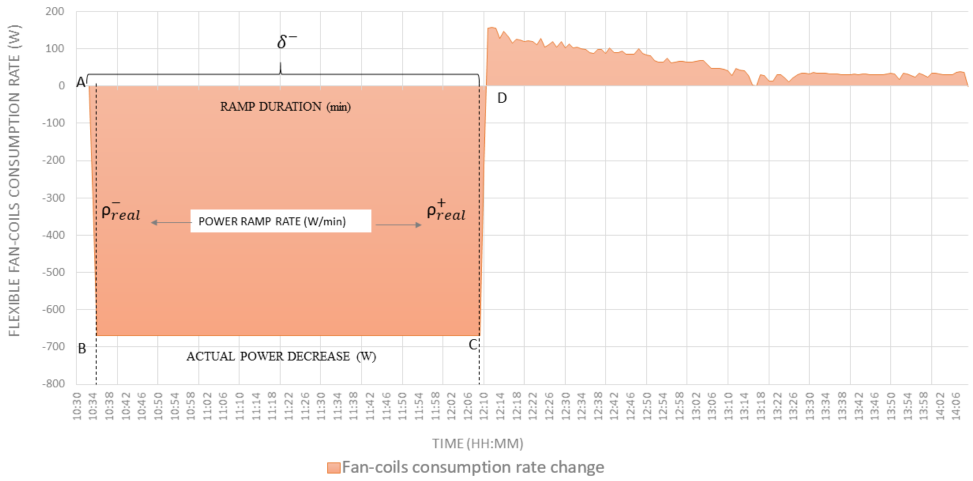

Figure 31 – Flexible fan-coils consumption in the demand flexibility event

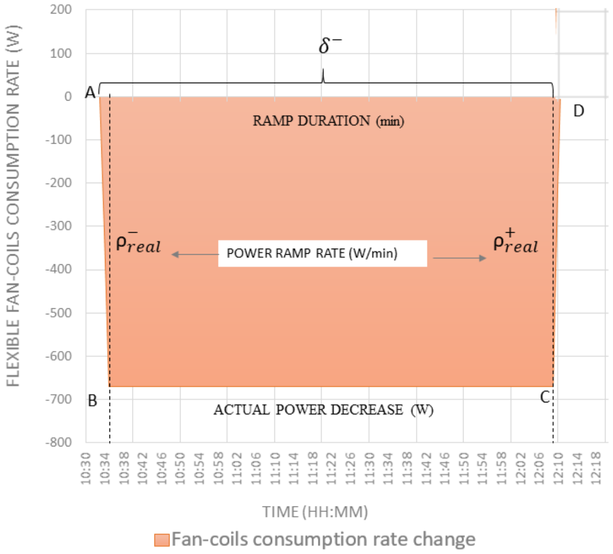

Figure 32 – Short version of Figure 31 with DF units

To compute how much time was the recovery, (Figure 33) shows the room's average MAT during the event, on a similar figure to the previous one. Because the temperature control was always done with the MAT, the recovery time was also computed from this temperature. The recovery time (min), σ^{-}, which is the time between point C (12:09) and F (13:07) was thus 58 min. Table 13 resumes all the results for the characteristic values from this event. Because the saved energy is not a directly measured unit in a demand flexibility event, it's usually not presented. Although, the total saved energy was approximately 100kwh. Because the comfort analysis will be studied in the next subtopic, the figure comparing the DF event and the operative temperature will only be shown there.

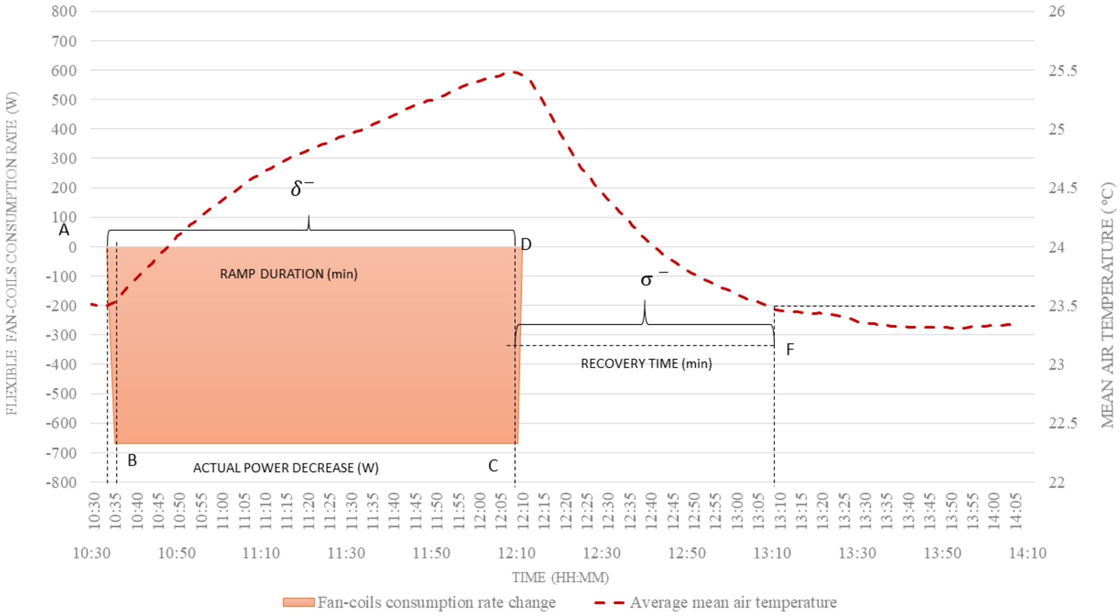

Figure 33 – Figure 32 with room's average MAT. Assessing the recovery time.

Unit	ρ^{-}_{real} (W/min)	π^{-}_{real} (W)	ρ^{+}_{real} (W/min)	δ^{-} (min)	σ^{-} (min)
Value	335 W/min	670	335 W/min	94	58

Table 13 – Demand Flexibility characteristic units

Now that the event was understood, it's time to study the complete version of Figure 31. Figure 34 joins the flexible fan-coils consumption rate (Figure 31) with the room's average MAT. After the fan-coils were turned on, the consumption rate increased directly up to 825 W (point E). This hype in consumption can be predicted to be because of the temperature difference to where the system was when it was turned off and where it was when it was turned on. Either by an increase of flow rate or a reduction of the inlet air temperature, different from before the event, made the consumption rate rise 155 W more than the 670 W that were expected. As temperature decreases, the consumption rate also decreases coming down from the 825W to the 717 W at 13:07 at the end of the event. Despite this misleading increase, the actual ramp rate can only be computed until the power returns to its initial value. Although this extra 155 W were not considered part of the event, they influenced the recovery time of this experiment. Without this extra consumption, recovery rate would've be longer and less steep than as it was. This is an error that has to be assumed, because the initial proposition for this event didn't contemplate an increase afterwards. If a real contract would've been signed and this extra consumption was not foreseen, this would mean a penalty for the building. On future real-time measurements, this type of errors cannot happen, to help understand better the demand flexibility of the building. If this type of errors cannot be controlled, this extra consumption must be analyzed and defined as a part of the demand flexibility profile. Although it did happen, it only affected minorly the recovery time.

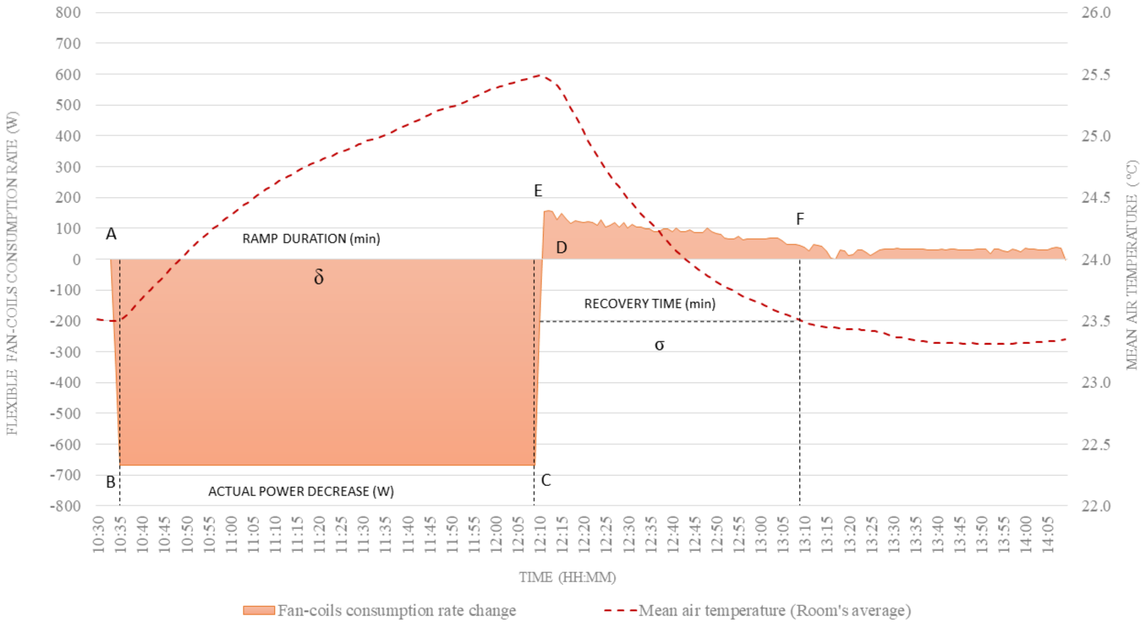

Figure 34 – Flexible fan-coils consumption rate during the whole event, with the room's average MAT. Complete version.

