Department of Mechanical and Aerospace Engineering

Project

Title: Energy performance and deep retrofit of UK office buildings – A screening study and detailed dynamic simulation

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Copyright Declaration

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Signed: Antonios Lemonias Date: 25/08/2017

Abstract

Nowadays, the extended use and combustion of fossil fuels release large amounts of carbon dioxide into the atmosphere which leads to climate changes and environmental pollution. In Europe, there are implemented many policies which aim to achieve a sustainable and low carbon economy by 2020.

The building sector accounts for around 40% of the total primary energy consumption and around 30% of the total carbon dioxide emissions. Commercial buildings account for around one fourth of the total European building stock. Typically, they are high energy consuming buildings and usually their energy performance is lower than the expected one. For these reasons, promoting and applying energy efficiency measures can lead to reduction of the total energy consumption as well as of the greenhouse gas emissions.

This study focuses on analysing the energy performance of a UK office building, exploring the energy performing gap and then investigating different design options to reduce the total energy consumption and minimize the carbon dioxide emissions. Firstly, an analysis is performed to investigate if there is a discrepancy between the actual energy performance of the office and the expected one. The second part of the study focuses on dynamic simulation tools and how they can be proved beneficial regarding the energy performance analysis of buildings. By using ESP-r, a simulation modelling tool developed by University of Strathclyde, a model of a typical office of James Weir Building is built and verified. Various retrofitting options to the thermal envelope, to the heating systems and the ventilation systems of the modelled office are examined and the results are collected and presented. One main part of the analysis refers to the implementation of retrofitting options to achieve the Passive House Standard. All the requirements are fulfilled and results about the heating energy performance and the carbon emissions are gathered.

To conclude, there is a significant discrepancy between the actual and the predicted energy performance of the building which is attributed to a variety of reasons. Therefore, the use of dynamic simulation tools in the design stage of a building can close this gap and lead to more real and accurate energy performance estimates because more detailed parameters are being considered. Furthermore, the different retrofitting options contribute to the reduction of both the energy consumption and the

carbon dioxide emissions compared to the current situation. It was found that lower heating energy consumption does not always mean lower carbon dioxide emissions as it depends on the type of the heating system (natural gas boiler, air to air and air to water heat pumps, biomass wood pellet boiler were examined). Moreover, improving the energy performance of the modelled office resulted in overheating problems which had to be tackled. Lastly, the limitations and conclusions of the project are presented and further work suggestions are provided in order to improve the performed analysis.

Acknowledgements

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1. Introduction

1.1 Motivation

Nowadays, there is the necessity to upgrade Europe into a low-carbon economy in order to reduce the greenhouse gas emissions and to improve the energy supply security. There is no doubt that our planet is facing serious problems regarding atmospheric pollution, water and soil contamination. Increased levels of carbon dioxide are believed that result in climate changes (Ahmed, et al., 2017). Greenhouse gases from human activities are increasing and are one of the most significant drivers of climate change. Worldwide, the energy demand is expected to expand by around 45% until 2030, and it is going to be tripled in comparison with the current energy demand by the end of the century. The depletion of fossil fuels and the rising need of generating clean, secure and sustainable energy tend to be one of the main and important concerns for the European countries. In order to tackle the excessive energy consumption worldwide and limit the effects that are already presented, these countries try to develop and implement saving strategies through international agreements with the most recent to be the Paris agreement in 2015. This global agreement aims not only to lower the greenhouse gas (GHG) emissions but also to follow a way towards developing low-carbon economies by minimizing or even diminishing the consumption of fossil fuels which constitute the main source of energy during the last two centuries.

The Europe 2020 strategy focuses on three main targets. The first one is the expected reduction of the energy consumption by 20% until 2020 which equals to a saving of 390 million tonnes of oil equivalent (toes) which will have as a result vast economic and environmental benefits for the European Union. The second one aims to the reduction of the greenhouse gas emissions (GHG) by 20% in conjuction with the levels of CO_2 in 1990 and the third one is the increase by 20% of the generated energy coming from renewable energy sources (European Commission – Eurostat).

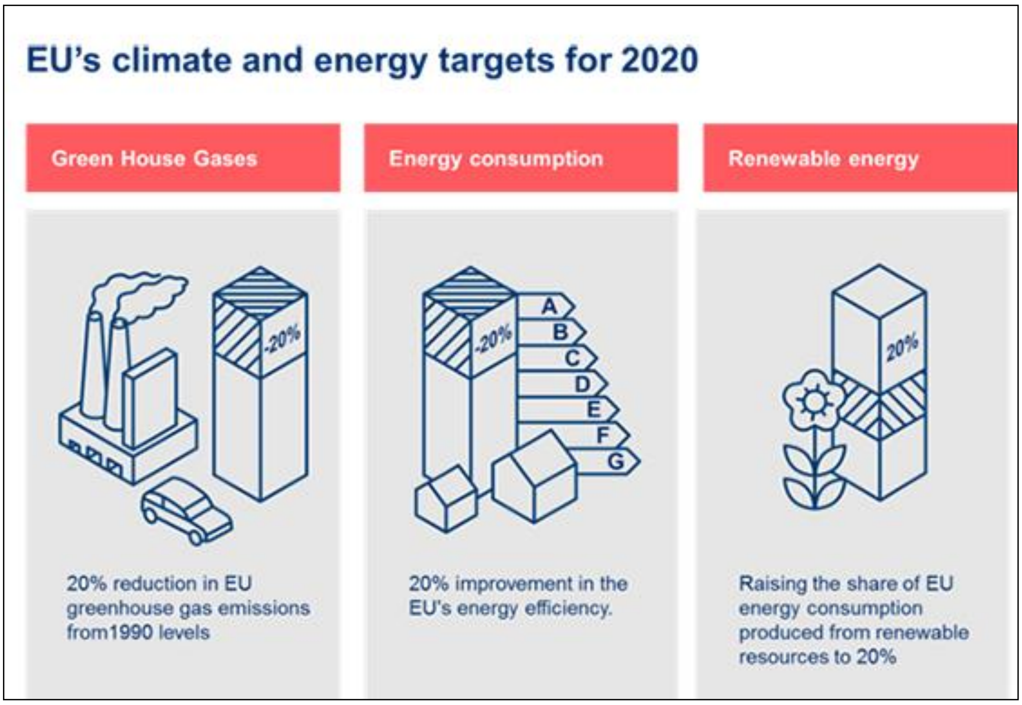

Figure 1. EU's climate and energy targets for 2020 (Caverion Corporation 2017)

Therefore, there is no doubt that the EU countries are moving towards a more sustainable future less dependent on fossil fuels.

Based on the Energy Performance of Buildings Directive (Directive 2010/31/EU) and the Energy Efficiency Directive (Directive 2012/27/EU), the greatest energy saving potential can be achieved in buildings (Zavadskas, et al., 2017). The building sector in Europe accounts for around 40% of the primary energy consumption and around one third (36%) of the greenhouse gas emissions.

The energy consumption in commercial buildings was increased during the last decade. Therefore, adopting energy efficiency measures and as an extend implementing renewable energy sources (RES) to achieve generating clean and sustainable energy, is the key element that can accelerate the transition towards a new low-carbon era.

1.2 Aim & Approach

Aim

The aim of this project is to assess the current situation of a UK office building in terms of energy performance and CO_2 emissions and investigate the implementation of various retrofit options to improve the energy efficiency, mitigate the CO_2 emissions and assess the feasibility towards achieving the UK targets. As a case study one typical office of the 8th floor of the James Weir Building was selected and the analysis was performed by using the ESP-r simulation tool.

Approach

In order to achieve the aim the following methodological steps should be completed:

1. **Literature Review – Part 1: Energy and Buildings**

Firstly, a summary of the energy use in buildings is presented in terms of energy consumption and carbon dioxide emissions and the situation in the UK is explained. A comparison also is performed between the reconstruction and the retrofitting of buildings and the need of adopting retrofitting strategies to the existing buildings is emphasized. Moreover, information regarding the energy consumption in the office and educational sector is presented and the main characteristics are demonstrated.

2. **Literature Review – Part 2: Energy Legislation and Standards**

In this section, a summary of the main principles and characteristics of the UK Legislation and targets regarding the buildings' energy consumption and energy efficiency are explained. Weight is given on key laws such as the Energy Performance of Buildings Directive (EPBD), the Energy Efficiency Directive and the UK's Building Regulations Part L.

3. **Literature Review – Part 3: Sustainability and "green" building rating systems**

In the third part of the literature review, the importance of achieving sustainability is indicated. Furthermore, the most established and important "Green" building practices that are coming into force in order to support and promote the implementation of high energy performance in buildings and in some cases achieve net zero energy buildings are discussed. Briefly, the main concepts and standards that are promoted are: Net Zero Energy Buildings, Passive House Standard, LEED, BREEAM, Green Star, NABERS.

4. Performance Gap: Literature Review & Case Study Analysis

In this chapter, the difference between the actual and the expected energy consumption in buildings is questioned. Briefly, this is called the Performance Gap. After presenting the main information regarding this topic, an analysis is performed by selecting as a case study the James Weir Building which belongs to University of Strathclyde. Finally, the results are discussed.

5. Dynamic simulation tools for building energy design

Here, information considering the importance of using dynamic simulation software is given. Moreover, investigation of the various software tools that are used in building simulation is completed and the reasons that ESP-r was selected are explained.

6. Model construction and description

Afterwards, a model of a typical office of the James Weir Building is created by using ESP-r. All the parameters regarding the location and climate, the geometry and its characteristics, the construction materials, the heating/ cooling systems, the ventilation systems and the casual gains are in depth investigated and explained.

7. Validation of the model

After having constructed the model for the analysis, the next step is to validate that the model operates according to the real office. Simulations are run and a variety of parameters are tested and examined. Lastly, the model’s heating energy consumption is calculated and a comparison between the actual and the model’s heating energy consumption is performed and the results are presented.

8. Parametric analysis of the retrofit options

In this part, the main analysis of the study is executed. The aim is to investigate the implementation of different retrofitting options to the model in order to check how the energy performance is affected. The retrofitting options refer to the following:

(1) Building thermal envelope
(2) Heating/ cooling systems
(3) Ventilation equipment
(4) Lighting equipment

Moreover, retrofitting options which can lead to the Passive House Certification are also considered.

9. Results analysis

A separate chapter refers to the results. After having completed the analysis, all the acquired results are extensively presented and the first conclusions are collected. Emphasis is given to the combination of retrofitting options that lead to achieving the Passive House Standard.

10. Discussion

In this section, all the results are widely discussed and the arising conclusions are stated.

11. Limitations

Like every project, there are some limitations that affect the final results. Here, the important parameters and assumptions of this project are indicated. In this way, a further work analysis can be performed with better precision.

12. Future work

Further work can arise after the completion of this project. The main ideas that can lead to further and more accurate analysis are explained.

13. Conclusions

In the last chapter of this project there is a summary of the main conclusions.

2. Literature Review: Part 1 – Energy and Buildings

2.1 Energy use in buildings

Nowadays, a large amount of energy is consumed in the building sector. Worldwide, this is one of the larger if not the largest energy consuming sectors, as most people spend almost 90% of their daily lives indoors. In the EU, the energy use of the 160 million buildings accounts for around 40% of the total primary energy consumption (Cao, et al., 2016). Hence, the energy used in buildings is one of the main factors that contribute to the emissions of carbon dioxide. Currently, about 35% of the EU's buildings are over 50 years old. By improving the energy efficiency of buildings, we could reduce the total EU energy consumption by 5-6% and lower CO_2 emissions by about 5%.

In the UK, the energy consumed in building services is estimated around 45 % of the national primary energy consumption which is mainly based on fossil fuel use and according to the UK Government, in 2016, both the domestic and services sector account for more than 40% of the total final energy consumption. As a result they are responsible for around one third of the CO_2 emissions (Martínez A., 2014). In the UK specifically, the operation and construction of buildings have a significant impact to half of UK's carbon emissions with 1.5% increase trend every year (Azzouz, et al., 2017); (Lou, et al., 2017). Bearing in mind that almost 87% of the already constructed buildings in the UK will be standing in 2050 (UK GBC, 2016), huge emphasis of construction projects in the future will be given for retrofitting and refurbishment of the existing buildings. The Chartered Institute of Building has informed that in the UK there are about 30 million domestic and non-domestic buildings, 28 million of which are going to be subject to be retrofitted or refurbished in order the UK Government to achieve the carbon emissions targets (CIOB, 2011); (Lou, et al., 2017).

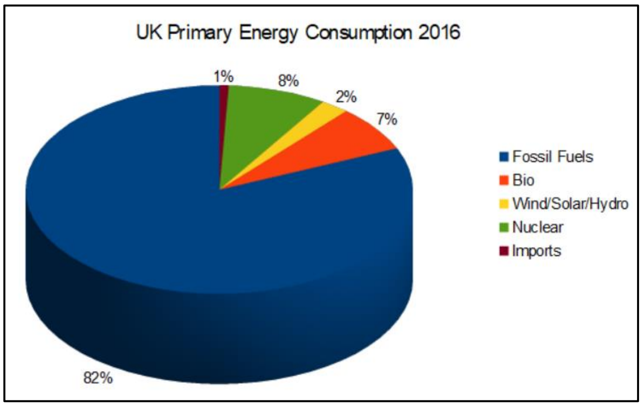

Figure 2. Primary energy consumption for the UK in 2016. Source: Department for Business, Energy & Industrial Strategy: Energy Trends March 2017

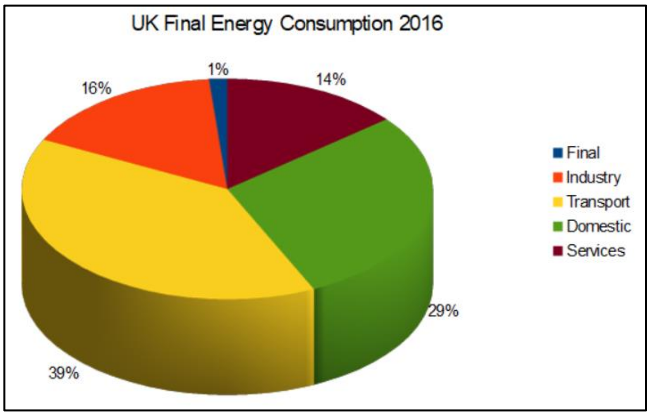

Figure 3. Final energy consumption for the UK in 2016. Source: Department for Business, Energy & Industrial Strategy: Energy Trends March 2017

In the services sector, the largest energy consuming parts are space heating and cooling followed by appliances, IT and other equipment, and lighting.

There is a variety of commercial buildings and each one of them has its own characteristics.

2.2 Demolition and reconstruction vs retrofitting of buildings

One main question is whether is it better to endorse the retrofitting of the existing old and inefficient buildings from a sustainable point of view or to promote the demolition and reconstruction of new ones with better design options to address the current energy situation. The answer to this question is complicated and it has to do with balance between the operational costs and the embodied energy costs of the building (Boardman, 2007). Embodied energy is the energy which is used for the construction of a building including the energy needed for maintenance reasons over a defined period of time. Operational energy is the energy used for the everyday needs of the building. In line with research and a number of studies it was revealed that in many cases it takes around 50 years in order a new well-insulated building with less operational energy requirements to balance the embodied costs. Although more work has to be carried out to examine in this field, the dominant belief is that retrofitting and refurbishment is often more environmentally friendly due to the fact that there is preservation of materials and reduction of the transport processes. (Paula Judson, 2010); (Empty Homes Agency); (Frits Meijer, 2009); (Lowe, 2010). Unquestionably, the role of the existing buildings with regards to energy consumption and carbon dioxide emissions is crucial and following a retrofit and refurbishment strategy can lead among others to environmental sustainability (Pacheco-Torgal, 2017).

2.3 Why is energy efficiency evident in buildings?

The conservation of energy and the rational use of it constitute a primary measure for the protection of the environment. There are significant factors that contribute to the energy problem that our societies face. Firstly, the continuous raise of the population results in a higher energy demand. Moreover, humans spend most of their time in indoor environments (buildings) and along with the improvement of their living conditions they use more and more energy consuming devices for the coverage of the basic needs. Another main reason is the degradation of the fossil fuels which until today are the main sources of heat plus electricity generation. Furthermore, other factors that should be considered are the losses during the generation and transportation of the final phase of energy as well as the limited use of renewable energy systems until recently.

Nowadays, there is no doubt that due to all the above reasons Governments need to take action. The use of renewable energy technologies ensures tackling the phenomenon of climate change as there are no greenhouse gas emissions and can increase the national energy supply security which means “the uninterrupted availability of energy sources at an affordable price” (International Energy Agency, 2017). However, the energy coming from renewable energy sources is not unlimited, is stochastic, intermittent and is not available in the same extent in every location. Especially in the cities, the performance of the solar and wind energy systems can be affected by obstacles usually other high buildings from the surrounding area. Another source of energy which can be also considered as renewable under specific conditions is biomass but it cannot be applied in a huge scale due to the raw materials that are required. Therefore, reducing remarkably the building energy consumption can change completely the current situation and will empower the implementation of renewable energy systems.