Although these consumption rates for the fan-coils are in accordance to their expected total power, this 670 W were the only ones measured by power energy loggers used in the event. When the fan-coils were turned off, both the AHU and the chillers designated to this space also must've suffered a decrease in consumption. Based on this assumption an extrapolation was done to assess which was the approximated value decreased during the event. The power ramp-rates were calculated also through the same process. This method will be explained in detail next.

The HVAC system's coefficient of performance (COP) is 2 [89]. This means that for each 1 W of electric power used, the system can extract 2 W of heat power from the space. This way, and by knowing the amount of heat that was generated, during the first part of the event, it is possible to extrapolate the amount of electric power that would have to be used if the fan-coils were not turned off. From the measurements regarding occupation and the measurements from the equipment and lighting energy consumption rate, the amount of total average heat that was to be extracted during the first part of the event can be estimated. Therefore, an approximation of the decreased power and the power ramp-rates were computed. The extrapolated values are in Table 14 below.

Unit	ρ_{real}^{-} (kW/min)	π_{real}^{-} (kW)	ρ_{real}^{+} (kW/min)	δ^{-} (min)	σ^{-} (min)
Value	4.48	8.96	4.48	94	58

Table 14 - Demand Flexibility extrapolated characteristic units

In conclusion, this proves how detailed and complex these types of measurements are and how difficult it is to really capture one event like this, even as successful as this one. Using globe thermometers to measure the operative temperature at any instant, using more energy power loggers to measure all loads affected by the event and increasing the positions of measurements in the room should increase the both sides (comfort and smart grid part) control in real-time of this kind of events.

5.2. Comfort analysis:

Users during the event had some comfort characteristics of the room changed, and the goal now isn’t only to understand how they changed but if comfort was ever interrupted, for how much and for how long. As there was no questionnaire made during nor after the event to collect the opinion of the users about the experiment, the practical data will be analyzed sole from the theoretical background for each variable. From the variables listed before, the room’s CO_2 concentration and operative temperature are the main characteristics that are being examined.

5.2.1. CO_2 concentrations:

When the event started, and the fan coils were turned off, no ventilation was occurring, and so the CO_2 concentrated increased with the respiration of the users. To analyze if and how much comfort was affected, during the event, regarding human bio-effluents (odors), the recommended ASHRAE CO_2 concentration upper limit between 1000 ppm and 1200 ppm was used. Although CO_2 concentrations aren’t the source for these unpleasant smells, they help determine if ventilation is being used properly, being the best resource available to measure this kind of discomfort. In this thesis, a CO_2 concentration upper limit of 1100 ppm was selected and Figure 26 shows that at any time this limit was surpassed. Even only in two positions, concentrations higher than 1000 ppm were reached and only for a time of 15 minutes for zone 4 and 10 minutes for zone 1 position 1. It can be concluded, that the ramp duration of the event didn’t bring users to a place of discomfort, as it wasn’t enough time for odors to be noticeable by the latter. As these CO_2 measurements were made at the sitting height of 0.7 m, the stratification sensors, placed at 1.5 m and 2.2 m, increase the understanding of this concentrations at bigger heights, specifically at 1.5 m, as being closer to the walking height. Even at this height the concentration limit of 1100 ppm is never reached. Heath problems due to high concentrations of CO_2 is not a problem as well, as these concentrations are too far from the 5000 ppm level.

5.2.2. Operative temperature:

The other chosen variable to evaluate comfort was the operative temperature. Assuming that, by having no ventilation, the air velocity is lower than 0.2 m/s, equation (28) will be used to compute the operative temperature. This way, an average between the mean radiant temperature and mean air temperature at every minute must be made. To calculate the mean radiant temperature of each zone, equation (26) is used and Figure 36 illustrates this temperature during the event for each of the different zones. Figure 37 shows how the operative temperature of each zone changed during the event. Additionally, Table 4 stablishes the comfort lower and upper limits for the operative temperature between 23.0 ºC and 26.0 ºC, respectively. Based on these limits, and since the lower limit was not crossed, one region was added in grey to easily identify if comfort was or was not assured during the event. As it can be seen, zone 1 was the only zone where comfort was not disrupted at any time. Although the operative temperature in zone 2 reaches an approximate value of 26.1 ºC for 8 minutes, this difference can’t be seen as a huge comfort interruption. Zone 3 and zone 4 cross the comfort limit proposal from ASHRAE, but despite this, it only surpassed 0.3 ºC (in zone 3) and 0.4 ºC (in zone 4) of the upper limit and so this discomfort can be almost neglected. If scenario C was selected, none of the zones would be over the upper limit. Although category B was selected in the beginning as an aim, results show that with 15% PPD comfort was still assured as category C states for a 27 ºC maximum operative temperature.

In the case of the zone 1 sensor, although the sensor was in a central position to the zone itself, it was also in a place with less occupants. Therefore, and despite it was capturing the mean air temperature of the zone, less heat gains were being transferred to the air around it, and so the sensor wasn’t measuring the real mean air temperature felt by the occupants in that zone. On the other cases, the operative temperature measured describes the users’ experience better, as their positioning was closer to them. The open space average operative temperature gives a sense of what was the comfort sensation in the room. It shows that thermal comfort was only interrupted for the 14 minutes, and only reaching 26.15 ºC, which doesn’t represent a huge overstep. This way, it can be concluded that thermal comfort was mainly assured on average with a peak of temperature in zone 4 at the end of the first part of the event.

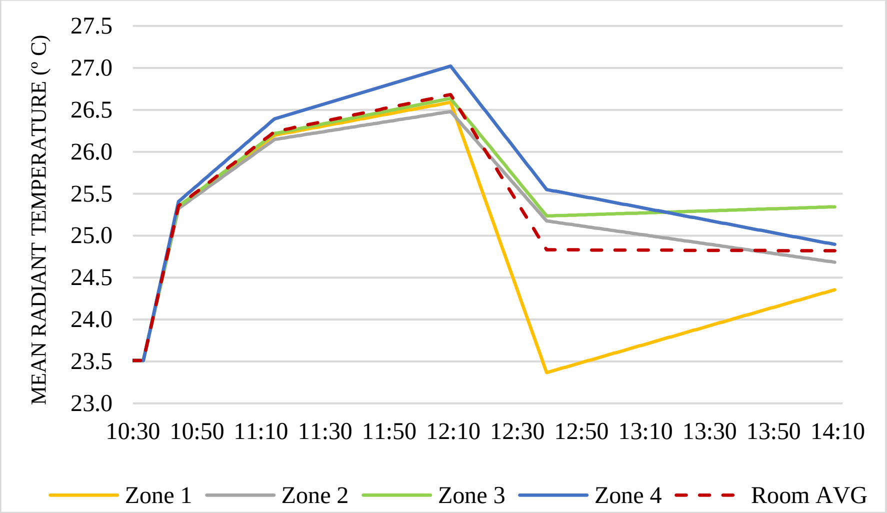

Figure 35 – Mean radiant temperature across the four zones during the event

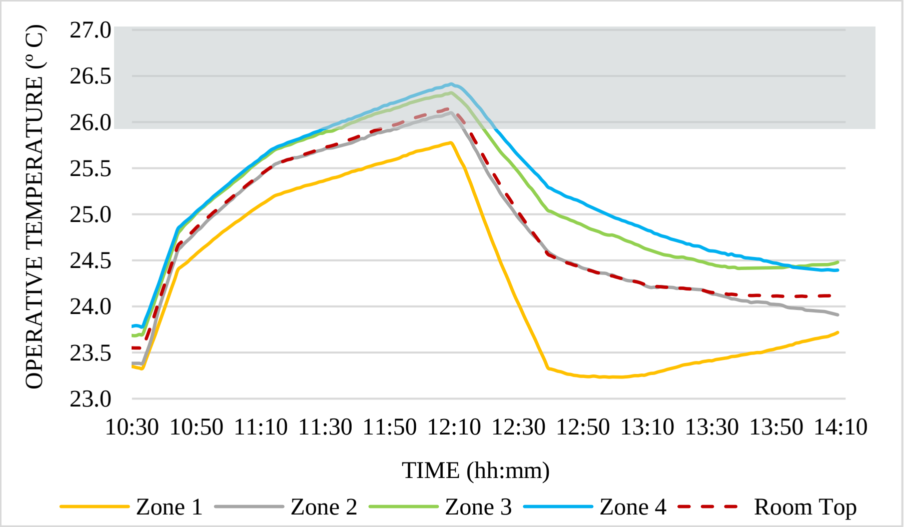

Figure 36 – Operative temperature in each zone during the event

As said before, for a clearer understanding of the demand flexibility event, Figure 37 shows how thermal comfort evolved during the event.

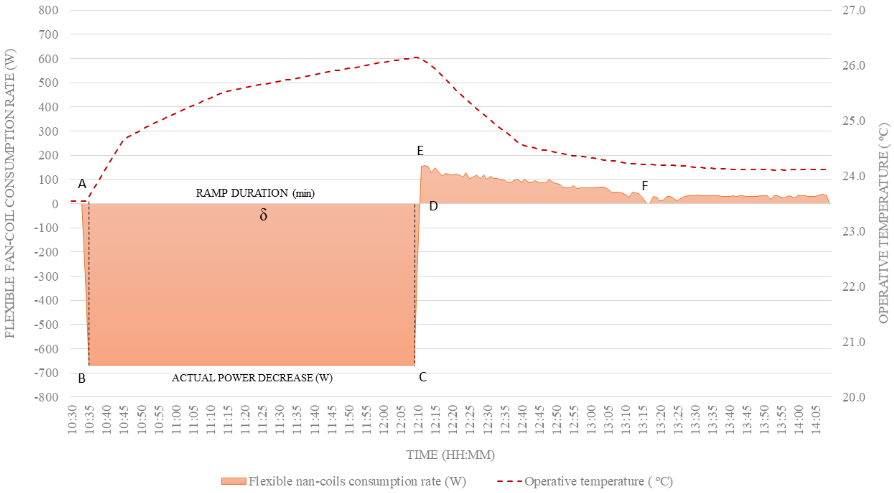

Figure 37 - Comparison between the consumption rate and the operative temperature during the DF event

Between both comfort variables, CO_2 concentrations and operative temperature, the latter proves to be the best characteristic to measure comfort. It, not only expresses the mean air temperature of the room, but also the effect of heat exchanged with the surrounding surfaces by an average between the mean radiant temperature and the mean air temperature. To better grasp, in future works, how comfort was affected, more sensors should be used, more surface temperature measurements should be made in more surfaces per zone, and a comfort questionnaire should be made to properly understand the users experience to this kind of events. Apart from this, globe thermometers could be used to measure the operative temperature with live screening of the values so that the event could be better managed by the BEMS and so the limits of thermal comfort would never be surpassed.

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6. Sixth Chapter – Comparing EnergyPlus Models with reality

6.1. Model design in Sketchup's Legacy open studio plugin

To create the model of the open space, twelve thermal zones were created for this space. One represented the open space itself and three the private office rooms that are inside the former. All with 3.05 m of height. Apart from these, each of these zones would have a plenum, with 0.5 m of height, on top of them and a raised floor, with 0.3 m of height, under each of them to simulate the thermal behavior happening inside these air spaces. After designing it with the Legacy open studio plugin, the windows were created with a metal frame surface around them. Then, unique names were set for each surface (wall, metal frames, floor and ceilings) and subsurface (windows), the type of surface was selected and the type of boundary condition was defined. Between all the types of surface conditions the ones used were: "adiabatic" when the thermal exchange of that surfaces was negligible; "outdoors" if the surfaces were connected with the outside, and so they were affected by solar radiation and wind; and "surface" if that surface was connected to another one. In this case, every surface that was connected to the inside of the building was considered adiabatic because its thermal behavior couldn't be assessed and so it had to be neglected. This meant it had to be assumed that both rooms were at the same temperature. Every surface of the façade, windows, metal frames and the exterior walls were assigned with the outdoors condition. Finally, the surface condition was used to connect the private office walls of their thermal zone to the corresponding surface of the open space thermal zone wall. This type of boundary condition was used as well in the floor of each of the four main rooms to the top surface of the raised floor thermal zone, the bottom part of these zone to the top part of the raised ceiling/plenum, and the bottom part of the plenum to the to the ceiling of that specific main thermal zone. Thus, a periodic relationship between those surfaces was created. This way, it's possible to mimic that e.g. the roof of the plenum is connected to the bottom part of the raised floor of another floor with the same characteristics of this one's raised floor bottom part. Instead of simulating the whole building, this solution only requires that a middle floor has to be designed, reducing the complexity of the design and assigning these relationships as they are. Furthermore, to mimic the influence, or in this case the non-influence, of the sun and wind in all surfaces where this is not a reality, shading groups (in purple in Figure 38) had to be designed. In the end, after the model is created, it has to be saved with an ".idf" extension, so that can be opened in the idf editor of energy plus.

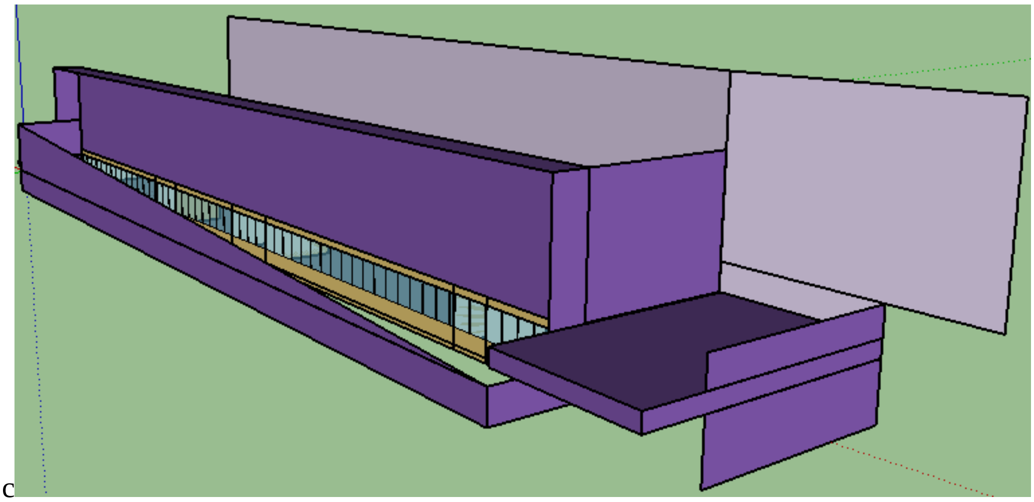

Figure 38 – Sketchup model of only the open space office with the shading groups

6.2. Simulation setup

After the design phase is complete, the idea is to set every specification of the system with the most detail possible in the energy plus idf editor, adding and editing every object of every component and option required in the intended simulation. A brief explanation of the simulation setup will be here described as it was implemented in this thesis. The simulation setup is divided in 7 groups of objects: the main simulation related options; the schedules used in the simulations; the different characteristics of each surface and how they help define the building model itself; the internal gains; the HVAC system detailed component description; and in the end, the outputs.

Starting from the beginning, the first step in a simulation setup is to understand what will be its goals. In the "Simulation control" object, the goal is to understand if the simulation requires pre-calculations regarding the cooling and heating load and flow rates for each zone (zone sizing), regarding these values for the whole system (system sizing) and for the plant maximum component flow rates (plant sizing). Because of the lack of detailed information about the whole HVAC system, some of these components had to be sized automatically, and so the sizing had to be selected. As the simulations had to be ran both in the sizing periods and in the weather file run periods, these options had to be selected as well. In order to test the simulation on similar conditions to the ones experienced in the office on the day of the event, a weather file (a ".txt" file) had to be created and used as input in the energy plus simulation. This file usually has hourly values for one year for different characteristics: outside air temperature, relative humidity, diffuse and direct radiation and wind speed and direction. In this case, the data was extracted only for the event day. As it was said before, the first two were obtained by an HOBO sensor, and the others were obtained by a weather station placed at a height of 10 meters in the outside of the city hall building. Then the building's orientation and some basic simulation options were filled, as well as the building location and the elevation of the weather station that was producing data to the weather file. Important as well was the definition of the sizing period and the run period, as well as the timestep at which the simulation would occur. The timestep used was of 60 timesteps per hour. This way, the results would be calculated for every minute.