2.4 Office - Educational sector

2.4.1 Energy efficiency in further and higher education buildings

The educational buildings are high energy consumers within a country’s non-industrial energy usage and by taking into consideration only the non- residential floor space of Europe it is easy to find out that this kind of buildings holds around 20% of it (Barbhuiya & Barbhuiya, 2013). In simpler words, this indicates that educational buildings in Europe possess a great percentage of the total floor space of buildings excluding dwellings and they have high energy requirements. Especially in the UK this sector constitutes around 27% of the total office stock (CIBSE Energy Consumption guide 54). The further and higher education (FHE) sector in the UK includes around 200 universities and 550 colleges of further education. The sector consumes annually around 5.2 billion kWh of energy with the annual energy costs to be more than £200 million and releasing more than 3 million tonnes of CO_2 into the atmosphere. According to Carbon Trust, the student numbers have been significantly increased over the last decade which indicates that the FHE sector is also growing and the energy demand is increasing. Therefore, the educational sector is a key point in reducing the greenhouse gas emissions in order to achieve the targets of the UK Government. (Barbhuiya & Barbhuiya, 2013)

Performing a low energy design will not only result in lower energy consumption which means lower costs and environmental benefits but also will lead to achieve a comfortable indoor working environment with improved air quality as well as will act to increase the productivity of the occupants.

2.4.2 Energy use by sector in universities

Universities present the best opportunity to lead the way towards achieving a low carbon economy. Based on their education and research, they can apply new technologies and strategies and promote this philosophy to students as well as to the society. In this way, universities can become an example and play an important role to the reduction of CO_2 emissions and of the energy costs and to the accomplishment of the EU energy targets.

In this section, the principal factors that influence the energy consumption related to Further and higher education sector are presented. These are mainly associated with the heating energy demand and the electrical consumption. As it is presented in the pie chart below, the biggest part of energy use is referring to space heating and lighting. Space heating is covered by consuming both fossil fuel and electricity. Heating constitutes around 60% of the total energy costs. Lighting accounts almost for 25% of the total electricity consumption. It of course depends on the office type, the utilization of daylight, operation time etc. One main point that is worth emphasizing is that the increasing use of IT has led to the increase of the electrical consumption (Song, et al., 2017) (Yoshida, et al., 2017).

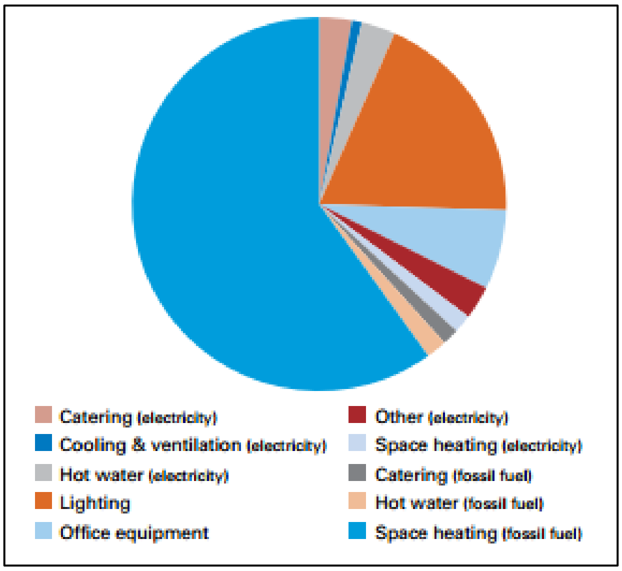

Figure 4. Energy use in further and higher education buildings (Carbon Trust, 2012)

3. Literature Review: Part 2 - Energy Legislation and Standards

3.1 Introduction

During the last decades, many policies have been developed worldwide which aim to improve the energy performance of new or already existing buildings. Governments with regards to improving the sustainability of the built environment promote strategies which focus on energy efficiency. Reducing the energy consumption as well as the carbon emissions are two key aims. In Europe, the largest energy consuming sector is the building sector which accounts for 40% of the total final energy consumption. Almost, two thirds of the buildings have high energy demand, are inefficient and only a very small proportion around 1% is renovated every year. Therefore, many legislation frameworks, policies, regulations and standards are being promoted and implemented.

3.2 Key Laws

According to the European Commission, the EU's existing main legislation regarding the reduction of energy consumption in buildings is centred on the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive.

3.2.1 Energy Performance of Buildings Directive

The Energy Performance of Buildings Directive (EPBD, Directive 2010/31/EU) is a revised version of the originally introduced EPBD (Directive 2002/91/EC) which aims to promote energy efficiency, carbon dioxide savings and integration of renewable energy in the building sector.

This Directive concentrates on improving the energy performance of buildings within the Member States of the European Union considering outdoor and local climatic conditions and indoor climate requirements under the most cost-effective ways.

The main key points of the Directive are:

4. a common general framework for calculating the energy performance of the building.
5. the establishment of minimum levels to the energy performance of new buildings.
6. the application of minimum requirements to the energy performance of:
   i) existing buildings or building units that are going to be renovated.
   ii) building elements that have a significant impact on the energy performance after the retrofitting, and
   iii) other technical building systems which are installed, substituted or improved.
7. the increase of the amount of nearly Zero Energy Buildings (nZEBs)
8. mandatory energy performance certification (EPC) of the buildings or building units
9. systematic inspection of the technical systems such as: heating, cooling, hot water and ventilation systems in buildings, and
10. independent experts and control systems will reassure the delivery of the EPCs and the regular inspection of the technical systems.

3.2.2 Methodology of calculating the energy performance of buildings

It is worth stating that the Directive does not specify a stringent detailed calculation methodology nevertheless the Member States have the right to define details in a transparent way in order to comply with the European standards. The general frame of the methodology covers the following aspects:

1. thermal characteristics of the building (thermal capacity, insulation levels, passive heating, cooling parts and thermal bridges) along with their insulation characteristics,
2. heating and hot water systems,
3. air-conditioning systems,
4. ventilation systems (natural and mechanical),

5. built-in lighting installations,
6. passive solar systems and solar protection,
7. orientation, design of the building and outdoor climate conditions,
8. indoor climatic conditions and designed indoor requirements,
9. internal loads

Active solar systems, energy generation coming from renewable energy sources, electricity generation from combined heat and power plants etc. have also to be taken into account.

Finally, in order to perform easier calculations the buildings are separated in different categories.

3.2.4 Energy Efficiency Directive

The Energy Efficiency Directive (2012/27/EU) established in 2012 indicates a general context of measures to be followed by all the Member States of the European Union. It indicates a common general way that the members should adopt in order to promote energy efficiency and as an extent to achieve the Union's 2020 targets. Key element of the directive is the elimination of the barriers observed in the energy market. Lastly, any Member State has the option to propose and introduce more strict measures as long as they comply with the European Union's laws. It is worth stating that so as to achieve the targets a long-term strategy for renovation of residential and commercial buildings, both public and private is set. Analytical information regarding the energy efficiency targets, the building renovation strategies, the energy management systems etc. can be found in the official website of the European Union- EU laws and publications

3.2.5 The Building Regulations (Part L)

Many of the articles of the EPBD have been included into the UK Building Regulations Part L. This part, refers to the conservation of fuel and power, sets the required energy efficiency standards and is applied in UK many years before the adoption of the EPBD. It is concerned about the values and the properties of the building envelope such as insulation levels, air permeability, lighting efficiency, commissioning and efficiency of the heating/ cooling systems, mechanical ventilation parameters etc. It is also split into two parts, for new buildings and for existing ones. Building regulations are managed independently in England, Wales and Scotland.

A calculation tool which takes into consideration almost all the above has been developed in the UK in order to calculate the energy performance of commercial or residential buildings. It can be used to analyse if the selected building complies with the national Building Regulations of each country. The Standard Assessment Procedure (SAP 2012) is used for the Energy Rating of Dwellings and there is a number of software tools which are widely used to produce energy performance certificates. For non-domestic buildings, a National Calculation Method (NCM) has been developed to implement the EPBD. The tool is called Simplified Building Energy Model (SBEM) and can provide an analysis of a building's energy consumption based on a predictive method (UK Government: https://www.gov.uk/).

4. Literature Review: Part 3 - Sustainability and green building rating systems

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4.1 Introduction

Achieving sustainability is one main challenge that our society faces. Green building practices are coming into force in order to support and promote the implementation of high energy performance in buildings, achieve net zero energy buildings and etc. Therefore, it is important to adopt a development approach that meets the present energy needs and will also ensure the preservation of the resources for future to meet the next generation's demands. This is identified as sustainable development. It is based on reaching a balance among the three core aspects named as the Triple Bottom Line (TBL). These are: *Environment, Society and Economy* (Awadh, 2017). Protecting the environment is vital as climate change can cause far-reaching negative impacts. Environmental responsibilities are related to waste and carbon emissions reduction, improvement of energy efficiency, sustainable use of natural resources etc. Adequate and suitable living conditions have to be maintained by overcoming any difficulties to ensure the quality life and well-being of people. Consequently, economics is another key parameter that defines the affordability (manufacturing and production costs) of implementing changes to satisfy the environmental and social responsibilities and making profit out of this process (Ageron, et al., 2012); (Demeter & Matyusz, 2011); (Gimenez, et al., 2012).

Introducing and implementing a "green" building rating system is evident in order to achieve a better sustainable development. As, it has been already stated, the building sector is responsible for around 40% of the total primary energy consumption in the developed counties, including the UK, and also for one third of the total carbon emissions of the countries. Therefore, there are many policies and industry incentives settled that focus on improving the building performance in terms of energy & water, indoor environmental conditions and carbon emissions. Different countries have different methods. However, although they present differences, all of them are focused on the following:

- Achieve high operational performance of buildings

- Define the effects and minimize the impacts on the environment
- Evaluate the development approach of a building under an objective prospect

4.2 Green Building Certifications and Practices

The most applicable systems and methods with their main emphasis points are discussed in the section below.

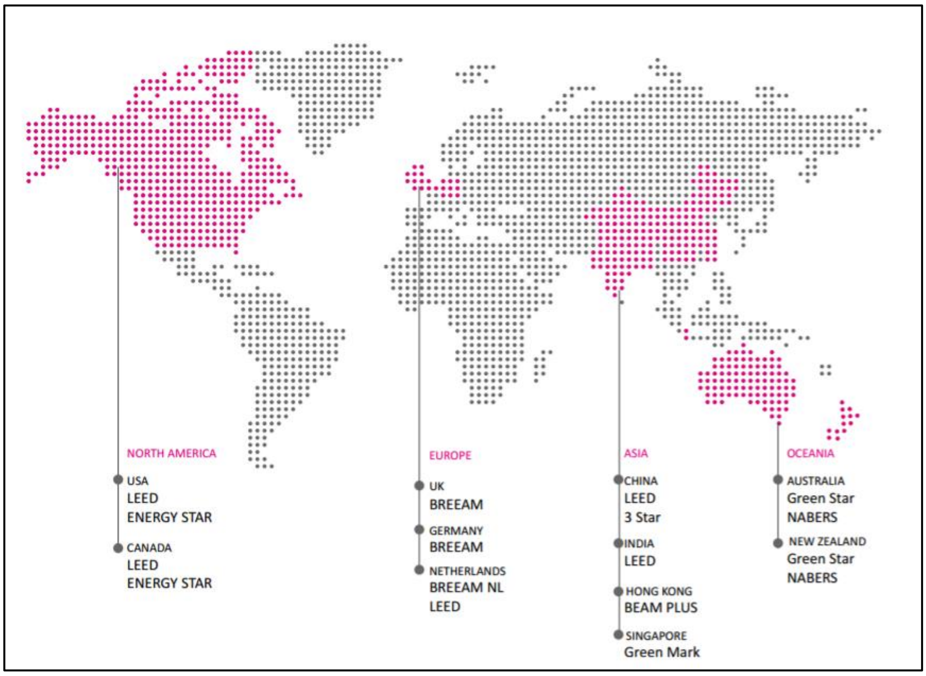


Figure 5. Countries and most applicable sustainability systems. Source: International sustainability systems comparison. Ove Arup & Partners Ltd. (2014)

4.2.1 Building Research Establishment's Environmental Assessment Method (BREEAM)

This method sets the standard for the best practice in building design and construction. It was firstly launched in the UK in 1990 and it is an international scheme which is also generally implemented in many European countries and other. Nowadays, more than 250,000 buildings have been already certified (Poveda & Young, 2015). The main concerns are to (bre, n.d.):

- Mitigate the environmental life cycle effects of buildings.
- Categorize buildings according to their environmental benefits.
- Offer a trustworthy label for buildings.

- Promote energy efficiency and reduce the energy demand of sustainable buildings.

4.2.2 Leadership in Energy & Environmental Design (LEED)

This rating system was launched in 2000 and it is the most commonly used system in the USA. It is also established in other countries such as Mexico, Canada, India etc. It rates the design features of a building through five criteria: sustainable sites, water efficiency, energy and atmosphere, materials and resources and indoor environmental quality. Each criterion is evaluated and then points are attributed. The summed points determine the level of certification of the building(International sustainability systems comparison. Ove Arup & Partners Ltd. (2014)).

4.2.3 Green Star

This sustainability rating system for buildings was introduced in 2003 in Australia. It takes into consideration a variety of building types such as commercial, residential, public etc. Results have revealed that an Australian building which complies with the Green Star emits 62% less greenhouse gases and consumes less than two thirds of the electricity compared to a typical Australian building of a similar size. This system is concerned about the energy and water consumption of a building, the indoor environmental conditions, the fabric selection for construction, the natural resources degradation etc. Instead of points, stars are awarded in this system and in most cases at least four stars are required to certify a building (International sustainability systems comparison. Ove Arup & Partners Ltd. (2014)).

4.2.4 National Australian Built Environment Rating System (NABERS)

This rating system was firstly introduced in 1998 in Australia. It aims to measure the environmental performance of a building in a reliable way. It is oriented to commercial and residential buildings etc. In order to certify a building, independent assessors take measurements of energy, water, electricity consumption; indoor conditions etc. and compare them to a baseline. Then, a score rated on stars is attributed and the building is certified (International sustainability systems comparison. Ove Arup & Partners Ltd. (2014)).

4.2.5 Net Zero Energy Buildings (NZEBs)

4.2.5.1 Introduction

The broad sense of a Zero Energy Building (ZEB) is not new. The meaning of ZEB is based on the following points: low energy needs, high energy performance and energy generation coming from renewable energy sources.

In order to comply with the European Union's Energy Performance of Buildings Directive (Directive 2010/31/EU) and the Energy Efficiency Directive (Directive 2012/27/EU) about achieving high performance in buildings, from 2020 all new buildings and especially from 2018 all new public or commercial buildings of the member countries should be Nearly Zero Energy Buildings (NZEBs).

This aim can be accomplished in two ways, either of constructing all new buildings under the new directive or by retrofitting the already existing buildings and implementing renewable energy technologies. The current situation indicates that around 90% of the already built buildings will be standing in 2050, so refurbishing these buildings is preferred over constructing new ones. This trend leads to energy savings as well as avoidance of pollution and waste of construction materials. This is also reinforced by the fact that over 35% of the standing buildings in Europe have been constructed since 50 years ago and require alterations and enhancements to comply with the up to date EU requirements. In the near future the energy demand of the buildings should be very low or even if possible nearly zero without affecting at the same point the thermal comfort levels and the behaviour of the occupants. This means that the buildings have to be designed in such a way that will make it possible to reduce the current energy needs by using passive design approaches. Moreover, renewable energy systems will be integrated in order to cover the building's energy consumption. Renewable energy technologies such as solar PVs, solar thermal systems, heat pumps, small scale wind turbines etc. are key elements to achieve energy efficiency, environmental protection and economic affordability (Wang, Zhao, & Li, 2017) (Zavadskas, Antucheviciene, Kalibatas, & Kalibatiene, 2017) (Ascione, et al., 2016) (Zhou, et al., 2016).

4.2.5.2 Definitions

A zero energy building can be defined in many ways due to the fact that a building is consisted of many different parts. Depending on the project aim, the building owner or the values of the design different definitions can be set. For example, governments care about achieving the national targets, environmental organisation care about achieving reduction in CO_2 emissions, the design team may care about achieving the highest potential energy autonomy of the building by implementing as much renewable energy technologies as possible. In all the definitions, grid connection of the building is allowed and is required in order to achieve energy balance. (Torcellini et al., 2006); (Hootman, 2012); (Torcellini, 2010)

4.2.5.3 Classification depending on the connection of the building to the grid

The zero energy buildings are divided into two categories depending on if they are connected or not to the national electricity grid.

Off-grid Zero Energy Buildings: Such a building is not connected to the national electricity grid. This building should cover its energy demands absolutely from the on-site energy generation. They are prohibited of using fossil fuels as they cannot offset this use by exporting energy to the grid. Due to the reason that renewable energy is dynamic, stochastic, intermittent and non-linear, mandatory requirement is the implementation of some kind of storage (e.g. batteries) in order to cover the energy demands when there is not on-site energy generation. Apart from that, the on-site installed renewable energy systems have to be sized in such a way that they will be able to address the peak loads on a daily basis. It is worth stating that this type of building complies with all the four previous definitions! The main challenge is the cautious management and installation of the size of the renewable energy systems and the storage as these two elements are significantly costly. Therefore, the actualisation of an off-grid zero energy building is difficult and is usually applied when there are no alternatives (Hootman, 2012) (Zavadskas, et al., 2017).

On-grid Zero Energy Buildings: This is the most common type of zero energy buildings. This kind of building is connected to the national electricity grid network. As a result it can export energy to the grid when there is an excess of production as well as import energy in the case that the demand is higher than the on-site generated or stored energy. This technique presents many advantages, as the capital costs are reduced and there are economic benefits from selling the excess of energy (Hootman, 2012) (Zavadskas, et al., 2017).

4.2.6 Passive House Standard

4.2.6.1 Introduction

The Passive House or Passivhaus Standard is one worldwide leading concept that fulfils all the criteria of the EPBD and constitutes the perfect base for achieving Nearly Zero Energy Buildings. It was developed in Germany in the early 1990s and can be applied not only to residential but also to commercial, industrial and public buildings. It is considered to be the fastest growing energy performance standard as more than 30,000 buildings already comply with the Passivhaus requirements and many of them have been built in the UK (Mihai, et al., 2017) (Wang, et al., 2017) (Robin Brimblecombe, May 2017) (PassivehausTrustOrganisation, n.d.).

The construction of a non-domestic building according to Passive House Standard is simple and is based on the following principles:

- Very high thermal insulation levels
- Minimizing the thermal bridges
- Excellent level of airtightness
- Passive solar gains and internal heat sources
- Implementation of mechanical ventilation with highly efficient heat recovery

According to Dr Wolfgang Feist, who is Head of Energy Efficiency Construction/ Building Physics at the University of Innsbruck and Director of the Passive House Institute in Germany, "*the losses of a building which is built according to the Passive*

House Standard are reduced so much that it barely needs any heating at all". (Passipedia, 2017)

4.2.6.2 Non- Residential Passive House Criteria

The Passivhaus design focuses on reducing the space heating and cooling energy requirements to specific low levels and at the same time achieving comfort indoor conditions. In order a building to comply with the Passive House Standard it should meet the following criteria:

Basic Principles	
• Entire Specific Primary Energy Demand	≤ 120 kWh/m^2 per year
• Specific Heating Demand	≤ 15 kWh/m^2 per year
• Specific Heating Load	≤ 10 W/m^2
• Specific Cooling Demand	≤ 15 kWh/m^2 per year
• Airtightness	≤ 0.6 ach @50pa

Table 1. Passive House Standard Criteria

The Passive House Standard is used not only to new but also to existing buildings. However, sometimes the use of Passive House principles in refurbishments of older buildings may not be feasible due to a variety of reasons such as the orientation of the building, the unavoidable thermal bridges of the basement walls, the construction materials etc. In the case that a building cannot comply with the Passive House criteria, then, another more relaxed certification can be attributed which is known as the EnerPHit standard (PassivehausTrustOrganisation, n.d.) (Passipedia, 2017) (Mihai, et al., 2017).

Guideline Targets	
• Opaque fabric U-values	≤ 15 W/m^2
• Windows U-values (both frame and glazing)	≤ 0.85 W/m^{2}K
• Thermal Bridges	< 0.01 W/m^{2}K
• Implementation of mechanical ventilation with heat recovery that is 75% efficient or better with low specific fan power.	

Table 2. Main guidelines of the Passive House Standard. (Source: https://passivehouse-international.org/index.php?page_id=80)

4.2.6.3 EnerPHit Standard criteria

In this case, the basic principles are also the same with Passive House. The difference is that the some of the limits are more relaxed.

Basic Principles	
• Entire Specific Primary Energy Demand	≤ 120 kWh/m^2 per year
• Specific Heating Demand	≤ 25 kWh/m^2 per year
• Specific Heating Load	≤ 10 W/m^2
• Specific Cooling Demand	≤ 25 kWh/m^2 per year
• Airtightness	≤ 1.0 ach @50pa

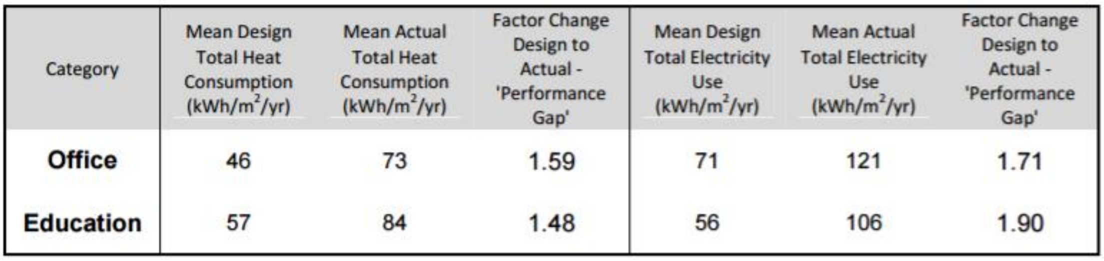
Table 3. EnerPHit criteria

5. Performance Gap: Literature Review and Case Study Analysis

5.1 Literature Review

All these sustainability certification methods aim to promote high energy performance regarding energy consumption, indoor environmental conditions and carbon emissions. However, several research studies are presenting that in many buildings which achieve high energy performance through certification awards the actual performance is lower than the expected one (Paul G Tuohy, 2015). It is worth stating that in some cases the energy consumption and the energy costs are even double compared to the initial assumptions. This means that there is a discrepancy which is commonly known as "the performance gap". NABERS is a rating system which is based on actual measurements of performance. However, the majority of the sustainability methods such as BREEAM, LEED etc. are based on predictive energy performance calculations and when the question comes to "What is happening regarding the actual energy performance?" then in many cases there are numerous discrepancies. Various causes can lead to lower energy performance. Papers in the past have indicated that such causes can be insufficient building construction by choosing different materials, failure to meet the design specifications, errors in installing the insulation and achieving airtightness, failure of avoiding the thermal bridging effect and etc. (Stoppel & Leite, 2013); (de Wilde, 2014); (de Wilde, et al., 2013). Furthermore, discrepancies can be attributed due to inaccuracies in the input data inserted in the simulation tools so as to calculate the energy performance of the building in the future operational phase. Misjudged occupancy levels inside the building, the use of lighting and other electrical equipment (e.g. computers) out of the regular operational hours are reasons that lead also to the energy performance gap (de Wilde, 2014). Now, sub-metering and acquisition of real energy measurements are encouraged in BREEAM and LEED so as to monitor the operational use of the building. To conclude, the performance gap can be attributed to poor predicted energy consumption due to the reasons above as well as lack of monitoring data during the operational phase in reality.

Differences between the actual and the predicted energy performance in the sector of offices and education buildings have also been observed in the UK. In 2013, a report which was published on the CarbonBuzz, an online platform developed for sharing energy consumption data in buildings, came up with surprising results. It was found that in offices in terms of heat consumption the actual performance was 58% more than the expected one. Similar results showed that the difference in electricity consumption was 71% on average. Except from the office sector, another one whose energy consumption data followed similar patterns is the educational sector with the actual electricity consumption to be up to 90% higher than the predicted one.



Category	Mean Design Total Heat Consumption (kWh/m^2/yr)	Mean Actual Total Heat Consumption (kWh/m^2/yr)	Factor Change Design to Actual - 'Performance Gap'	Mean Design Total Electricity Use (kWh/m^2/yr)	Mean Actual Total Electricity Use (kWh/m^2/yr)	Factor Change Design to Actual - 'Performance Gap'
Office	46	73	1.59	71	121	1.71
Education	57	84	1.48	56	106	1.90

Figure 6. Predicted vs Actual energy consumption results to office and education buildings in the UK (2013). Source: CarbonBuzz (Access at: http://www.carbonbuzz.org/downloads/PerformanceGap.pdf)

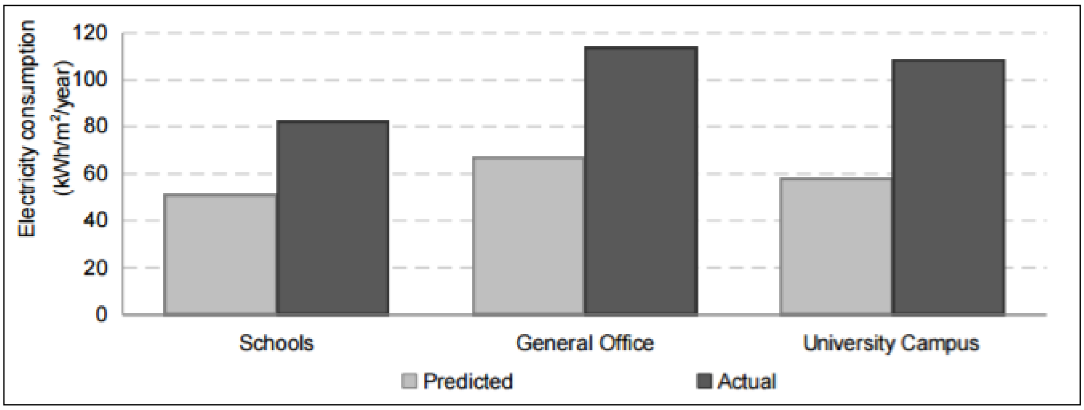


Figure 7. Predicted vs Actual electricity consumption results to office and education buildings in the UK (2011). Source: BUSWELL, R.A. ... et al., 2011. Analysis of electricity consumption for lighting and small power in office buildings. CIBSE Technical Symposium, DeMontfort University, Leicester, UK

Therefore, there is strong evidence of existence of energy performance gap in the non-residential building sector in the European countries and as a result in the UK.

5.2 The case of James Weir Building

5.2.1 James Weir Building Information

The James Weir Building is an academic building and belongs to University of Strathclyde. It was built in Glasgow in 1958 and is one of the largest buildings of the university. It has a rectangular shape (Figure 21.) and its main characteristics are presented in the table below:

Parameters	**Values**
Length (m)	around 102 m
Width (m)	21 m
Total floor area (m^2)	21892.4 m^2
Number of floors	9

Table 4. James Weir Building characteristics

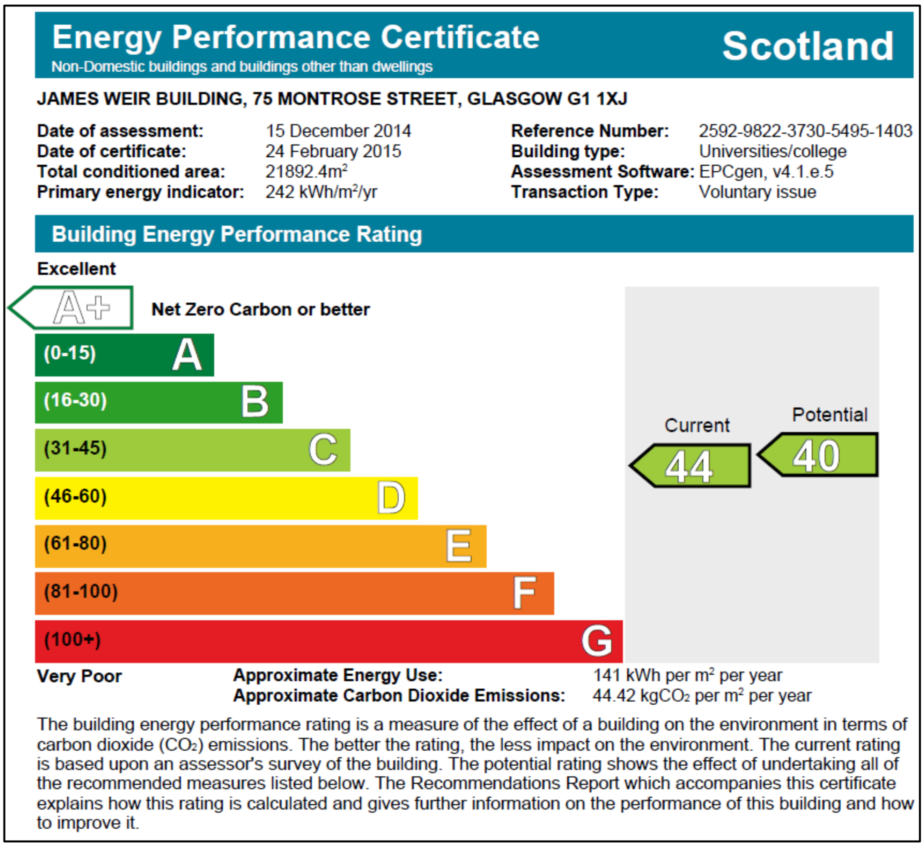
The building is almost homogenous and except from the ground floor, the rest are more or less the same.

Figure 8. James Weir Building.

(Source: https://www.strath.ac.uk/whystrathclyde/news/)

5.2.2 Analysis

An analysis was performed for the James Weir Building so as to validate if the energy consumption values based on the Energy Performance Certificate (EPC) match with the actual energy consumption values. The University of Strathclyde Estates Service provided the EPC rating (Figure x.) along with actual energy consumption data for the last three years.



Energy Performance Certificate **Scotland**

Non-Domestic buildings and buildings other than dwellings

JAMES WEIR BUILDING, 75 MONTROSE STREET, GLASGOW G1 1XJ

Date of assessment:	15 December 2014	**Reference Number:**	2592-9822-3730-5495-1403
Date of certificate:	24 February 2015	**Building type:**	Universities/college
Total conditioned area:	21892.4m^2	**Assessment Software:**	EPCgen, v4.1.e.5
Primary energy indicator:	242 kWh/m^2/yr	**Transaction Type:**	Voluntary issue

Building Energy Performance Rating

Approximate Energy Use:	141 kWh per m^2 per year
Approximate Carbon Dioxide Emissions:	44.42 kgCO$_2$ per m^2 per year

The building energy performance rating is a measure of the effect of a building on the environment in terms of carbon dioxide (CO$_2$) emissions. The better the rating, the less impact on the environment. The current rating is based upon an assessor's survey of the building. The potential rating shows the effect of undertaking all of the recommended measures listed below. The Recommendations Report which accompanies this certificate explains how this rating is calculated and gives further information on the performance of this building and how to improve it.

Figure 9. EPC for James Weir Building, Source: University of Strathclyde Estates Service

According to the EPC the current rating label for the building is said to be of class C. The approximate energy use was calculated to be 141 kWh/ m^2 per year and the approximate carbon dioxide emissions 44.42 kgCO$_2$/ m^2 per year.

Data regarding the actual energy consumption of the building were also collected and analyzed. These data presented the natural gas and electricity monthly consumption over the last three years. Summing the monthly values for each year led to the following results:

Electricity consumption year	Value (kWh)	Value (kWh/m2)
2016	2,359,734	107.78
2015	2,275,651	103.94
2014	2,247,562	102.66

Table 5. Electricity consumption data for James Weir Building per year

Natural gas consumption year	Value (kWh)	Value (kWh/m2)
2016	2,525,456.13	115.35
2015	2,249,480.68	102.75
2014	1,822,099.61	83.2

Table 6. Natural gas consumption data for James Weir Building per year

It is clear that the actual electricity consumption is almost stable throughout all these three years with an exception in 2015 between April and May that the values seem to reach very high and very low values respectively. A variation of ± 5 kWh/m^2 per year can be considered as negligible as this can be attributed to factors that cannot be identified with certainty such as the occupancy and operation hours.