On the next group, the schedules were defined. These schedules were used across the whole simulation setup and will be explained each at their time during this chapter. After it, the materials (as the ones presented on Table 18) that constitute the walls were defined as well as a set of characteristics from their thickness, thermal conductivity, density, specific heat, thermal absorptance, etc. The window materials were also defined, regarding the solar heat transmittance and reflectance, their visible and infrared transmittance and reflectance, their conductivity, emissivity and other characteristics. Some of those characteristics were also defined for the shading that was used, as well as its position regarding the window. The names and characteristics of most of these materials were used from a report made in an energy efficiency retrofit on the building [89]. After defining all the materials, the way they were constructed in each surface had to be filled in. Table 18 shows the construction details of each surface, including the order of which they are built. Then, every window surface was assigned with the corresponding materials and shading control schedule, according to what happened during the event. The internal mass of each room was also defined in accordance to the total surface area exposed to the air, and so able to absorb/emit heat from/to any other emitting source, such as people, equipment, lighting, etc.

After the model's physical structure was set, the thermal simulation inputs could now be defined. Starting with the internal gains related to the people inside, the maximum number of people in each room and an occupancy schedule (in fraction) were set as it happened during the event. This way, the software can multiply the occupancy fraction (in the schedule) to the maximum registered number of people (in this case it was 50), for each timestep. The sensible/latent heat split (radiant fraction field) was also defined as 0.5 and the activity level was established in 100 W, as it's recommended in [88] for standard seating and reading office activities. This means that the 50% of the 100W produced by people is set as a sensible load to the system. The CO_2 generation rate used was the value of 0.005 L/s, as it's an approximation for an adult person's generation rate at an office [92, 93]. Regarding the internal gains from lighting and equipment, a schedule file with values for every 10 minutes was uploaded as input, based on the data extracted from the power energy logger, as explained on the third chapter, upon the measurement setup description. These values were transformed into fractions of the total maximum power reached at the event by these sources (14.66 kW), and energy plus reproduced it to every timestep as it did for the people object, described right before. The radiant fraction was also set for 0.5 as the amount of radiant heat emitted to the zone by these loads. The fraction lost was set to 0.25 as it was the amount of energy that was lost and that didn't affect the energy balance. This 25% loss can be due to many aspects of either the lighting or the equipment, e.g. the heat that is transmitted to the skeleton metal frame that supports the lighting and to drop ceiling next to it.

On the next group of objects are the HVAC system and the infiltration through the surfaces. Starting from the latter, this was defined as 0.2 air changes per hour, always on. The HVAC system was finally defined as close as the implemented system in the building. First a thermostat was defined with a heating and a cooling schedules as it was set by the BEMS of the building. This way, for temperatures lower than the temperature value set in the heating schedule, the HVAC system would activate its heating system, and would heat the rooms until that minimum setpoint was achieved. The opposite would happen if the maximum temperature value for each timestep (set in the thermostat cooling schedule) would be over-crossed, activating the cooling system. These thermostat schedules were defined for a basic schedule along the run period, except for the day before and the day of the event. In these days, the heating setpoint was set to 18 ºC (under this value the heating system would turn on, until the setpoint was met). The cooling setpoint was set to 21 ºC for the previous day. For the event day, the cooling setpoint was scheduled for 23.5 ºC, until the start of the event at 10h35. As described before, the AHU uses a boiler to pre-heat the air and sends it through pipes to the drop ceiling of the specific zone. The boiler is also used to send hot water through a hot water loop that arriving at the fan-coils heats up the supply air coming from the AHU. The cooling load is provided by a similar system: a chiller type plant pre-cools the air that passes through the AHU, cooling also the water that travels to the fan-coils in chilled water loops. That pre-cooled air arrives at the fan-coils (as in the heating process) and are cooled down by becoming in contact with the cooling coils. Thus, all these components of the HVAC system were defined in the energy plus with their capacity being seized by the software with the sizing plant simulation control. When it comes to the fan-coils, more details had to be defined (apart from the standard values and settings). The supply air maximum flow rate was defined for 0.9882 m^3/s (90 % of the 1.098 m^3/s stated before). The outdoor air that would arrive to the AHU was set to 0.5 m^3/s. This air would then be mixed with extracted air from the open space, making the total of 0.9882 m^3/s. The system availability schedule that defines the periods at which the fan-coils are able to function, was set to be on from the start of the previous day until 10:35 of the day of the event, time at which the event started. They would only be available at 12:10 when the fan-coils were turned on again.

Depending on the analysis that would be made, the output variables are selected and extracted for the whole run period, with the user able to choose which frequency of results he/she wants, varying from one result per year, month, day, hour, or the timestep of the simulation. The thermal zone can also be selected, to focus the results into the zones being studied. In this case, as the private offices were not the point of this study, they were still drawn and simulated because of their importance to the system as a whole, but their results were not important. They were extracted in the beginning to see if everything was done accordantly to reality, but nothing more. And this is another reason for extracting any kind of outputs. Although some outputs are more important than others because of their relevance to the study of the event, others can be extracted to check if the simulations are being done properly and if all the assumptions are corrected. As extracting the temperatures of the inside window surfaces can give a hint on the level of solar gains being transmitted into the office, the availability schedule for the fan-coils can confirm if it's well programmed, and if they are making the expected impact on the indoors environment. Although the most significant outputs are the open office zone's relative humidity, mean radiant temperature, mean air temperature, CO_2 concentration, and operative temperature, the most central ones are the last three. As the idea was to validate the measured results, this simulation had to be programmed the most near to reality and the results had to mirror it.

Starting off with the mean air temperature, Figure 19, presents both the measured results in yellow and the simulation results in green. The blue line is the outside air temperature. The first noticeable aspect is the shape. Equation 17, describes how temperature increases in a room. As the simulation results are the theoretical version of this increase, the first part of the green line represents this equation. Despite that, the measurement's average still reproduces a close curve, both in the first part of the event and in the second part. With an average difference of 1.2 ºC in the first part and a difference of 1.3 ºC at the end of this part, at 12:10, the results are a bit far from what was measured. This can happen for two main reasons: errors in the simulation and errors in the measurement. Regarding the simulation, the temperature increase rate, although resulting a more theoretical curve has a more intensified increase. This can result on the b, the inverse of τ being higher than what really happened during the experiment. Because in the simulation, the gains and the cooling air flow are spread evenly throughout the space, it can derive in a more averaged response where the effect of the movement of users doesn't affect the results. Regarding the actual measurements, this can have a different outcome. Because the sensors were positioned one per zone, there are some errors that can happen: the sensors can be have a measuring defect, they are also measuring how the temperature (in this case) changes in a specific part of the zone and not an average of that zone, with occupation variations near the sensor, or even in the zone altering the measurement in a different way as in the simulation. Even the number of people changing in the simulation is the total for the whole space, when the number of people was documented per zone, and different zones had different sensors. The movement itself of people is never considered in the simulation, where in reality it produces extra heat in sometimes more than in others, closer or more far from the sensors making the it difficult for the sensor to capture what really happened. In the second part, of the even, the cooling air inflow seems to be close to the real one, as the curves are way more similar, having an average difference of 0.3 ºC, bringing the whole experiment difference average to 0.7 ºC.

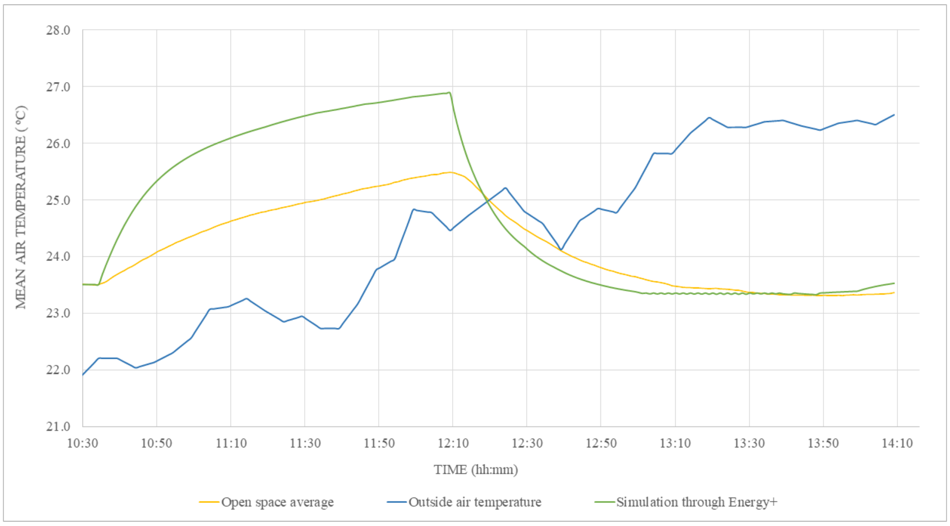

Figure 39 – Mean air temperature comparison: reality vs simulation

In the case of the operative temperature (Figure 40) both the measurements and the simulation are closer, validating the former. Although both temperatures don't start at the same value, the difference is just 0.1ºC, and that can be due to the cooling loads being different in the hours prior to the event. At the end of the first part the difference was of 0.2C, the bigger difference is of 0.7 ºC at 12:22 with and average difference of 0.2 ºC throughout the whole event.

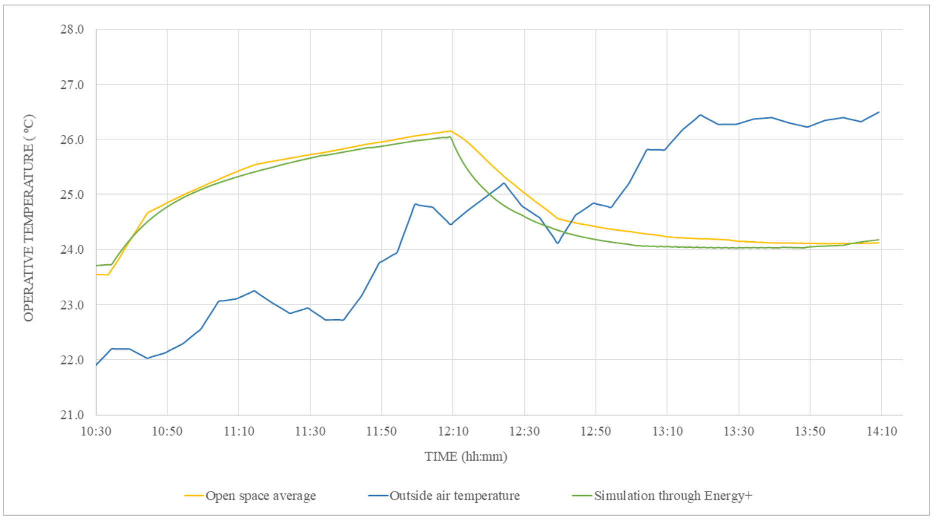

Figure 40 – Operative temperature comparison: reality vs simulation

When it comes to the CO_2 concentration, Figure 41 shows the moving average of 4 previous and forward values of the measured room average, because as it was described before and seen on Figure 26, the k33 sensor delivers a very turbulent set of results. Despite the similar curve, there are some variables that were not gathered during the experiment, making it hard to create a simulation of what happened, with results clear on the second part of the event. These two variables were the outdoor air rate that is used by the AHU and the infiltration rate. Despite this, as ventilation was turned off in the first part of the event, the increase in concentration is only dependent on the CO_2 generation rate. As it was documented before, the CO_2 generation rate was set to 0.005 L/s/person, and Figure 41 shows how close the generation rate was from reality. When those two variables detailed before are crucial for the CO_2 concentration, the results tend to disperse from reality. In the beginning, before the event starts, the concentration difference was only 45 ppm, and this difference was kept until the fan-coils were turned again, arriving with a difference of 67 ppm at 12:10. The dispersion occurs after this moment, when the fan-coils are turned on again and outdoor air is arriving to the space, renovating the inside air and lowering the CO_2 concentration to values similar to when the event started. The difference in the end of the event was also the maximum, arriving at a difference of 189 ppm. The uncertainty about how much outdoor air was brought in to the space, makes it hard to approximate these two curves, having nonetheless the same shape and a total average difference of 100 ppm.

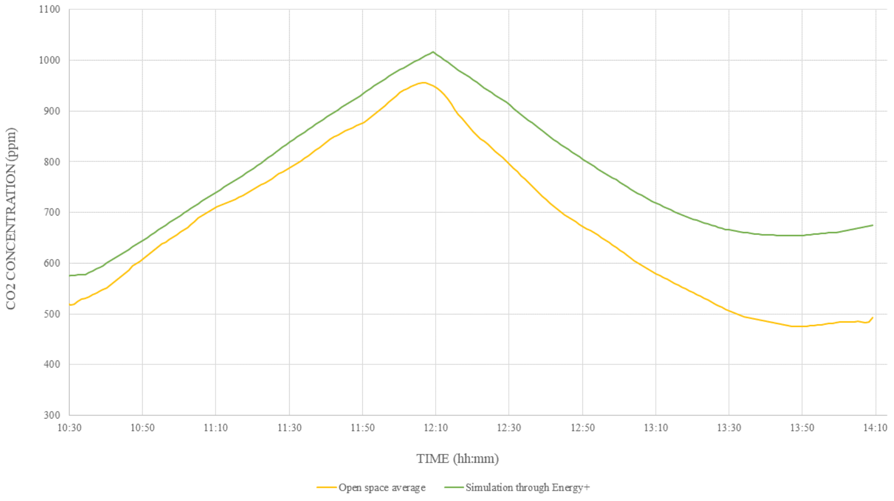

Figure 41 – CO_2 concentrations comparison: reality vs simulation

It can be concluded that the values obtained in the experiment are close to what theory explains, both in shape and in numerical values. Despite the lower number of sensors, their positioning, measuring device errors, and other uncontrollable variables that make real tests like this one, really difficult to be achieved, this experiment was a success. When a very complex subject as demand flexibility is studied only in theory, as it was in many of the studies presented in the state-of-the-art, many ever unproven assumptions have to be made. The problem with all these studies relies every time, on the impossibility to confirm if the real results would undoubtedly prove the veracity of these assumptions. Only in real case studies, as the one made in this thesis, bring true value to the understanding of such intricate theme. Very important as well is the validation of the last two plots: operative temperature and CO_2 concentration. Both, the most relevant ones in the characterization of comfort of the inside environment and a central piece for the validation of a demand flexibility event, were here confirmed by the simulation.

7. Seventh Chapter – Conclusion

This thesis starts by giving a general look to the current state of the electric power system, how it's currently operated, and the integration of variable and uncontrollable RES are forcing it to change. Buildings appear as the solution and an operation shift using them is explained through a new solution called demand flexibility. After defining demand flexibility and the concept of its events, its presentation is proposed as it was demonstrated through Figure 7. Then, the target buildings are selected. After analyzing each group of buildings some aspects were concluded: commercial buildings offer a better solution when it comes to demand flexibility. Inside commercial buildings offices and educational buildings are the ones that fill all requisites regarding a possible target for a DF event. Their high share of flexible power (HVAC systems). Their huge similarities between offices and educational buildings, and even between offices, and between educational buildings, are unique in the groups referred in the study. Finally, can be easily available towards managing their consumption in a way that the grid could take advantage of. To satisfy both sides (the building and the smart grid), these criteria are not the only ones, therefore comfort is a requirement that buildings cannot afford to lose. Because in a demand flexibility event, the building's purpose can never be disrupted, comfort plays a huge part on the planning and execution of these events. Turning the electric power grid into a smart grid and building into smart buildings with BEMS installed and able to be managed at any time must be a requirement for these events, as communications need to be faster between all parts that constitute the S&D sides. Although the HVAC systems are a huge source of consumption in a building, the aggregation between multiple buildings must happen in the future as well, to enable huge demand flexibilities to be accessible by the smart grid. After a review across many studies on demand flexibility, it was found that because its research and development is very recent, it has majorly been studied through mathematical and theoretical formulations. Few are the ones that contemplate building simulations, and even only two one found had practical experiments regarding these events. Based on that, the goal for this master thesis was to test how buildings would behave on a DF event, and how their flexibility would display in different scenarios. To really capture how flexible office buildings could be, two case studies were made.

From the first case study, it was concluded that some construction characteristics in buildings have a major impact on their ability to uphold an event. As the idea is to increase or decrease the energy consumption from an HVAC system, the time the building takes from its initial temperature to the comfort temperature upper or lower limit, plays a huge role on determining its flexibility. On the one hand, buildings with no insultation, take longer time to heat up and so can have higher ramp durations. On the other hand, buildings with layers of insulation achieve much higher temperatures in way more faster times. Although the DF units were not tested in this first case study, the recovery time in this event was almost the same for each case. This can be a promising effect to be studied in future works, as well as the effect of thermal inertia or the lack of it. Taking advantage of the different times to which surfaces take to heat up or cool down can have a significant effect on the buildings overall flexibility.