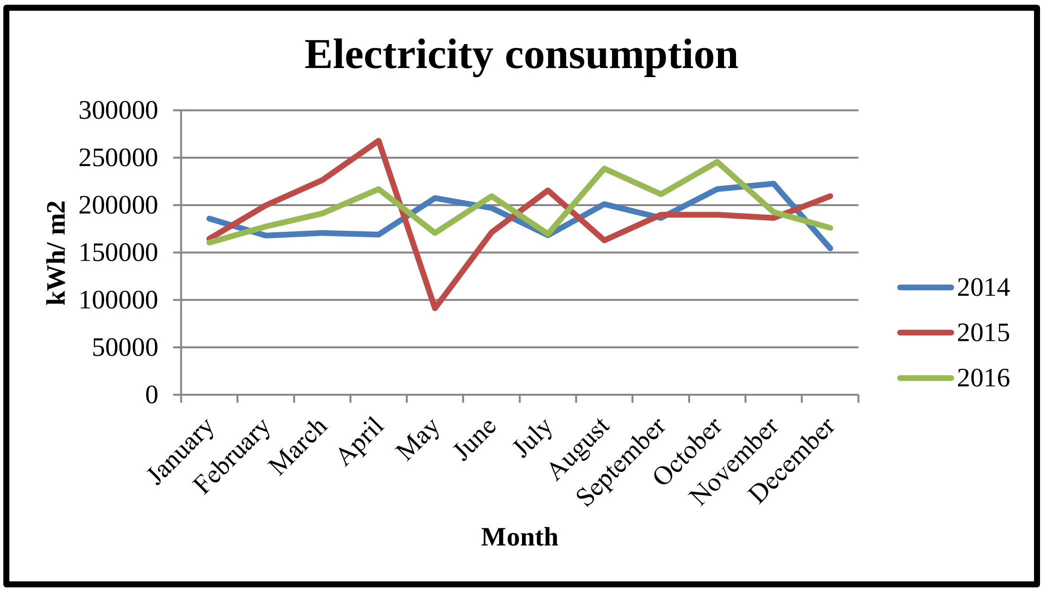


Figure 10. Monthly electricity consumption over three different years

On the other hand, as far as it concerns the natural gas consumption it can be observed that there is a steady increase of around 15 kWh/ m^2 per year. This also can be attributed to different climate conditions, occupancy patterns and operation times.

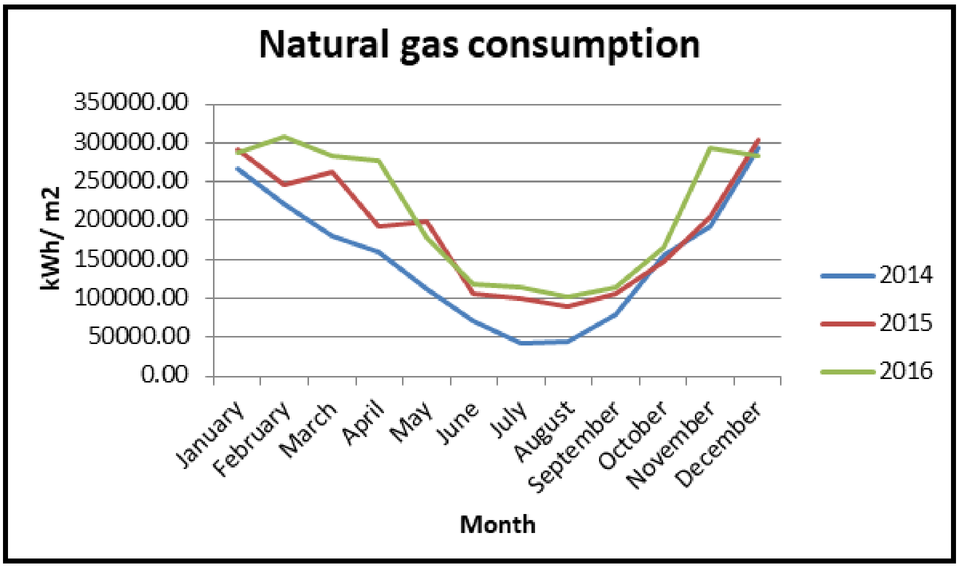


Figure 11. Monthly natural gas consumption over three different years

Total annual energy consumption in kWh/ m^2 can be found by adding the monthly electricity and natural gas consumptions for each one of the three years. The results are displayed in the figure below.

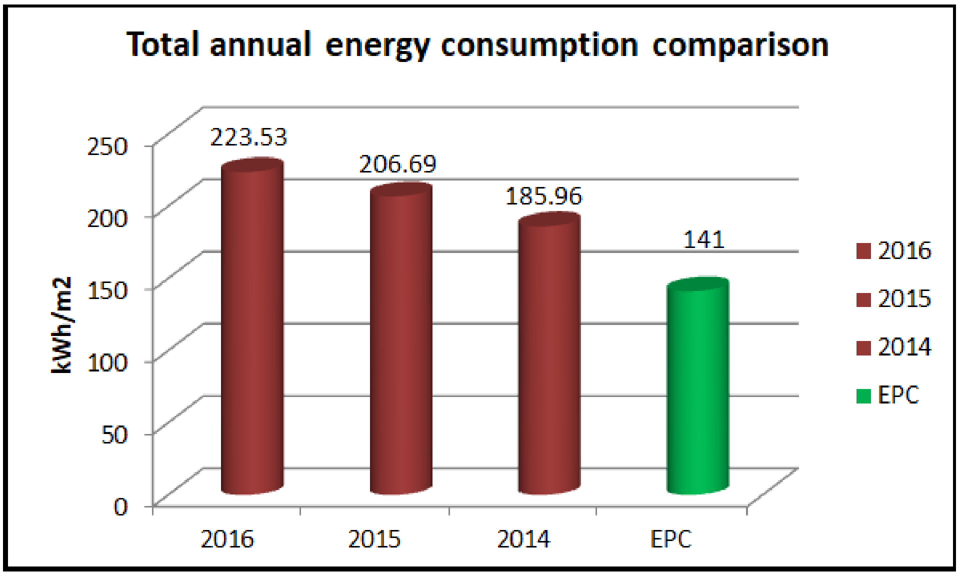


Figure 12. Comparison of the actual annual energy consumption to the EPC value

5.2.3 Conclusions

A variation among the compared data can be observed. The approximate energy use per floor area given by the EPC which is 141 kWh/ m^2 is considerably lower than the actual energy consumption data even in the best year scenario which is 186 kWh/ m^2. Comparing the EPC value to the mean average actual energy consumption of the three years leads to a difference of -65 kWh/ m^2 or -31.4 %.

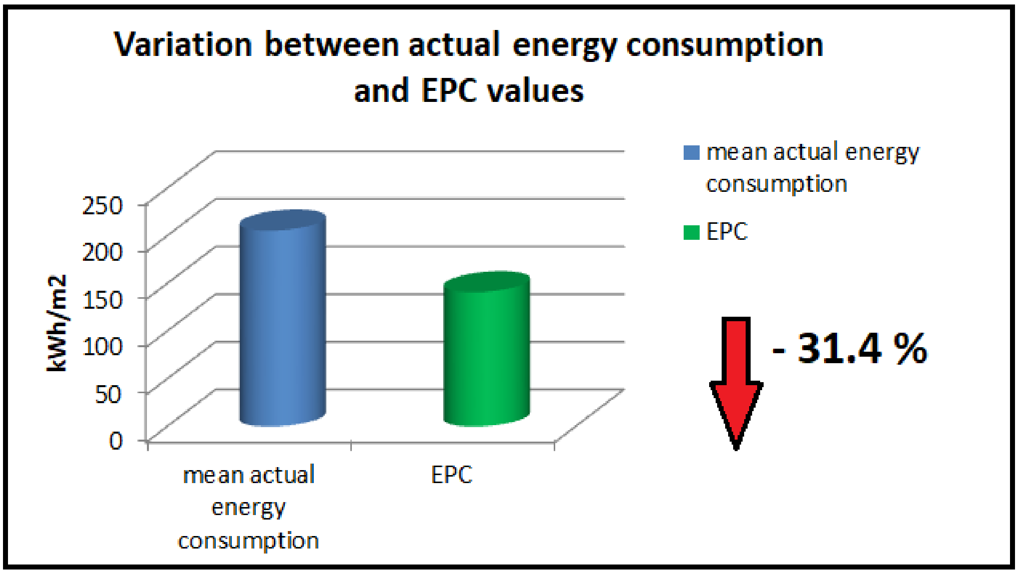


Figure 13. Variation between the mean actual energy consumption and the EPC value.

Of course here it is important to state that many studies have shown that the EPC and the actual energy consumption values differ (Demanuele, 2010) (Bordass B, 2004) (B. Bordass, 2001). There are lots of factors that lead to these variations. For example, the EPC does not take into account the electrical appliance use which means that the electricity consumption is lower than the actual one. There are also many uncertainties and assumptions made while modelling and simulating the building performance that can lead to differences on the modelling input and output data. Moreover, the thermal bridging effect plays a considerable role in calculating the actual thermal losses and it is difficult to model. Lastly, information regarding occupancy patterns and operation hours have significant effect on the energy performance of a building and can contribute to false calculations as these values are usualy estimated.

Therefore, in this analysis it can be concluded that the EPC which as already has been stated is based on a predictive energy performance calculation method overestimates the building’s energy performance as it underestimates the energy consumption by around one third compared to the actual one.

6. Dynamic simulation tools for building energy design

6.1 Introduction

There are various tools that can be used in building design and simulation. As it was observed in the case above, buildings usually do not perform as it they are predicted to do. It is encouraged that buildings should aim to achieve a Building Energy Rating which will be lower than the Target Energy Rating. In this way it will be possible for the building to comply with the Building Regulations of the country (Menezes, et al., 2012). Nevertheless, following this methodology does not help to predict with accuracy the actual energy performance of the building. It just helps to achieve the EU targets.

Therefore, an alternative method to calculate the actual energy performance of a building is by using dynamic simulation software tools. This kind of tools can achieve higher accuracy regarding energy performance as they take into account much more aspects such as thermal flow paths, casual gains etc. that can affect in a great extent the behavior of the building. Especially, in the case of non–domestic buildings analysis, dynamic simulation tools can allow a better representation of the building model as they take into account in-use variables such as occupancy and small equipment that have a very significant influence on the energy performance of the building. Simulation tools are encouraged to be used during the early stages of designing a new building or retrofitting an already existing one as they offer the possibility of examining different design options in relation to the building envelope and the operational systems before they are implemented in practice (Michael Pollock, n.d.). In the case of retrofitting an existing building this methodology can assist in selecting the best and most appropriate retrofit options and in reducing the capital costs. There are different building energy simulation tools such as DOE-2, EnergyPlus, ESP-r etc. (Choi, 2017). For this analysis, ESP-r was selected to be the modelling tool in order to assess the energy performance of a typical office of a university building as it was available from the University of Strathclyde.

6.2 ESP-r

ESP-r is an open-source program which was created by the Energy Systems Research Unit (ESRU) of University of Strathclyde in 1974. It is a modelling tool that can allow an in depth analysis of the energy and environmental performance of buildings. ESP-r calculations are based on a finite volume approach where conservation equations are solved. It successfully attempts to simulate the buildings' behavior in the real world. ESP-r is suitable for designing the shape and geometry of a building, selecting construction materials and setting operational conditions. Moreover, it allows the user to insert inputs regarding the casual gains from occupancy, lighting etc., air flows, shading, plants and controls. The large database of ESP-r contains many fabric elements, operation patterns and climate conditions that help the user to select the appropriate ones for each case analysis but also offers the possibility to create his own materials which in many cases can lead to extremely accurate results (ESP-r Cookbook 2015) (Strachan, et al., 2008).

7. Model construction and description

7.1 Introduction

In this chapter, the main characteristics of the model which was created in ESP-r are described.

A typical office of the 8th floor of James Weir building (JWB) of University of Strathclyde was selected to be modelled due to the fact that lots of information could be gathered regarding all the required modelling aspects. The JWB has a simple geometry and it is comprised of 8 physically similar floors. The 8th floor was chosen as it was possible to have access and collect data. This floor is consisted mainly of offices which are constructed along the outer perimeter of the building and are connected with a corridor in the middle. Except from offices, there are also small areas such as staircases, toilets, printing rooms etc. However, having access to one typical office of the floor made it possible to model it and do an analysis regarding the thermal behavior of the building.

In order to be able to execute this analysis in ESP-r, information on the following categories was required:

- location and climate
- building geometry and characteristics
- construction materials
- casual gains
- infiltration and ventilation
- heating and cooling systems

Once these parameters had been determined the model was built and will be presented later.

7.2 Location and climate

The James Weir Building belongs to the University of Strathclyde Campus and it was built in 1958. It is located in the city center of Glasgow (Figure 18.) with an orientation of 281° N. The climate of Scotland and as an extent of Glasgow is oceanic and on one hand it tends to be very changeable but on the other hand it is not too extreme. The ESP-r database contains a climate file which refers to the climate extremely close to Glasgow and it was used in this simulation analysis. The ambient temperatures throughout a whole year are presented in Figure 19. In winter, the average temperatures are close to 5° C but in some days it can be much colder with the temperature to reach values below 0° C. During the summer months, the weather varies significantly from day to day and the temperatures are on average between 15-20° C. The warmest month seems to be July, with the temperatures to reach values equal or higher than 25° C. In Figure 20, the solar irradiation values over a typical year are presented and can be observed.

Figure 14. Location of James Weir Building on the map. (Source: Google Maps, 2017)

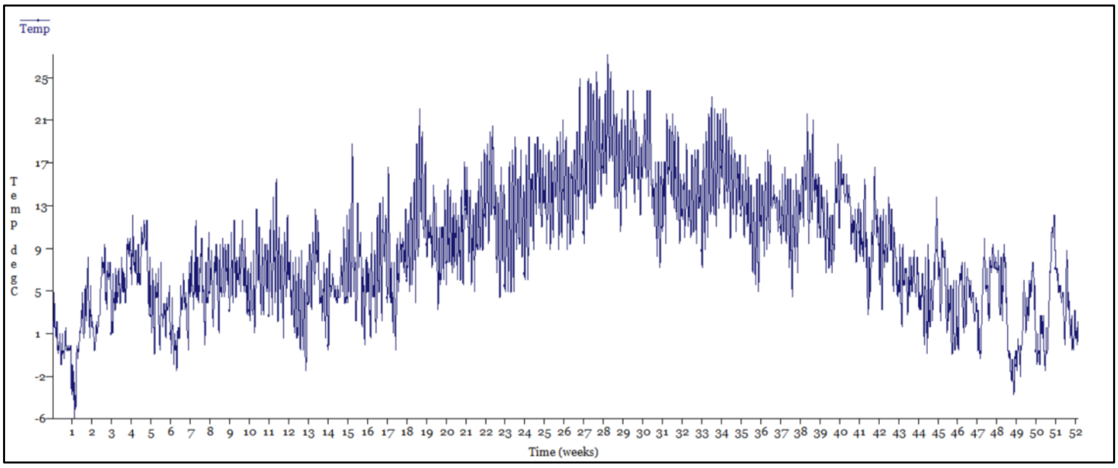


Figure 15. Ambient temperatures (ºC) over a typical year as presented in ESP-r.

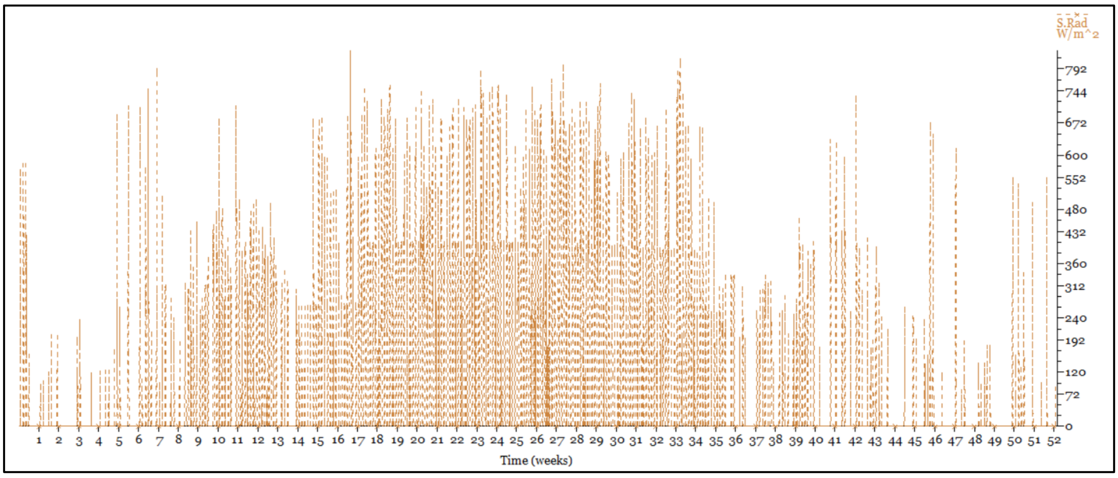


Figure 16. Solar irradiation values over a typical year as presented in ESP-r.

7.3 Building geometry and characteristics

The next step of the analysis was to define the geometry and build the envelope of the model.

The James Weir Building is almost homogenous and except from the ground floor, the rest are more or less the same. Therefore, having access to the 8th floor made it possible to model a typical office.

Figure 17. James Weir Building, Source: https://www.strath.ac.uk

As it is already stated, the 8th floor of JWB follows a specific pattern with offices along the outer perimeter of the building and a corridor in the middle which connects the offices. One of these offices with one part of the corridor consist the modelled office (Figure 22.).