After understanding how to measure comfort and how to plan a DF event, the second case study resulted from the desire to assess the real demand flexibility from a real open space office, during working hours, with real people, and without compromising neither comfort nor the workability of workers in the space. In this event, two main sides were studied: the electric power grid side; and the users' comfort side. In the former, as the goal was to assess the different characteristic units of a demand flexibility, the fan-coils consumption was measured, and these units were achieved. Because there was no cooling consumption during the first part of the event, the chillers and the AHU that are directed to this space had a decrease in their consumption, and so the impact of the event was bigger than the one measured on the fan-coils. This is a fair assumption, and the extrapolation gave the missing piece to determine correctly this event's impact. On future times even though this units are not meant to be turned off during the event, their consumption must be measured and assessed its impact. Regarding the power ramp rates, results show that in approximately two minutes the buildings fan-coils were completely turned on and off, which shows how quick a response to a grid request would be, compared to other operational flexibility solutions. The ramp duration was of 90 min which gives the grid control over the S&D over longer periods. Even though the room’s ramp duration was long, this room was facing north, and so it had fewer solar gains. This value would’ve come down if the indoor space was affected by higher solar gains during the event, and so inside air temperature would’ve risen much faster. Regarding the recovery time, 58 minutes is still a long time, if the smart grid requires the buildings to recover faster and more times in a day. Despite this, the recovery time took less time than it would, if the HVAC system was programmed correctly. Because there was an extra consumption from the fan-coils when they were turned on, the decrease of temperature was faster than it should. This option of increasing the consumption in a small fraction to faster their recovery time should also be studied as a backup solution.

Regarding comfort, although its study could’ve been more complete with a PMV or a PPD estimation, thermal comfort was measured by the surface temperatures and the mean air temperature, which brought quite accurate results, as proven by the simulations. Comfort was mostly assured as the room’s average operative temperature didn’t cross further than 0.1 ºC of the comfort temperature upper limit. Regarding the CO_2 concentrations, their values were also below the 1100 ppm limit defined by the ASHRAE, indicating that although the ramp duration was of 94 min, odors and body smells would be hardly sensed by the occupants at the sitting level of 0.7 m. On the stratification measurements, temperature and CO_2 concentrations were higher as expected.

Because this topic is at a very young age, and still very wide, on the one hand, increases the difficulty in creating a solid concept, in testing a real DF event and in assessing its real impact, as this case studies are too specific. On the other hand, it brings many other solutions that need to be tested, to narrow the conclusions about this type of events. On future experiments, to fully capture the demand flexibility many other measurements must be done, including more sensors around the space, more surface temperature measurements, more stratification measurements, the correct use of globe thermometers to assess comfort etc. Further work must be done to perfectly plan out control settings, measurements tools and required initial conditions. Further work in this area, apart from assessing the demand flexibility of buildings in all types of climate conditions throughout the year, different scenarios of gains, occupation and flexible strategies must be studied. Apart from assessing the demand flexibility from the HVAC system, strategies combining natural illumination, automatic shading and continuous automatic dimming can be a promising way to extract flexibility from the lighting system. As one building doesn’t represent the sufficient help that the grid would needs, building’s aggregation strategies for demand flexibility events still require research and empirical tests.

Bibliography

[1] Iea, “The Way Forward - Five Key Actions to Achieve a Low - Carbon Energy Sector,” pp. 1–8, 2014.

[2] J. A. Dunne, S. C. Jackson, and J. Harte, *Encyclopedia of Biodiversity*. Elsevier, 2013.

[3] IPCC, “Climate Change 2014 Synthesis Report,” *Contrib. Work. Groups I, II III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, pp. 1–151, 2014.

[4] C. O. P. President and M. Pulgar-vidal, “COP21 Paris 2015,” *http://www.cop21paris.org/about/cop21*, 2015. .

[5] European Union, “Energy Policies of IEA Countries: Executive Summary: 2014 Review,” 2014.

[6] F. Eurostat, E. Union, and M. States, “Energy from renewable sources Main statistical findings,” *http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources*, 2015. .

[7] Ren 21, *Renewables 2014 Global Status Report*. 2014.

[8] L. Bird, M. Milligan, and D. Lew, “Integrating Variable Renewable Energy: Challenges and Solutions,” *Nrel/Tp-6a20-60451*, no. September, p. 14, 2013.

[9] H. C. Gils, Y. Scholz, T. Pregger, D. Luca de Tena, and D. Heide, “Integrated modelling of variable renewable energy-based power supply in Europe,” *Energy*, vol. 123, pp. 173–188, 2017.

[10] A. Ulbig and G. Andersson, “Analyzing Operational Flexibility of Electric Power Systems,” vol. 72, p. 10, 2014.

[11] F. F. Wu, K. Moslehi, and A. Bose, “Power System Control Centers: Past, Present, and Future.”

[12] D. Müller, A. Monti, S. Stinner, T. Schlösser, T. Schütz, P. Matthes, H. Wolisz, C. Molitor, H. Harb, and R. Streblow, “Demand side management for city districts,” *Build. Environ.*, vol. 91, pp. 283–293, 2015.

[13] L. Gelazanskas and K. a. a. Gamage, “Demand side management in smart grid: A review and proposals for future direction,” *Sustain. Cities Soc.*, vol. 11, pp. 22–30, 2014.

[14] Wartsila, “Combustion Engine vs Gas Turbine : Startup Time,” *http://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-ramp-rate*, 2015. .

[15] K. Asano and T. Kumano, “Dynamic economic load dispatch by calculus of variation considering ramp rate,” *2007 Int. Power Eng. Conf. (IPEC 2007)*, 2007.

[16] I. E. A. Clean, C. Centre, I. E. Agency, I. E. A. Clean, C. Centre, E. Commission, N. Zealand, S. Africa, I. E. A. Clean, C. Centre, C. Henderson, I. E. A. Clean, C. Centre, P. House, and N. L. Sw, “Increasing the flexibility of coal-fired power plants,” no. 12, pp. 12–14, 2014.

[17] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, “Review of energy system flexibility measures to enable high levels of variable renewable electricity,” *Renew. Sustain. Energy Rev.*, vol. 45, pp. 785–807, 2015.

[18] S. K. Mishra and S. K. Mishra, “A Comparative Study of Solution of Economic Load Dispatch Problem in Power Systems in the Environmental Perspective,” *Procedia Comput. Sci.*, vol. 48, no. Iccc, pp. 96–100, 2015.

[19] X. He, Y. Rao, and J. Huang, “A novel algorithm for economic load dispatch of power

systems," *Neurocomputing*, vol. 171, pp. 1454–1461, 2016.

[20] T. Zheng, J. Zhao, F. Zhao, and E. Litvinov, "Operational flexibility and system dispatch," *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–3, 2012.

[21] M. Economidou, B. Atanasiu, C. Despret, and J. Maio, *Europe's buildings under the microscope*. 2011.

[22] K. Smith and K. Managan, "EnErgy EfficiEncy and dEmand rEsponsE : Working togEthEr in an intEgratEd approach to managing EnErgy," no. february, p. 8, 2012.

[23] F. Boshell and O. P. Veloza, "Review of developed demand side management programs including different concepts and their results," *2008 IEEE/PES Transm. Distrib. Conf. Expo. Lat. Am. T D-LA*, pp. 1–7, 2008.

[24] Y. Lin, P. Barooah, and J. L. Mathieu, "Ancillary Services Through Demand Scheduling and Control of Commercial Buildings," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 186–197, 2017.

[25] Y. Lin, S. P. Meyn, and P. Barooah, "Commercial building HVAC system in power grid ancillary services."

[26] M. Maasoumy, J. Ortiz, D. Culler, and A. Sangiovanni-Vincentelli, "Flexibility of Commercial Building HVAC Fan as Ancillary Service for Smart Grid," *IEEE Green Energy Syst. Conf. (IGESC 2013)*, pp. 1–7, 2013.

[27] S. Koch, J. L. Mathieu, and D. S. Callaway, "Modeling and Control of Aggregated Heterogeneous Thermostatically Controlled Loads for Ancillary Services," *Proc. 17th Power Syst. Comput. Conf.*, 2011.

[28] H. Hao, A. Kowli, Y. Lin, P. Barooah, and S. Meyn, "Ancillary Service for the Grid via Control of Commercial Building HVAC Systems," 2013.

[29] P. Siano and D. Sarno, "Assessing the benefits of residential demand response in a real time distribution energy market," *Appl. Energy*, vol. 161, pp. 533–551, 2016.

[30] K. O. Aduda, T. Labeodan, W. Zeiler, and G. Boxem, "Demand side flexibility coordination in office buildings: A framework and case study application," *Sustain. Cities Soc.*, vol. 29, pp. 139–158, 2017.

[31] B. Davito, H. Tai, and R. Uhlaner, "The smart grid and the promise of demand-side management," *McKinsey Smart Grid*, pp. 38–44, 2010.