It has three different zones which are:

- the main office area (office B)
- another office area (office A) which is separated from Office B with a glass wall and
- a corridor

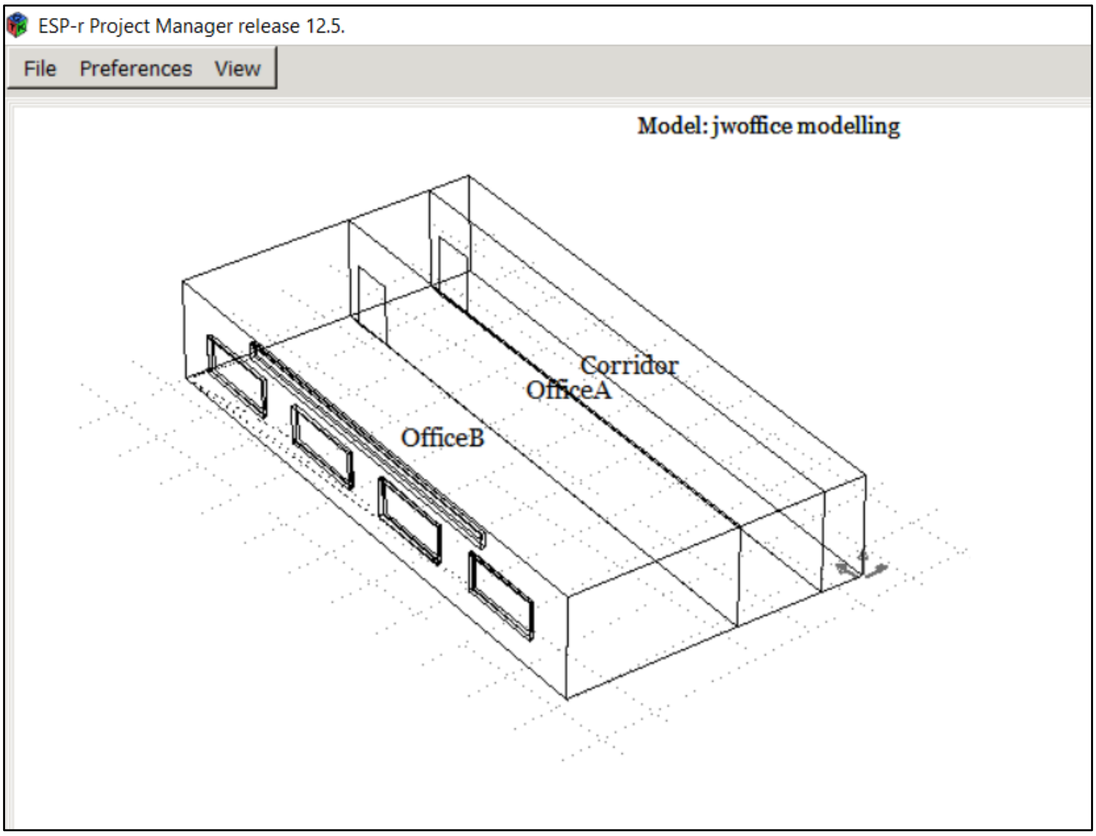


Figure 18. The modelled office as presented in ESP-r.

The aim of the analysis was to develop a model as accurate as possible and this is the reason that the modelled office is consisted of these three different zones. In ESP-r the easiest way to represent and simulate a building is to set it as one zone which means that all the building has the same conditions. In reality, buildings are complex constructions and there are many parts that can affect the thermal behavior and that are important to take into consideration so as to be as accurate as possible.

In the tables below are presented the dimensions of the three areas (Office A, Office B, Corridor).

Modelled office parameters	**Value**
Length (m)	20 m
Width (m)	10.5 m
Height (m)	3.5 m

Table 7. Modelled office dimensions

Here are presented the dimensions of the three zones (Appendix I: Figure 39., Figure 40, Figure 41.)

Office B parameters	**Value (m)**
Length	20
Width	6
Height	3.5

Table 8. Office B dimensions

Office A parameters	**Value (m)**
Length	20
Width	3
Height	3.5

Table 9. Office A dimensions

Corridor parameters	**Value (m)**
Length	20
Width	1.5
Height	3.5

Table 10. Corridor dimensions

The Office A and the corridor are two areas that have no windows and are interconnected with a door. Office B is next to Office A and it has four big and four small windows.

The dimensions of the doors and windows are presented below:

Door parameters	**Value (m)**
Length	1.5
Height	2.1

Table 11. Door dimensions

Big window parameters	Value (m)
Length	3
Width	1.3

Table 12. Big window dimensions

Small window parameters	Value (m)
Length	3
Width	0.5

Table 13. Small window dimensions

However, due to complex model reasons and operational restrictions set by the ESP-r, it was mandatory to adjoin all these four small windows to be presented as one element. Therefore, for simplicity it was created one bigger window equal to all four of them with total length of 12 m and the same width of 0.5 m.

Shading

Moreover, another parameter that was considered during the building process of the model was the window reveals. External shading can be inserted in ESP-r by placing horizontal shades around every window. Visiting and measuring in the office resulted in a window reveal width of 15 cm. These data were introduced to ESP-r as the window reveals influence the solar gains to the modelled office. Finally, running simulations with and without shading resulted in a small difference (around 3%) in the total heating consumption as the width of the window reveals are designed to be small in order not to obstruct the daylight to reach the interior of the office.

Thermal bridges

The thermal bridging effect which also affects the energy performance of the model was taken into consideration. According to BRE the heat losses of a building that can be attributed to thermal bridges can reach 30% of the total heat losses. Default linear thermal transmittance (psi-values) and temperature factors based on the BRE information publication 1/ 06 were used.

7.4 Construction materials

The construction materials have a crucial role regarding the performance of the building and how it interacts with the surrounding environment. In order to build a model that would represent the actual situation, information was gathered regarding the construction materials of the building. Many studies have presented that while modelling an existing building it is difficult to know exactly the construction materials and assumptions based on the literature and on in situ investigation are evident to be made.

The thermal transmittance (U-Value) of the building envelope is the main factor that determines the steady-state heat losses and gains through the different materials (CIBSE, Guide A, 2006).

7.4.1 External walls

The James Weir Building was constructed in 1958. Based on the literature and on the in situ investigation, the external walls were assumed to be constructed of cavity brick. Exact details of the construction were impossible to be found and everything was defined based on the existed building regulations of that time. However, due to a fire incident in 2012, the building had to be refurbished and based on information gathered from the University of Strathclyde Estates Services an insulation level was added into the cavity. This resulted in a lower U–Value which reduces the thermal losses and increases the air tightness of the building. Therefore, a new construction material was created in order to reflect better the actual situation. One part of the air gap was substituted by a mineral fiber insulation layer. More details are unknown.

External wall				U–Value = 1.119 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Outer leaf brick	100	0.96	2000	650	0.90	0.93
2	Air gap	30	0.00	0.00	0.00	0.99	1
3	Mineral fiber	10	0.040	105.0	1800	0.90	0.60
4	Inner leaf brick	100	0.62	1800	840	0.93	0.70
5	Dense plaster	12	0.50	1300	1000	0.91	0.70
6	Lime plaster	10	0.70	1400	920	0.91	0.70

Table 14. External walls fabric information of James Weir Building

7.4.2 Internal walls

The internal walls were assumed to be typical due to lack of exact information and were defined using the “internal wall” option in ESP-r. They do not have any insulation level as they are only used internally to separate rooms that have same conditions.

Internal wall				U–Value = 1.552 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Perlite plasterboard	12	0.18	800.0	837.0	0.91	0.60
2	Breeze block	150	0.440	1500.0	650.0	-	-
3	Perlite plasterboard	12	0.18	800.0	837.0	0.91	0.60

Table 15. Internal walls fabric information of James Weir Building

7.4.3 Internal glass walls

There is also one wall made out of glass which separates Office A from Office B and was defined using an “internal glass” option available in ESP-r for the same reason.

Internal glass wall				U–Value = 2.200 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Glass	4.0	1.050	2500.0	750.0	0.40	0.06
2	Air gap	16.0	0.00	0.00	0.00	-	-
3	Glass	4.0	1.050	160.0	2500.0	0.90	0.70

Table 16. Internal glass walls fabric information of James Weir Building

7.4.4 Ceiling/ Floor

The ceiling is of the same construction as the floor as both are used to separate the floors of the building. The difference is that the floor is the inverted construction of the ceiling. Based on collected data, on in situ observations and due to lack of satisfying options available on the ESP-r database, the construction material of the ceiling/ floor was constructed and is presented below. It is important to state that simulations with different ceiling/ floor materials were also run in order to check whether or not the different construction materials play an important role in the heating demand of the office. The conditions above and below the modelled office were set to be equal to the conditions of the modelled office and it was found that the different construction materials had a small impact on the heating demand of the office. The results of the simulations showed a mean difference of around 2% which is considered to be negligible.

Ceiling/ Floor				U–Value = 1.255 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Ceiling tile	20.0	0.06	250.0	1000.0	0.90	0.70
2	Concrete block	170.0	1.060	1950.0	1000.0	-	-
3	Cellular rubber underlay	5.0	0.100	400.0	1360.0	-	-
4	Synthetic carpet	5.0	0.060	160.0	2500.0	0.90	0.65

Table 17. Ceiling/ floor fabric information of James Weir Building

7.4.5 Windows

The windows are double glazed and the option from the database of ESP-r “dbl_glz” was assigned.

Window double glazing				U–Value = 2.811 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Plate Glass	6.0	0.760	2710.0	837.0	0.83	0.05
2	Air gap	12.0	0.00	0.00	0.00	-	-
3	Plate Glass	6.0	0.760	2710.0	837.0	0.83	0.05

Table 18. Window fabric information of James Weir Building

7.4.6 Window frames

The frames of the windows after in situ investigation are considered to be constructed out of aluminum.

Window frame				U–Value = 2.193 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Aluminum	100	210.0	2700.0	880.0	0.22	0.20
2	Air gap	10.0	0.00	0.00	0.00	-	-
3	Aluminum	100	210.0	2700.0	880.0	0.22	0.20

Table 19. Window frame fabric information of James Weir Building

7.4.7 Doors

The doors are considered as oak wood doors.

Door				U–Value = 1.500 W/mK			
Layer	**Material**	**Thickness (mm)**	**Thermal Conductivity (w/mK)**	**Density (kg/m3)**	**Specific Heat Capacity (J/ kg K)**	**Emissivity**	**Absorptivity**
1	Oak	12.5	0.190	700.0	2390.0	0.90	0.65
2	Woodwool	36.5	0.100	500.0	1000.0	-	-
3	Oak	12.5	0.190	700.0	2390.0	0.90	0.65

Table 20. Door fabric information of James Weir Building

7.5 Casual gains

Casual gains affect the energy performance of a building. Occupancy, lighting and small equipment plug loads are factors that can influence the energy consumption. The internal heat gains from these components affect the heating and cooling requirements of a building (Sun, et al., 2016). Especially, in commercial buildings the casual gains are extremely important as there is high amount of people and as an extent there is also high usage of lighting and small equipment such as PCs, printers etc. The casual gains density (per space floor area) is uncertain as it depends on time and space (Brouns, et al., 2017) (Elsland, et al., 2014) (Zhang, et al., 2017). In order to perform an accurate analysis, input data regarding the casual gains had to be inserted in ESP-r and they are explained next.

7.5.1 Occupancy

James Weir is an office building. Information gathered from people working in the building showed that the operational hours are typical from 09:00 to 17:00 on weekdays only which means from Monday to Friday. Therefore, there will not be occupancy out of these hours and days.

The modelled office has a maximum occupancy of 23 people (18 people in Office B, 5 people in Office A, no occupancy in the Corridor). However, discussing with the people working in the office resulted in the assumption that there is occupancy of around 70% of the maximum. Therefore, using the *Table 6.3: Typical rates at which heat is given off by human beings in different states of activity* (ASHRAE Handbook: Fundamentals, 2013) the total heat generation from occupancy could be calculated.

Degree of activity sensible	**Location**	**Total rate of heat emission (W)**		**Rate of heat emission for mixture of males and females (W)**	
		Adult male	**Adjusted male/ female**	**Sensible**	**Latent**
Moderate office work	Offices	140	130	75	55

Table 21. Typical rates at which heat is given off by human beings in different states of activity in offices (ASHRAE Handbook: Fundamentals)

The heat gains from people are separated to the sensible and the latent load and for a number of *n* occupants they can be calculated with the following equation:

$$Q_{occupants} = n * (Q_{sens} + Q_{lat})$$

where Q_{sens} the sensible load of one person and Q_{lat} the latent load of one person.

For Office B an occupancy level of 70% compared to the maximum is equal to 10 people and for Office A is equal to 3.

The casual gains are presented below:

Weekdays (Monday – Friday)			
Period (h)	**Label**	**Sensible load (W)**	**Latent load (W)**
0 - 9	People	0	0
9 - 17	People	750	550
17 - 24	People	0	0
Saturday/ Sunday/ Holiday			
Period (h)	**Label**	**Sensible load (W)**	**Latent load (W)**
0 - 24	People	0	0

Table 22. Casual gains from occupancy periods in Office B.

Weekdays (Monday – Friday)			
Period (h)	**Label**	**Sensible load (W)**	**Latent load (W)**
0 - 9	People	0	0
9 - 17	People	225	165
17 - 24	People	0	0
Saturday/ Sunday/ Holiday			
Period (h)	**Label**	**Sensible load (W)**	**Latent load (W)**
0 - 24	People	0	0

Table 23. Casual gains from occupancy periods in Office A.

Weekdays/ Saturday/ Sunday/ Holiday			
Period (h)	**Label**	**Sensible load (W)**	**Latent load (W)**
0 - 24	People	0	0

Table 24. Casual gains from occupancy periods in Corridor.

7.5.2 Lighting Equipment

Except from the occupancy another important parameter concerning casual gains is lighting. A large percentage of the energy consumed by a lamp is converted and released into the office as sensible heat. The lighting profile follows the occupancy pattern as lighting in the office will be switched on while people are working inside. Otherwise, lights were supposed to be switched off. Different lamp types present differences in the casual gains. In the modelled office the lamps that are used are T5 Fluorescent which hang below the ceiling.

The heat gains can be calculated with the following equation:

$$Q_{lighting} = P * N$$

where P is the power (W) of one lamp and N is the number of fittings.

However, the power of the lamps was unknown. Therefore, the definition of the lighting power was based on surveys which have been carried out and have shown that for normal office work the average light level is around 300 - 500 lux which means sensible heat gains of 8 – 12 W/ m^2(CIBSE Guide A, 2006). An average value of 10 W/m^2 lighting power was assumed.

Considering that Office B is 120 m^2, Office A is 60 m^2 and the Corridor is 30 m^2 the following heat gains from lighting were calculated:

Weekdays (Monday – Friday)					
Period (h)	**Label**	**Sensible load (W)**			**Latent load (W)**
		Office B	**Office A**	**Corridor**	
0 - 9	Lighting	0	0	0	0
9 - 17	Lighting	1200	600	300	0
17 - 24	Lighting	0	0	0	0
Saturday/ Sunday/ Holiday					
Period (h)	**Label**	**Sensible load (W)**			**Latent load (W)**
		Office B	**Office A**	**Corridor**	
0 - 24	Lighting	0	0	0	0

Table 25. Casual gains from lighting in Office B, Office A and the Corridor.

7.5.3 Small Equipment

The last parameter that was taken into account while calculating the internal heat gains in the modelled office was the PC and monitor equipment installed. The casual gains from small office equipment have only sensible load. Every occupant has his own PC and every PC is accompanied with one monitor.

Device	**Continuous use (W)**	**Idle (W)**
PC	65	25
Monitor (medium size)	70	0

Table 26. Recommended heat gain form typical computer equipment

(Source: ASHRAE Handbook: Fundamentals)

Based on Table x. above the casual gains from the modelled office equipment were calculated and inserted in ESP-r:

Weekdays (Monday – Friday)					
Period (h)	**Label**	**Sensible load (W)**			**Latent load (W)**
		Office B	**Office A**	**Corridor**	
0 - 9	equipment	250	125	0	0
9 - 17	equipment	1350	675	0	0
17 - 24	equipment	250	125	0	0
Saturday/ Sunday/ Holiday					
Period (h)	**Label**	**Sensible load (W)**			**Latent load (W)**
		Office B	**Office A**	**Corridor**	
0 - 24	equipment	250	125	0	0

Table 27. Casual gains from small equipment in Office B, Office A and the Corridor.

7.6 Infiltration & Ventilation

Air infiltration and ventilation have a significant effect on the building’s energy performance. Infiltration is the air flow that enters a zone of the building from the exterior environment and ventilation is the air flow coming from other zones. In ESP-r both infiltration and ventilation rates can be modelled. It was very difficult to know exact values of air flows as they depend on the wind speed, the wind direction, the ambient temperature etc. Moreover, the comfort conditions for people differ and as a result it is impossible to know how they would react (open or not the windows in the feel warm etc.) while working in the office. So, logical assumptions had to be made based on (Ng, et al., 2013), standards (ASHRAE Handbook: Fundamentals) and guides (CIBSE Guide A, 2006). The aim is to simulate the building operation throughout a whole year period. The best selection was to model the infiltration and ventilation rates as stable rates without depending on the climate conditions. This technique is not representing the everyday building operation in reality with much detail but on a yearly basis provides accurate results.

Office B is naturally ventilated and the infiltration rate was set all the time at 1 ac/ h. According to the literature, the recommended air flow rate for an office environment is around 8 – 12 L/ s per person (CIBSE Guide A, 2006). Office A is a mechanical ventilated area during the operational hours and following the same methodology resulted in a rate of 2 ac/ h during occupancy periods. The remaining time the air flow rate was set to be 1 ac/ h (CIBSE Guide A, 2006).

7.7 Heating & Cooling Systems

The last parameter that had to be defined was the heating and cooling systems of the building. The James Weir Building has only a natural gas heating system without cooling system. ESP-r offers the possibility to include data referring to the installed heating system and the desired conditions. According to *Table 1.5 Recommended comfort criteria for specific applications* from CIBSE Guide A, the comfort temperatures for office buildings are:

Building type	Winter comfort temperature (º C)	Summer comfort temperature (º C)
Offices/ corridors	19 - 22	21 - 25

Table 28. Recommended comfort criteria for offices/ corridors.

In ESP-r, three heating zones were defined, one for each area (Office B, Office A, Corridor). The power of the heating system of James Weir Building was unknown.

However, having in mind that it was always capable to cover the heating demands of the building, a very high capacity value was set up in ESP-r. Then, heating profiles for weekdays, Saturday, Sunday and Holidays were determined based on the operational hours. On weekdays, in order to achieve comfort conditions during the occupancy hours, the heating was set up to operate from 06:00 until 18:00 and outside of these hours as well as on Saturdays, Sundays and Holidays the heating system was switched off and there are free floating conditions. Based on table x. above, the heating set point was set at 22º C which is the average value.

Moreover, in cases where the inside temperature in Office B exceeds the average comfort limit of 23º C there is the choice of opening the windows. Therefore, for comfort reasons and due to lack of a cooling system, an ON/OFF control loop was also set up during occupancy hours in Office B that would allow people to open the windows at 50% when the temperature would rose higher than 23º C.

8. Verification of the model

8.1 Simulation tests

Once all these parameters, location and climate - building geometry and characteristics - construction materials - casual gains - infiltration and ventilation - heating and cooling systems, were defined, the next step was the verification of the model to check if the results correspond to the reality.

Firstly, the casual gains patterns had to be checked in order to be sure that they follow the defined profiles and are presented below:

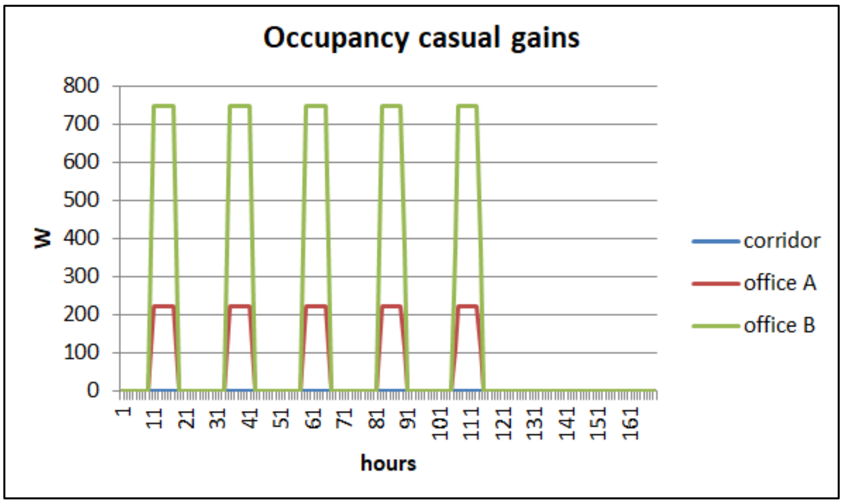


Figure 19. Occupancy casual gains during a week period (Monday to Sunday).

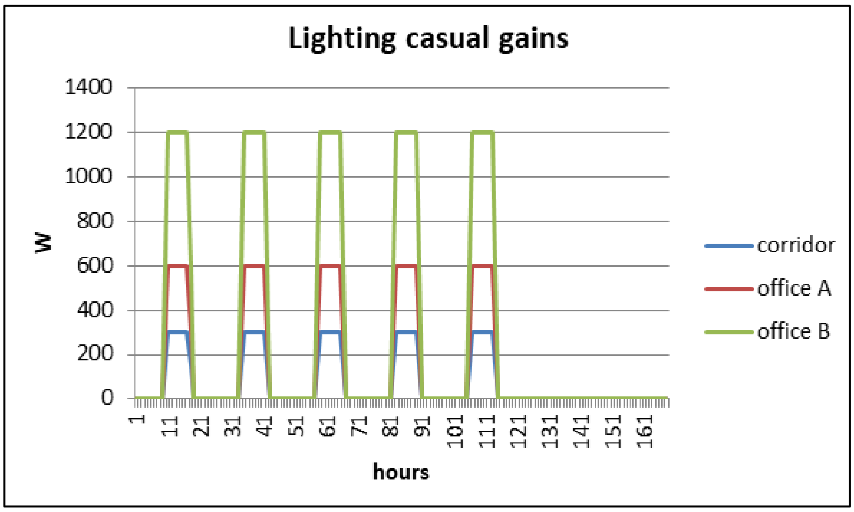


Figure 20. Lighting casual gains during a week period (Monday to Sunday).

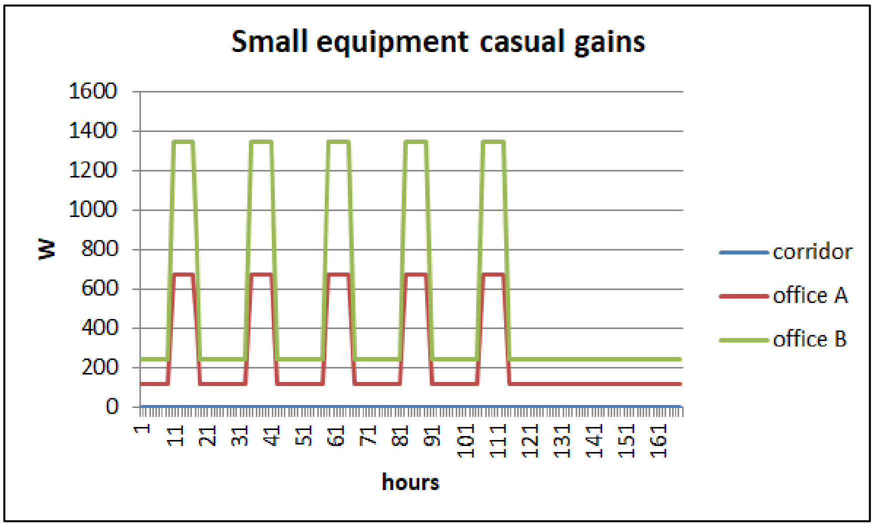
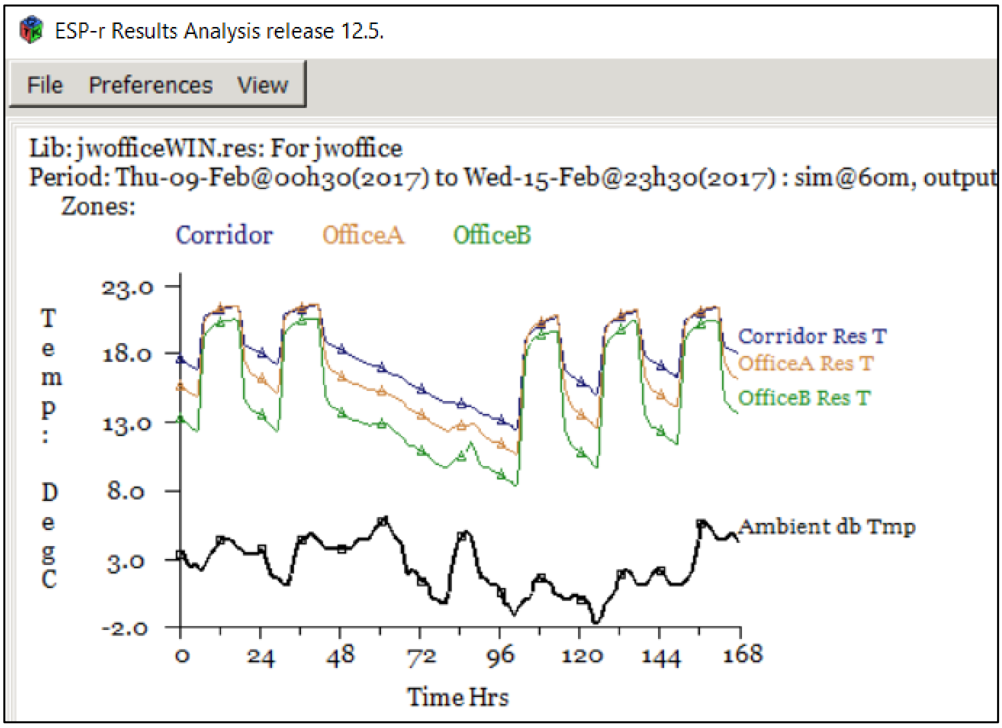


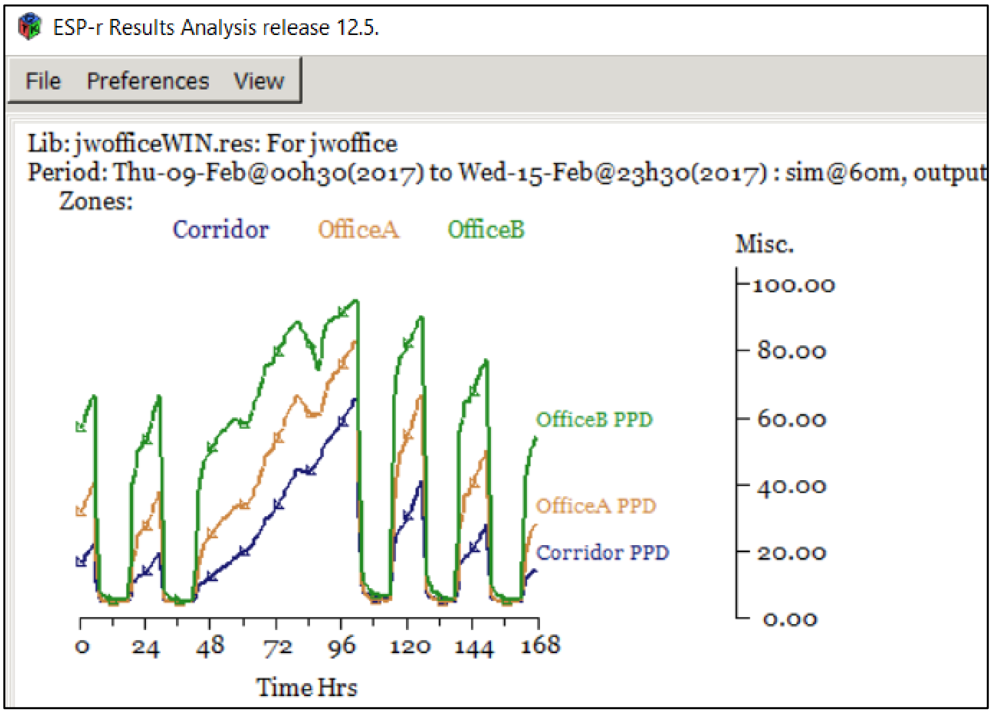
Figure 21. Small equipment (PC + monitors) casual gains during a week period (Monday to Sunday).

Then, a simulation for a winter week period from 09/02 to 15/02 (Thursday to Wednesday) was run to check if the heating system works properly. In Figure 26 below it can be observed that during the five weekdays the temperature inside the three areas is constant at 22º C and during the weekend the temperature profile is based on free floating conditions. The figure below represents the operative temperature also known as dry resultant temperature along with the ambient temperature of the environment. It is clear that during the free floating conditions the temperature patterns of the three zones are similar to the ambient temperature pattern. According to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55 – 2013 Thermal Environmental Conditions for Human Occupancy suggests that the recommended temperature ranges for thermal comfort should satisfy at least around 80% of the people during occupancy periods. In Figure 27. it can be seen that the percentage of dissatisfied people (PPD) is 5 – 10% which is less than 20%. Therefore, it can be concluded that thermal comfort conditions exist in winter. However, the situation in summer is different. As there is no cooling system in the office, the temperatures tend to be high and especially in Office B they rise up to 30 – 32 ºC in some cases. As a result the percentage of dissatisfied varies from 25 - 73% (Figure 29.).



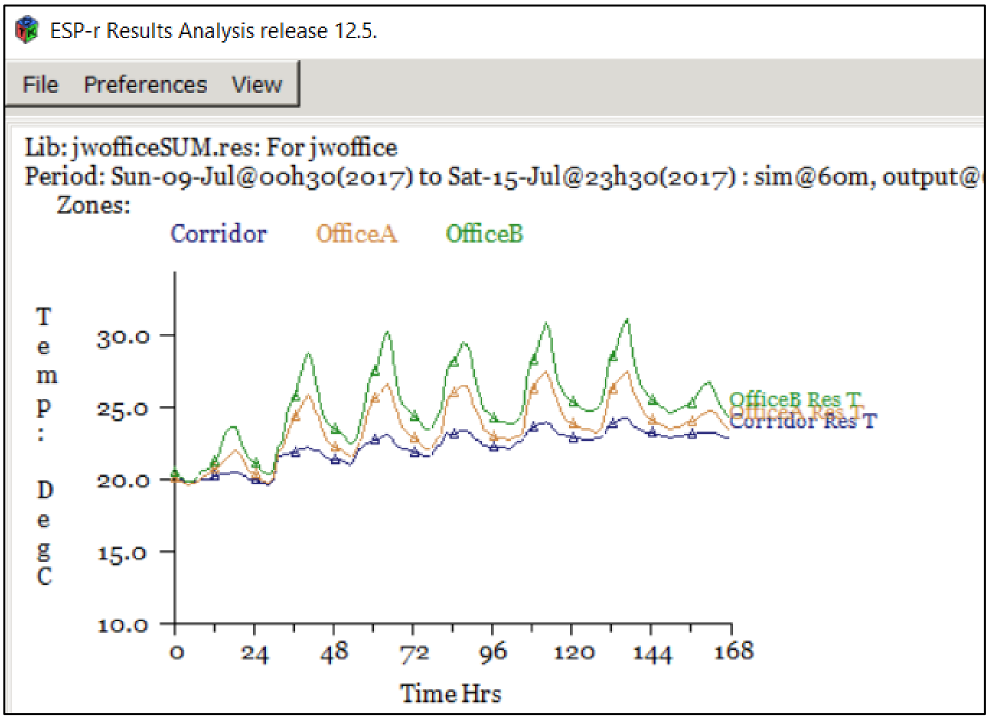
Lib: jwofficeWIN.res: For jwoffice
Period: Thu-09-Feb@00h30(2017) to Wed-15-Feb@23h30(2017) : sim@60m, output
Zones:

Figure 22. Operative and ambient temperature during a winter week period as presented in ESP-r.



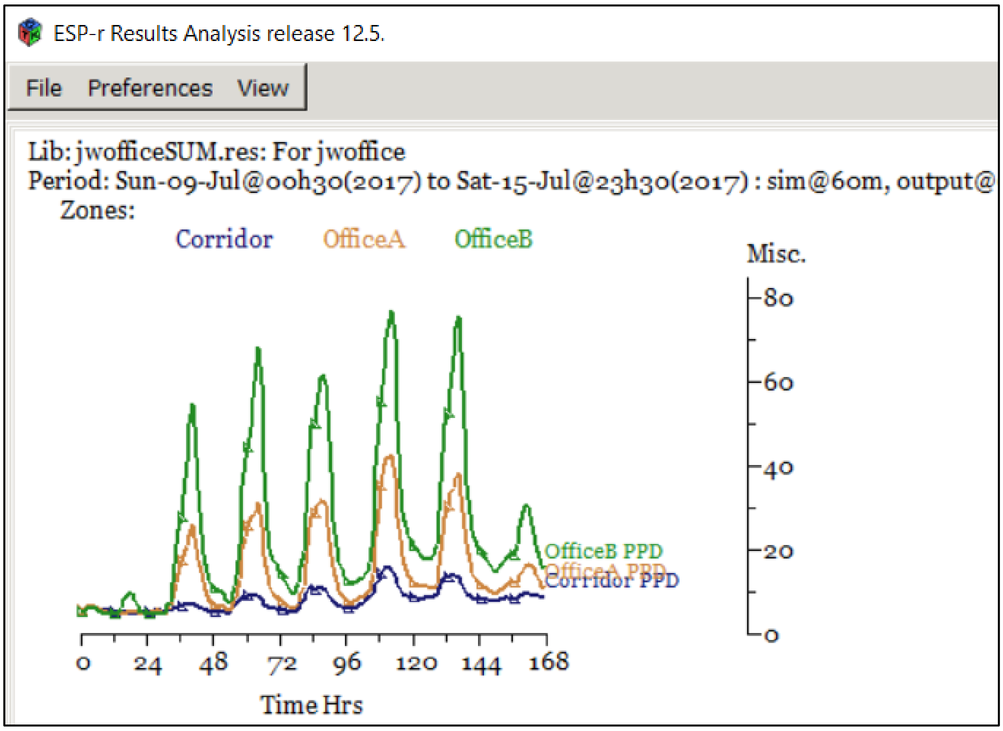
Lib: jwofficeWIN.res: For jwoffice
Period: Thu-09-Feb@00h30(2017) to Wed-15-Feb@23h30(2017) : sim@60m, output
Zones:

Figure 23. Percentage of dissatisfied during a winter week period as presented in ESP-r.