[32] N. Motegi, M. A. Piette, D. S. Watson, S. Kiliccote, and Peng Xu, "Introduction to Commercial Building Control Strategies and Techniques for Demand Response," no. 500, pp. 1–107, 2007.

[33] J. P. S. Paiva, *Redes de Energia Eléctrica: uma análise sistémica*, Third edit. IST Press, 2011.

[34] Cea, "The smart grid: a pragmatic approach," 2012.

[35] R. Kempener, P. Komor, and A. Hoke, "Smart Grids and Renewables - A Guide for Effective Deployment," no. November, p. 47, 2013.

[36] International Energy Agency, "Technology Roadmap - Smart Grids," *Current*, p. 52, 2011.

[37] M. Clark, "Aging US Power Grid Blacks Out More Than Any Other Developed Nation," *Int. Bus. Times*, 2014.

[38] U. S. DoE, "Buildings energy databook," *Energy Effic. Renew. Energy Dep.*, p. 286, 2011.

[39] L. Gynther, B. Lappillone, and K. Pollier, "Energy efficiency trends and policies in the household and tertiary sectors. An analysis based on the ODYSSEE and MURE databases," no. June, p. 97, 2015.

[40] P. Bertoldi, B. Hirl, and N. Labanca, *Energy Efficiency Status Report 2012*. 2012.

[41] A. . Fallis, *Fundamentals of HVAC Systems*, vol. 53, no. 9. 2013.

[42] E. O'Broin, "Energy Demands of European Buildings," p. 205, 2007.

[43] T. Llc, "U . S . Residential Miscellaneous Electric Loads Electricity Consumption," pp. 258–269, 2008.

[44] A. Kamilaris, B. Kalluri, S. Kondepudi, and T. K. Wai, "A literature survey on measuring energy usage for miscellaneous electric loads in of fi ces and commercial buildings," vol. 34, pp. 536–550, 2014.

[45] IPCC, "Buildings.In: Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," *Ipcc*, vol. 33, pp. 1–44, 2014.

[46] C. S. American and C. S. American, "The Geography of Poverty and Wealth - The Earth Institute," *Scientific American*, 2001.

[47] X. He, I. Azevedo, and L. Meeus, *Shift , not drift: Towards active demand response and beyond*. 2013.

[48] V. S. K. M. Balijepalli, V. Pradhan, S. A. Khaparde, and R. M. Shereef, "Review of demand response under smart grid paradigm," *2011 IEEE PES Int. Conf. Innov. Smart Grid Technol. ISGT India 2011*, pp. 236–243, 2011.

[49] EIA, "Commercial Buildings Energy Consumption Survey (CBECS)." [Online]. Available: http://www.eia.gov/consumption/commercial/data/2012/.

[50] B. T. Samad, E. Koch, and P. Stluka, "Automated Demand Response for Smart Buildings and Microgrids: The State of the Practice and Research Challenges," *Proc. IEEE*, vol. 104, no. 4, pp. 726–744, 2016.

[51] M. B. Bulut, M. Odlare, P. Stigson, F. Wallin, and I. Vassileva, "Active buildings in smart grids - Exploring the views of the Swedish energy and buildings sectors," *Energy Build.*, vol. 117, pp. 185–198, 2016.

[52] L. A. Hurtado, J. D. Rhodes, P. H. Nguyen, I. G. Kamphuis, and M. E. Webber, "Quantifying demand flexibility based on structural thermal storage and comfort management of non-residential buildings : A comparison between hot and cold climate zones," 2016.

[53] CENELEC, "SG-CG / M490 / L Flexibility Management Overview of the main concepts of flexibility management," pp. 1–36, 2014.

[54] F. Tahersima, P. P. Madsen, and P. Andersen, "An intuitive definition of demand flexibility in direct load control," *Proc. IEEE Int. Conf. Control Appl.*, pp. 521–526, 2013.

[55] A. Ulbig and G. Andersson, "On operational flexibility in power systems," *IEEE Power Energy Soc. Gen. Meet.*, 2012.

[56] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy Build.*, vol. 40, pp. 394–398, 2008.

[57] IEA, "Technology Roadmap Energy-efficient Buildings: Heating and Cooling Equipment," 2011.

[58] M. Maasoumy, C. Rosenberg, A. Sangiovanni-Vincentelli, and D. S. Callaway, "Model predictive control approach to online computation of demand-side flexibility of commercial buildings HVAC systems for Supply Following," *Proc. Am. Control Conf.*, pp. 1082–1089, 2014.

[59] D. Westphalen, S. Koszalinski, and A. D. Little, *Energy Consumption Characteristics of Commercial Building HVAC Systems Volume I : Chillers , Refrigerant Compressors , and Heating Systems And*, vol. I, no. April. 2001.

[60] “Heating and Cooling With a Heat Pump,” 2004.

[61] C. Spataru and S. Gauthier, “How to monitor people ‘smartly’ to help reducing energy consumption in buildings?,” *Archit. Eng. Des. Manag.*, vol. 10, no. 1–2, pp. 60–78, 2014.

[62] H. E. Design, “Lighting, HVAC, and Plumbing,” *Los Alamos Natl. Lab. Sustain. Des. Guid.*

[63] M. Mysen, J. P. Rydock, and P. O. Tjelflaat, “Demand controlled ventilation for office cubicles—can it be profitable?,” *Energy Build.*, vol. 35, no. 7, pp. 657–662, 2003.

[64] A. G. A. Silva, “PROJECTO DE LICENCIAMENTO - INSTALAÇÕES DE AVAC.”

[65] W. Paper, “Smart Grid Transforming the Electricity System to Meet Future Demand and Reduce Greenhouse Gas Emissions,” no. November, 2008.

[66] P. Bertoldi and B. Atanasiu, *Electricity consumption and efficiency trends in the enlarged European Union - Status Report 2009*. 2009.

[67] C. Duarte, V. Den Wymelenberg, B. Acker, B. Acker, C. Duarte, and B. J. Mcwinn, “Office building plug load profiles,” pp. 1–54, 2012.

[68] I. Statistics, “Analysis and Representation of Miscellaneous Electric Loads in NEMS,” no. December, 2013.

[69] O. Mure, “Energy Efficiency Buildings in the EU Trends in Lessons from the ODYSSEE MURE project,” no. September, 2012.

[70] Y. Agarwal and T. Weng, “The Energy Dashboard : Improving the Visibility of Energy Consumption at a Campus-Wide Scale.”

[71] V. Giordano, F. Gangale, G. F. Jrc-ie, M. Sánchez, J. Dg, I. Onyeji, A. Colta, I. Papaioannou, A. Mengolini, C. Alecu, T. Ojala, and I. Maschio, *Smart Grid projects in Europe : lessons learned and current developments*, vol. 2011. 2011.

[72] M. De Groote and O. Rapf, “The active role of buildings in a transforming energy market Discussion paper,” p. 20, 2015.

[73] F. P. Incropera, *Fundamentals of heat and mass transfer*, 7th ed. 2011.

[74] H. S. L. C. Hens, *1. Building Physics: Heat, Air and Moisture*. 2007.

[75] S. Liaison, F. E. Jakob, W. A. Dunn, G. S. Brager, K. A. Brown, D. R. Clark, J. J. Deringer, J. J. Hogeling, D. Int-hout, B. W. Jones, J. N. Knapp, A. G. Kwok, H. Levin, A. K. Melikov, P. Simmonds, J. M. Sipes, E. M. Sterling, and B. P. Sun, “ASHRAE STANDARD Thermal Environmental Conditions for Human Occupancy,” vol. 2004, 2004.

[76] W. Olesen, “Thermal comfort,” pp. 3–43.

[77] P. E. Michael J. Brandemuehl, Ph.D., “Predicting Thermal Comfort,” *http://ceae.colorado.edu/~brandem/aren3050/docs/ThermalComfort.pdf*, 2005. .

[78] *EN ISO 7730*. 2007.

[79] Robert Bean, “Mean Radiant Temperature | Indoor Environmental Quality with Energy Efficiency,” *Copyright (c) 2010, Robert Bean, R.E.T., P.L.(Eng.) and www.healthyheating.com*, 2010. [Online]. Available: http://www.healthyheating.com/Definitions/MeanRadiant.htm#.WZhGKSiGPIV. [Accessed: 23-Aug-2017].

[80] M. Kazkaz and M. Pavelek, “OPERATIVE TEMPERATURE,” vol. 20, no. 3, pp. 319–325, 2013.

[81] Robert Bean, “Operative Temperature | Indoor Environmental Quality with Energy Efficiency,” *Copyright (c) 2012, Robert Bean, R.E.T., P.L.(Eng.) and www.healthyheating.com*, 2012. [Online]. Available: http://www.healthyheating.com/Definitions/Operative-temperature.htm#.WZ2B3CiGMdU. [Accessed: 23-Aug-2017].