Lib: jwofficeSUM.res: For jwoffice
Period: Sun-09-Jul@00h30(2017) to Sat-15-Jul@23h30(2017) : sim@60m, output@
Zones:

Figure 24. Operative temperature during a summer week period as presented in ESP-r (closed windows).



Lib: jwofficeSUM.res: For jwoffice
Period: Sun-09-Jul@00h30(2017) to Sat-15-Jul@23h30(2017) : sim@60m, output@
Zones:

Figure 25. Percentage of dissatisfied during a summer week period as presented in ESP-r (closed windows).

The results presented in the figures above verify that the temperatures in the three zones both under winter and summer conditions seem to make sense and to represent the real ones.

8.2 Actual vs Model's heating energy consumption analysis

The final step was to do an analysis of the energy consumption data in order to verify that the model simulates the real office's operation. A comparison was made between the actual energy consumption and the modelled energy consumption data in order to prove that the model's behavior is similar to the real one.

8.2.1 Actual heating energy consumption

As it has been already stated in previous sections, data about the actual energy consumption of the James Weir Building had been gathered. These data refer to three annual periods 2014, 2015 and 2016. The variations that were detected are ordinary, reasonable and may be attributed to weather conditions, different occupancy levels and patterns, infiltration or ventilation rates, heating levels and hours, etc. The average actual heating energy consumption value of these three years was found to be 100.3 kWh/ m^2. The building has simple and homogenous geometry but except from offices there are also different kinds of areas such as small kitchens, toilets, staircases etc.

8.2.2 Model's heating energy consumption

Simulations were run in order to define the energy performance of the model and check the heating energy consumption. The modelled office is assumed to have one external and three internal walls. Running an annual simulation of the modelled office ended up with a heating energy consumption value of 93 kWh/ m^2.

Trying to be as accurate as possible, simulations were also run for the same modelled office with the only difference that there were two external and two internal walls in order to see the variation in energy consumption compared to an office that is on the corner of the building. The results showed an annual heating energy consumption of 101 kWh/ m^2.

Simulations were also run for cases that the modelled office was on the ground floor and on the top floor. It was believed that ground and top floor conditions would affect the heating consumption of the office as the heat losses would be higher. The results showed an annual heating energy consumption of 119 kWh/ m^2 and 114 kWh/ m^2 respectively.

8.2.3 Comparison conclusions

The comparison between the actual and the model's energy consumption can be observed below:

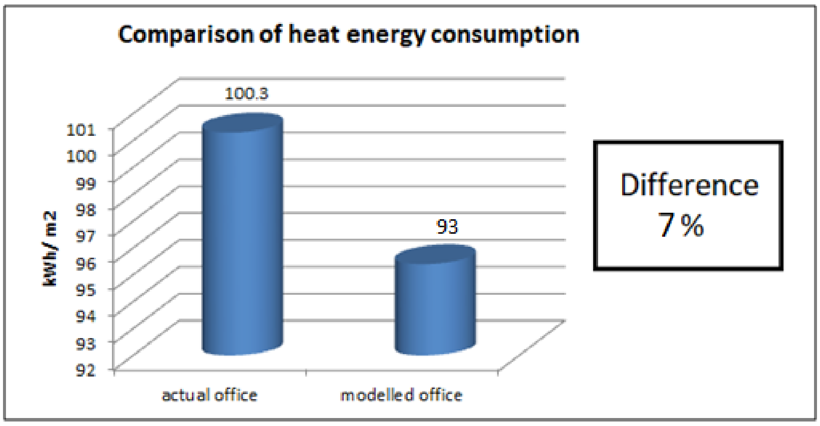


Figure 26. Comparison between the actual and model's heating energy consumption.

Finally, the comparison resulted in a difference of 7%. This difference was said to be reasonable due to all the uncertainties that exist and that have been discussed in all the previous sections and chapters. Therefore, the results of the verification of the modelled office, based on the assumptions made and the input data, showed that the model's behavior is very similar to the real one.

9. Parametric analysis of the retrofitting options

9.1 Introduction

The design of a building should optimize the conditions that exist indoors. According to ASHRAE, as thermal comfort is defined the condition of the human mind that is satisfied with the environment and does not want any thermal changes.

It is needed to regulate the climate conditions in the internal environment of buildings in order to achieve desirable conditions and well-being for the occupants. According to the European Standard EN 15251 the indoor environment is affected from factors such as thermal comfort conditions, summer thermal comfort conditions, humidity, air quality (infiltration and ventilation flow rates) as well as other factors such as acoustic and lighting levels. Appropriate components and thermal insulation of the building envelope, use of appropriate heating/ cooling systems and use of ventilation and other electromechanical systems is required to achieve the best indoor air quality while reducing the energy consumption and the CO_2 emissions.

9.2 Methodology

In this chapter, the potential building energy retrofitting options are considered, analyzed and compared to the original modelled office. The benefits regarding the thermal comfort, energy consumption and the CO_2 emissions are investigated and explored.

These retrofit options concern the following categories:

- thermal building envelope
- lighting systems
- heating systems
- ventilation systems

9.2.1 Thermal building envelope

Windows

One of the thermal envelope components of the building that is extremely important regarding its operation is the total amount of openings (windows) that exist in its opaque and solid surfaces which allow the passage of air and light. A window is consisted of the frame and the glazing which is attached to the frame. Due to the great significance of windows to the total heating energy consumption of a building, rapid technological development and evolution has been made in this sector compared to other building materials. The result of this was the construction and use of new, upgraded frames and glazing types with different properties and applications. The thermal transmittance coefficients of the frame and the glazing affect the overall thermal transmittance of the window which can be calculated according to the following equation:

$$U_{win} = (A_{fr} \cdot U_{fr} + A_{gl} \cdot U_{gl} + I_{gl} \cdot \Psi_{gl})/A_{win} \quad [W/m^2K]$$

Where,

U_{win}, is the thermal transmittance of the window

U_{fr}, is the thermal transmittance of the frame

U_{gl}, is the thermal transmittance of the glazing

A_{win}, is the area of the window

A_{fr}, is the area of the frame

A_{gl}, is the area of the glazing

I_{gl}, is the length of the inside edge of frame profile

Ψ_{gl}, is the linear heat transfer coefficient of the insulated glazing edge seal

In many reports, the areas A_{fr} and A_{gl} are expressed as percentages of the total window area A_{win}. It is clear from the equation above that the total energy behavior of the window depends also on the thermal transmittance and area of the frame. The level of dependence varies according to the area that occupies the frame compared to the total area of the window.

During the last years, the U-Values of the window glazing and frame types have been significantly decreased. Typical values can be found in CIBSE Guide A, 2006 and SAP 2012.

Frames

Frame is called the section of the window that in its inner perimeter the glazing is adjusted. The first frames used were made out of wood which on hand present high thermal insulation capacities but on the other hand they offer reduced air- tightness to the building. Then came the metal frames which were originally made out of iron and then of aluminum. They offer high air-tightness to the building but low thermal insulation capacity. There are also available synthetic (plastic) frames which present both high thermal insulation capacities and also offer high air-tightness to the building.

Glazing

The glazing is the biggest part of the window. It allows the solar irradiation to enter the building contributing to the lighting and heating of the building. However, it is also a section of the window which is responsible for the highest percentage of heat losses due to the fact that the glass has low thermal insulation capacity. Window glazing U-Values vary and are based on many parameters such as the number of glazing, the thickness of the cavity, the selection of the cavity fluid (e.g. air, argon, krypton) etc.

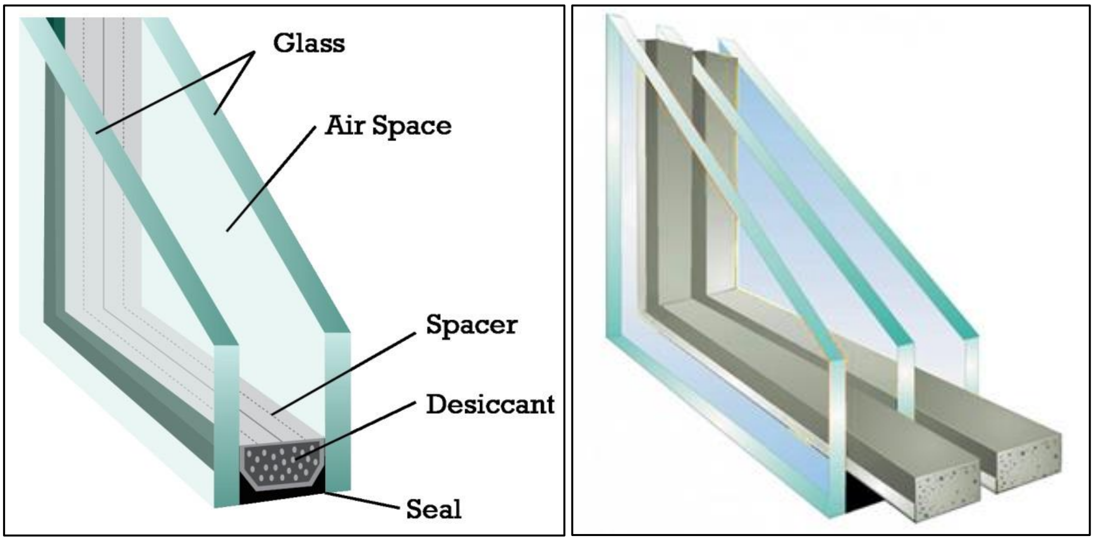


Figure 27. Double and triple glazing windows respectively. (Sources: http://www.theglazingpeople.co.uk/triple-glazing-noise-reduction/, http://www.nec-online.co.uk/4-benefits-double-glazing/)

Insulation of external walls

A closed space that is heated radiates heat to the surrounding environment. Heat can escape through the imperfections of the façade and as a result the thermal behavior of a building is affected of the thermal insulation of its envelope to address these problems. However, it is also important not to obstruct the required ventilation of the building in order to reassure the necessary refreshment of the air inside the building. In order for a building to operate well and efficiently it is significant to minimize the heat losses. Applying thermal insulation to the external walls of a building can contribute to the reduction of the thermal losses and as a result of the heating energy consumption.

9.2.2 Lighting equipment

Lighting corresponds to a significant amount of the total electricity consumption in office buildings. In commercial buildings, lighting generally accounts for 20 - 45% of the total electricity demand.

One way of reducing the energy consumption of lighting in existing buildings is to implement control strategies. For example, such strategies can be linking the lighting with the daylight and implement an automatic control or setting occupancy based control of the lights etc. In office buildings, that the lighting consumes a large amount of energy, implementing an occupancy based control system can lead to a significant reduction of the energy use. Studies have shown that in some cases the percentage of energy saving can reach up to 60% (Dubois & Blomsterberg, 2011) (de Bakker, et al., 2017). Of course this depends on the building space characteristics, the working times of the employees or the configuration type installed (Von Neida, et al., 2001).

Another way of saving energy from lighting is to use more efficient luminaries such as T5 Fluorescent or LEDs. Over the last decade, the interior lighting technologies are evolving and a new generation of lights is now widely used in commercial buildings. Light-emitting diodes (LED) are expected to replace half of the total lamps in 2020. This type of lamps present many benefits compared to other types of lamps. They have properties such as long lifetime, higher efficacy, lighting quality, dimmability.

9.2.3 Heating Systems

Heat Pumps

The effort to minimize the operating costs of the heating systems, to become independent from the fossil fuels, to reduce the energy consumption and the carbon emissions so as to protect the environment has led to the evolution and use of heat pumps.

Heat pumps are electrical devices that have the potential to extract heat from one area and transfer it to another. As it is known, heat has a natural flow from warmer conditions to colder conditions. Heat pumps have the ability to operate in the opposite way by absorbing heat from low temperature heat sources and releasing it to warmer ones. The efficiency is measured with the coefficient of performance (COP) which can even reach a value of 5.

There are different types of heat pumps which exploit different sources of low grade heat like ground source, air source and water source heat pumps and all of them have the same operating principles.

Biomass wood pellet boilers

Biomass heating is a mature and proven technology which is used in many countries since many years ago. A biomass wood pellet boiler can be another alternative heating system solution instead of the natural gas boiler.

Biomass is called every material that is produced by living organisms such as wood, remains of crops, livestock waste etc. and can be used as fuel for energy generation. According to the Carbon Trust's Biomass Sector Review, there is a high potential for the UK to save up to 20 million tonnes of CO_2 annually by using biomass for heating purposes.

Biomass is thought to be a renewable source of energy. However, there is an argument into this topic. Of course burning biomass releases carbon emissions but this can be offset if the amount of biomass used to produce the fuel materials is regrown. The situation in reality is more complicated because there are more emissions that refer to the harvest, transport and distribution of biomass but theoretically the carbon cycle can remain in balance.

Wood pellets are a kind of wood fuel which are usually made from compressed sawdust, branches and other wood waste remains. They are small, extremely dense and contain low percentage of moisture which allows them to burn with very high combustion efficiency.

Their main characteristics of the pellets according to the international ENplus certification - ISO 17225-2 standard are:

Parameter	**Value**
Diameter	6 – 8 mm
Length	30 – 40 mm
Ash content	< 3%
Humidity	8 – 10%

Table 29. Wood pellet parameters

Figure 28. Wood pellet

There is a wide range of pellet boilers in the market for different appliances. This kind of boilers presents very high efficiencies and very low emissions to the environment. However, important is the cleaning and the maintenance in order to operate properly (Energy Saving Trust - Biomass).

9.2.4 Ventilation systems

Mechanical ventilation with heat recovery systems

The use of a heat exchanger allows the HVAC systems to recover most of the heat which is rejected with the exhaust air and transfer it to the supply air. In each building type that there is mechanical ventilation, large amounts of air are discharged into the environment and replenished by incoming air which has to be heated (or cooled in some cases) by several degrees Celsius. Thus, the use of a heat exchanger allows the exploitation of the heat of the rejected air in order to preheat the incoming air. This reduces the thermal energy load and can be achieved energy savings up to 95%.

10. Results analysis

10.1 Thermal Envelope

10.1.1 Windows

The following glazing and frame options were analyzed so as to investigate the influence on the heating energy consumption of the modelled office.

Window type	U - Value (W/m2K)	Frame type	U - Value (W/m2K)	Annual final energy consumption (KWh)			
				Office B	Office A	Corridor	Total
Double glazing	2.811	Aluminum	2.193	10048.6	6484.2	3520.45	20053.25
		PVC	1.751	9937	6505.2	3523.1	19965.3
		PVC	1.054	9807.16	6478.53	3521.28	19806.97
Triple glazing_u1.8	1.897	Aluminum	2.193	9746.2	6482.1	3521.24	19749.54
		PVC	1.751	9644.2	6504.4	3525.9	19674.5
		PVC	1.054	9508.9	6485.96	3521.86	19516.72
Triple glazing_u1.08	1.081	Aluminum	2.193	9417.2	6460.21	3513.2	19390.61
		PVC	1.751	9293.7	6482.1	3521.2	19297
		PVC	1.054	9123.58	6452.35	3413.72	19069.65
Triple glazing_u0.831	0.831	Insulated Frame	0.46	8886.34	6425.07	3438.53	18750.5

Table 30. Annual heating energy consumption based on different glazing and frames options.