[82] S. Petty, “Summary of Ashrae’S Position on Carbon Dioxide Co2 Levels in Spaces,” *Refrig. Air Cond.*, p. 6, 2002.

[83] Q. What, N. Hcfc, M. Protocol, U. States, M. Protocol, S. European, M. Protocol, T. Protocol, and T. L. Answer, “ASHRAE Technical FAQ,” pp. 0–2, 2016.

[84] Northern Arizona University, “Thermal Comfort (Relative Humidity (RH) and Air Temperature),” 2013.

[85] P. Wolkoff and S. K. Kjærgaard, “The dichotomy of relative humidity on indoor air quality,” *Environ. Int.*, vol. 33, no. 6, pp. 850–857, 2007.

[86] W. Energyplus, R. Energyplus, B. Envelope, and I. Loads, “Getting Started with EnergyPlus - Basic Concepts Manual,” pp. 1–49.

[87] W. Energyplus, R. Energyplus, B. Envelope, and I. Loads, *Engineering Reference - The Reference to EnergyPlus Calculations*. .

[88] W. Energyplus, R. Energyplus, B. Envelope, and I. Loads, “Input Output Reference - The Encyclopedic Reference to EnergyPlus Input and Output,” pp. 1–1577.

[89] N. Le and A. N. Assimec, “Optimização Energética e Verificação de RSECE (D . L . 79 / 2006) Fase I do processo de Certificação Energética,” 2006.

[90] *CIBSE Concise Handbook*. .

[91] T. Steen, “Natural Ventilation Driven by Wind and Temperature Difference,” 2006.

[92] S. Emmerich and A. Persily, “State-of-the-art review of CO2 demand controlled ventilation technology and application,” *Natl. Inst. Stand. Technol.*, no. NISTIR 6729, 2001.

[93] X. Lu, T. Lu, and M. Viljanen, “Estimation of Space Air Change Rates and CO2 Generation Rates for Mechanically-Ventilated Buildings,” *Adv. Comput. Sci. Eng.*, pp. 237–260, 2011.

[94] K. O. Aduda, T. Labeodan, W. Zeiler, G. Boxem, and Y. Zhao, “Demand side flexibility: Potentials and building performance implications,” *Sustain. Cities Soc.*, vol. 22, pp. 146–163, 2016.

[95] X. Xue, S. Wang, C. Yan, and B. Cui, “A fast chiller power demand response control strategy for buildings connected to smart grid,” *Appl. Energy*, vol. 137, pp. 77–87, 2015.

[96] F. Zhang and R. De Dear, “Thermal environments and thermal comfort impacts of Direct Load Control air-conditioning strategies in university lecture theatres,” *Energy Build.*, vol. 86, pp. 233–242, 2015.

[97] J. Le Dréau and P. Heiselberg, “Energy flexibility of residential buildings using short term heat storage in the thermal mass,” *Energy*, vol. 111, pp. 991–1002, 2016.

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Annex

Surface name	SR_South_A	SR_South_C	SR_South_D	SR_South_E	SR_South_G
Outside layer	Tiles (11 cm)	Metal (3.5 cm)	HardConcrete (48.5 cm)	Glass (5 cm)	EPS (1 cm)
Layer 2	Concrete (17 cm)	-	-	-	EPS (1 cm)
U-value (W/m^2.K)	2.533	6.671	2.51	5.816	1.479

Surface name	SR_West_Wall	SR_East_Wall	SR_North_Wall	SR_Ceiling	SR_Floor
Outside layer	Tiles (11 cm)	XPS (10 cm)	Wood (4 cm)	HardConcrete (18.5 cm)	HardConcrete (18.5 cm)
Layer 2	-	XPS (10 cm)	Air space resistance	-	-
Layer 3	-	Gypsum board (2 cm)	Tiles (11 cm)	-	-
U-value (W/m^2.K)	3.659	0.175	1.389	4.306	3.486

Table 15 – Surface names, materials in the constructions, for the Small Room (SR)

Surface name	BR_South_A	BR_South_B	BR_South_C	BR_South_D	BR_South_E	BR_South_G
Outside layer	Tiles (11 cm)	Marine Plywood (2.5 cm)	Metal (3.5 cm)	HardConcrete 51.5cm	Glass 5mm	Marine Plywood (1.5 cm)
Layer 2	Concrete (17 cm)	-	-	XPS (10 cm)	Air Gap Double Glazing (2 cm)	-
Layer 3	XPS (10 cm)	-	-	-	Glass (5mm)	-
U-value (W/m^2.K)	0.315	2.898	6.671	0.313	2.717	3.64

Surface name	BR_East_Wall	BR_North_Wall	BR_Ceiling	BR_Floor	SR_BR_Door	BR_West_Wall
Outside layer	HardConcrete (18 cm)	Wood (4 cm)	HardConcrete (18.5 cm)	HardConcrete (18.5 cm)	Wood (3.5 cm)	Gypsum board (2 cm)
Layer 2	XPS (10 cm)	Air space resistance	XPS (10 cm)	XPS (10 cm)	-	XPS (10 cm)
Layer 3	-	Tiles (11 cm)	XPS (10 cm)	XPS (10 cm)	-	XPS (10 cm)
Layer 4	-	XPS (10 cm)	-	-	-	-
U-value (W/m^2.K)	0.313	0.286	0.173	0.171	4.286	0.175

Table 16 – Surface names, materials in the constructions, for the Small Room (BR)

	Small Room (SR)	Big Room (BR)
Name of surface	SR_West_Wall	BR_East_Wall
U-values (W/m^2.K)	3.659	0.313
Name of surface	SR_Roof	BR_Roof
U-values (W/m^2.K)	4.306	0.173
Name of surface	SR_Floor	BR_Floor
U-values (W/m^2.K)	3.486	0.171
Name of surface	SR_East_Wall	BR_West_Wall
U-values (W/m^2.K)	0.175	0.175
Name of surface	SR_North_Wall	BR_North_Wall
U-values (W/m^2.K)	1.389	0.286
Name of surface	SR_South_E	BR_South_E
U-values (W/m^2.K)	5.816	2.717

Table 17 – Comparison of opposite surfaces' U-values

Surface Name	Interior Floor/Ceiling	Exterior Wall	Interior Wall	Raised Floor	Drop Ceiling	Exterior Window	Metal frames
Outside layer	Concrete (25 cm)	Plaster (1 cm)	Plaster (1.5 cm)	Wooden Flooring (0.1 cm)	Gypsum board (1 cm)	Planillux pane (0.6 cm)	Metal (5 cm)
Layer 2	-	EPS (4 cm)	Brick (11 cm)	-	-	Air-gap (1.2 cm)	-
Layer 3	-	Brick (11 cm)	Plaster (1.5 cm)	-	-	STADIP 44.1 pane (0.6 cm)	-
Layer 4	-	Air-gap (10 cm)	-	-	-	-	-
Layer 5	-	Brick (15 cm)	-	-	-	-	-
Layer 6	-	Gypsum board (1 cm)	-	-	-	-	-

Table 18 – Surface names and materials in the construction of the open space

Bibliography	Type of building	Type of construction	Type of case study	Units		
				Power capacity	*Ramp rate duration*	*Recovery duration*
[94]	Office	-	Real case study	7 kW	Up to 20 min	20 to 40 min
				3.6 kW	135 min	30 min
[95]	Office	-	Simulation	32-66% of HVAC system normal operation	Up to 60 min	30 min
[96]	University	Good insulation	Simulation	67% off cycle fraction	60 min	
		Poor insulation		33% off cycle fraction	30 min	
[97]	Residential	Good insulation	Simulation	100% off the heating system	24 h	
		Poor insulation		Up to $25kWh/m^2year$	2 to 5 h	
[52]	Offices	Good insulation	Simulation	26 to 44 kW	72 to 80 min	54 to 72 min
		Poor insulation		45 to 88 kW	56 to 68 min	57 to 86 min

Table 19 – State-of-the-art regarding demand flexibility events

Building type	Use	Density of occupation/ person m^2	Sensible heat gain $/W.m^{-2}$			Latent heat gain/ $W.m^{-2}$	
			People	Lighting	Equipment	People	Other
Offices	General	12	6.7	8-12	15	5	-
		16	5	8-12	12	4	-
	City center	6	13.5	8-12	25	10	-
		10	8	8-12	18	6	-
	Trading/dealing	5	16	12-15	40 +	12	-
	Call center floor	5	16	8-12	60	12	-
	Meeting/ conference	3	27	10-20	5	20	-
	IT rack rooms	0	0	8-12	200	0	-

Table 20 – Table A6.2 Benchmark allowances for internal gains in typical buildings, from [90]