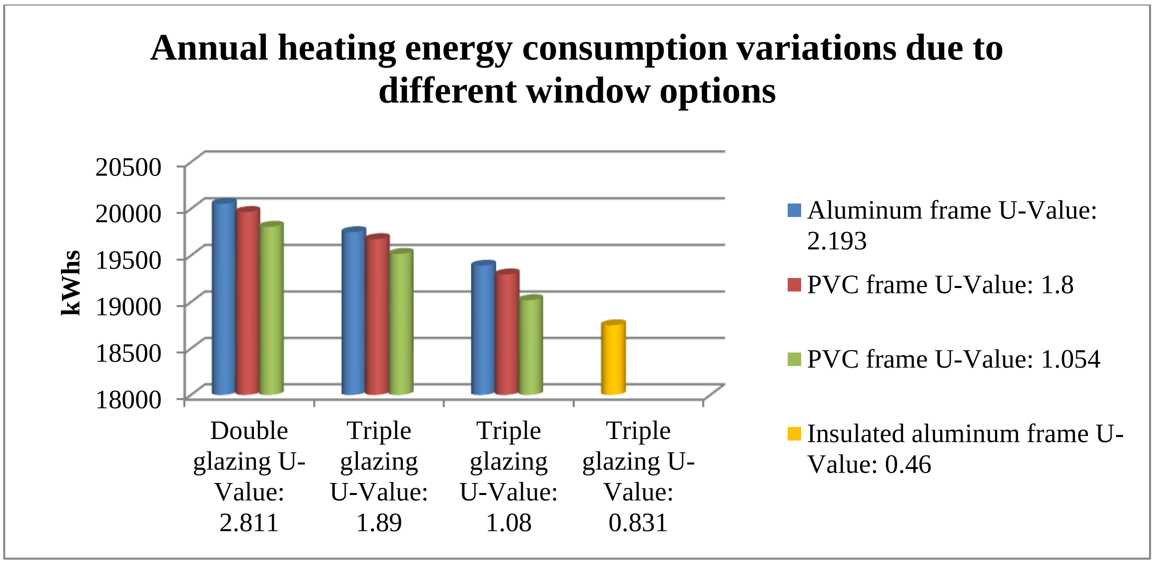


Figure 29. Comparison of annual heating energy consumptions based on different window options.

From Figure 33 it is clear that the annual heating energy consumption is affected from the window types. As the thermal transmittance of the window elements decreases, the annual heating consumption also decreases. Replacing the current windows (double glazing, aluminum frame) with windows of triple glazing with U-Value 1.08 and PVC frame with U-Value 1.054 can lead to 5% reduction of the annual energy consumption of the modelled office.

10.1.2 Insulation of the external walls

Cavity filling insulation

As it was explained in section 7.4 in chapter 7, the external walls are cavity brick walls. They consist of a 100 mm outer leaf brick layer, a cavity of 40 mm and an inner leaf brick layer. The modelled office has one external wall and Different thicknesses of mineral fiber insulation were tested in order to investigate the differences on the heating energy consumption throughout a whole year.

Insulation type	**Thickness (mm)**	**U - Value (W/m2K)**	**Annual heating energy consumption (KWh)**			
			Office B	**Office A**	**Corridor**	**Total**
mineral fiber	10	1.19	10048.6	6484.2	3520.45	20053.25
mineral fiber	20	0.874	9725.45	6442.9	3505.22	19673.57
mineral fiber	30	0.717	9510.05	6414.7	3494.75	19419.5
mineral fiber	40	0.618	9315.29	6393.31	3486.2	19194.8

Table 31. Annual heating energy consumption based on different thicknesses of insulation.

Implementing the maximum amount of insulation in the cavity reaches to a total reduction of 4.2% of the annual heating energy consumption. This value is not matching to the reality as the energy savings from the insulation of the external walls will be higher if an analysis for the whole floor of the building is performed. Office A and the Corridor do not have any external walls so the difference in the annual energy consumption is very small. The most important observations of this analysis refer to Office B.

The results show that as the insulation thickness increases, the annual energy consumption decreases. Implementing the maximum amount of mineral fiber in the cavity means around 8% and 4.2% reduction of the annual heating energy consumption of Office B and the modelled office respectively.

Exterior insulation to the external wall

Apart from filling the cavity with insulation material, insulation can also be added to the exterior surface of the external walls of the modelled office. In order to meet the Passive House Standard criteria, the U-Value of the external walls should not exceed 0.15 W/ m^2 K. Thus, apart from filling the cavity with insulation (40 mm), adding a layer of exterior insulation to the external wall results in:

Insulation type	Thickness (mm)	U - Value (W/m2K)	Annual heating energy consumption (KWh)			
			Office B	Office A	Corridor	Total
mineral fiber (exterior)	300	0.109	8552.19	6372.5	3349.38	18274.07

Table 32. Annual heating energy consumption based on full (40 mm) cavity insulation plus (300 mm) exterior insulation.

10.2 Lighting

In the James Weir office analysis, the lamps which are already installed are of T5 Fluorescent type (28 W and 35 W) which present high efficacy between 96 lm/ W and 104 lm/ W. As a result there is no need to replace them as T5 Fluorescent lamps have excellent performance rating, long life and are considered to have an A+ energy efficiency class (EEC).

10.3 Heating Systems

10.3.1 Current situation – Natural gas boiler

At the moment, a natural gas boiler is installed in the James Weir Building. According to CIBSE Guide KS14 a standard, non-condensing natural gas boiler has a seasonal efficiency of around 70 – 80 % depending on the design. The Carbon Trust (2012) Low temperature hot water boilers report informs that a typical seasonal efficiency for a standard, good condition natural gas boiler is around 70%. As there were no available data about the natural gas boiler that is used for heating, an average value of 75% was selected in order to perform an analysis.

Heating system type	**Efficiency**	**Final heating energy consumption (kWh)**	**Primary heating energy consumption (kWh)**
Natural gas boiler	75 %	20053.25	26737.66

Table 33. Primary and final heating energy consumption using a natural gas boiler.

10.3.2 Alternative options

Firstly, simulations were run in ESP-r in order to find the maximum heating load for the modelled office, which was found to be 28 kW.

Area	**Maximum heating load (kW)**
Modelled office	28
Office B	14
Office A	9
Corridor	5

Table 34. Maximum heating loads

Heat pumps

An analysis was performed to investigate the effects of different types of heat pumps to the total annual energy consumption of the modelled office.

Air Source Heat Pumps - Air to water

This kind of heat pumps absorbs heat from the outside air and heats water which is then recirculated through radiators or underfloor to provide heating to the building.

The air to water heat pump that was selected for the analysis was the NIBE F2300 to cover the heating demand. These heat pumps can provide a maximum heating output of 14 or 20 kW and can be connected in parallel so as to cover higher demands. These air source heat pumps operate with outside air temperatures from -25º C to +35º C. Of course the COP varies according to the climate temperature. The UK is considered to have a moderate winter climate with an average winter temperature of 5º C. The seasonal COPs of the 14 and 20 kW heat pump are 3.18 and 2.91 respectively for outlet water temperatures of 55º C.

Air Source Heat Pumps - Air to air

This kind of heat pumps absorbs heat from the outside air, transfers it and releases it to the interior of the building as hot air. This type can also provide cooling during the summer period with an EER of 3.11. The air to air heat pump Panasonic CU-5Z90TBE with power from 4.5 to 17.5 kW was selected which has a seasonal COP of 4.2 (minimum and maximum COP values of 3.42 and 6.42 respectively).

The results from the analysis are presented below:

Heating system	**COP**	**Final heating energy consumption (kWh)**	**Primary heating energy consumption (kWh)**
Air to water heat pump	3.18	20053.25	6306.05
Air to air heat pump	4.2	20053.25	4774.5

Table 35. Primary and final heating energy consumption using different types of heat pumps.

Biomass wood pellet boiler

For this analysis the Windhager Biowin 2 Touch was selected. It is a state of the art boiler which consumes wood pellets, can provide heat outputs from 3 – 33 kW and has a nominal efficiency of 94%.

Heating system	**Efficiency**	**Final heating energy consumption (kWh)**	**Primary heating energy consumption (kWh)**
Wood pellet boiler	94%	20053.25	21333.24

Table 36. Primary and final heating energy consumption using different types of wood pellet boiler

Comparison

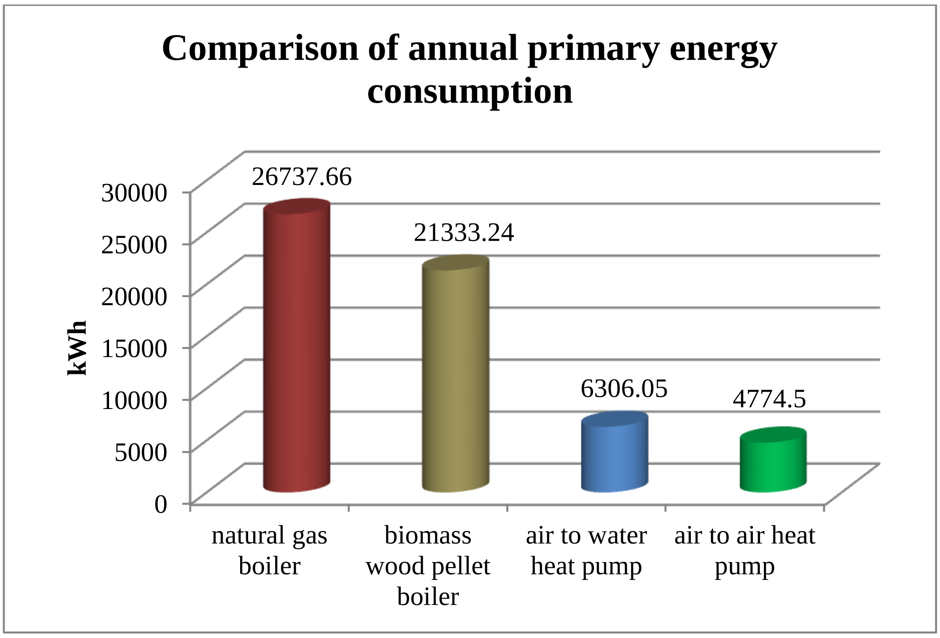


Figure 30. Comparison of annual primary energy consumption based on different heating systems.

From Figure 34 above can be observed that the biomass boiler consumes less primary energy compared to the natural gas boiler but the implementation of air source heat pumps reduces significantly the amount of the annual primary heating energy consumption. From the tested air source heat pumps, the air to air heat pump performs better. A comparison between the air to air heat pump and the current situation's natural gas heating system demonstrates a reduction of 79 % to the annual primary energy consumption.

10.4 Ventilation systems

10.4.1 Mechanical ventilation with heat recovery systems

In Office A there is a mechanical ventilation system. Hence, an analysis was performed to investigate the differences between the current annual energy consumption and the one after installing a heat recovery system.

As it has been already explained before, in Office A during occupancy periods the mechanical ventilation system delivers 2 ac/ h in order to achieve a ventilation rate of around 10 L/s/ person or 116 L/s.

There are many options of heat recovery systems in the market. For this analysis the CA550 ComfoAir 550 Model of the Greenwood Airvac Company was used as there were available the datasheet features. This system can allow an air flow rate of up to 170 L/s with a heat efficiency of 85%. More information can be accessed to Greenwood Airvac: http://www.greenwood.co.uk/uploads/docs/344.pdf

Air from outside is entering in Office A through the mechanical ventilation system. This air has then to be heated to 22º C which is the heating set point. This air flow is constant at 2 ac/ h during occupancy periods and the heat losses every hour were calculated in ESP-r. After installing the heat recovery system the heat losses were reduced by 85%.

Simulations were run in ESP-r in order to investigate the difference in the annual energy consumption and the results are presented in the Figure 35 below:

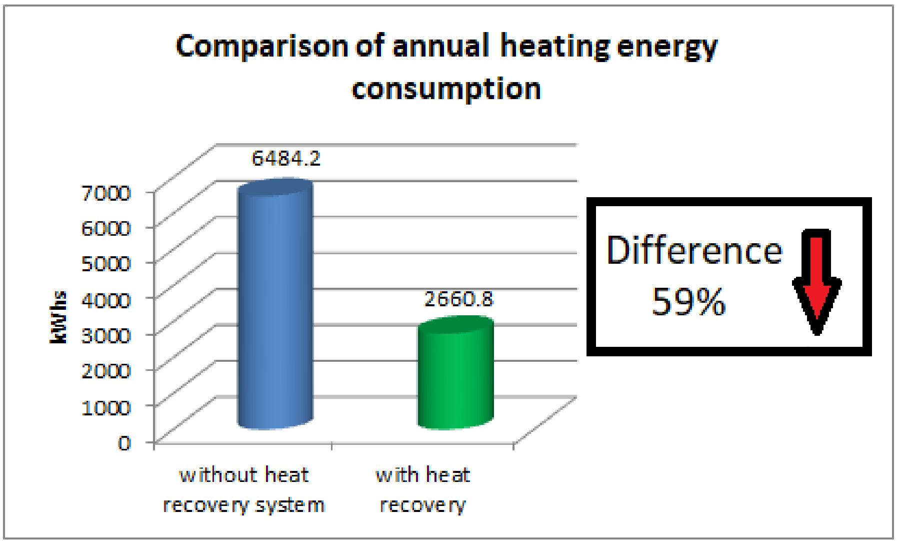


Figure 31. Comparison of the annual heating energy consumption

It is clear that there is significant difference between the current annual energy consumption and the one after implementing the heat recovery system. Such a system with high efficiency leads to an annual heating energy reduction of 59%.

However, in order to be accurate, the electricity consumption of the fans of the heat recovery system has also to be included in the total energy consumption. According to the datasheet this heat recovery unit consumes around 105 W when operating on boost mode. Therefore, knowing from ESP-r that the total heating hours for Office A were 2352 throughout a whole year, results in an energy consumption of 246 kWh. Adding this value to the annual heating energy consumption with installed the heat recovery system equals to 2906 kWh of total energy consumption. In other words, the total energy consumption is reduced by 55.2%.

In Office B, there is not a mechanical ventilation system and there is only natural infiltration. The same mechanical ventilation system was also considered in order to investigate the differences to the annual heating energy consumption. Based on the occupancy levels and in order to have appropriate ventilation rates per person, it was found that there is a need of providing a ventilation level of 2.5 ach. Adding the mechanical ventilation with recovery reduced the annual heating energy consumption and the results are presented in the figure below:

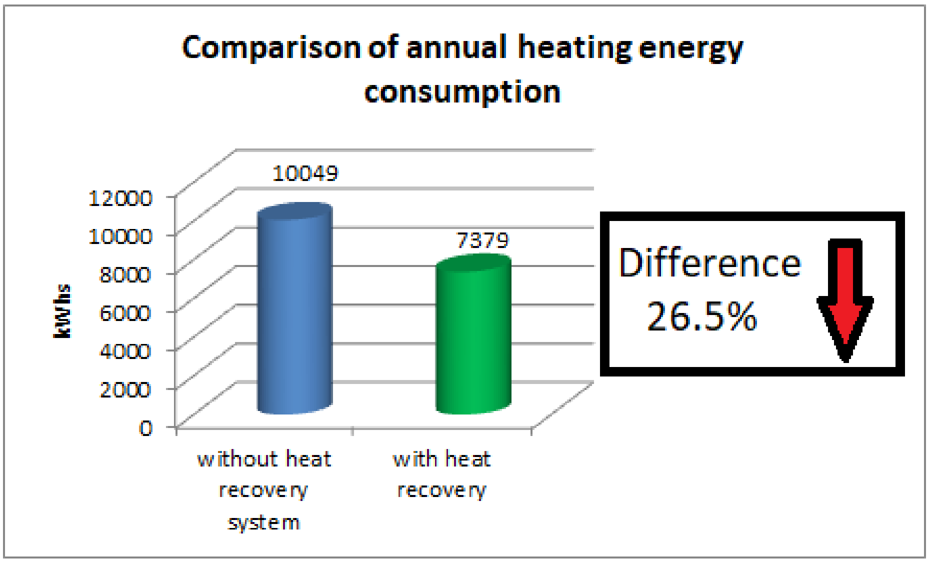


Figure 32. Comparison of the annual heating energy consumption for Office B

The total heating hours over a yearly period for Office B are 2489 h. Thus, the electricity consumption of the heat pump equals to 261 kWh. Therefore, the total annual final energy consumption of Office B is 7640 kWh which is 24% less than the current energy consumption.

The difference in the annual final heating energy consumption of the Office B which is 24% less than the current situation is much lower than in case of Office A which is 55% less than now. However, this has a logical explanation. Currently, Office B does not have a mechanical ventilation system. It is naturally ventilated only and the infiltration rate is 1 ach which is not enough to provide with 8 – 12 L/s per person of fresh air. Therefore, by adding the mechanical ventilation system the ach are increased to 2.5 ach during occupancy periods in order to provide the recommended air flow rate for an office environment and improve the indoor air quality.

10.5 Combination of retrofitting options

10.5.1 Results analysis

Simulations were also run after combining many different retrofit options. For this analysis the best retrofit options regarding the thermal building envelope and the ventilation systems have been selected in order to examine the heating energy performance.

These were:

- Triple glazing_u1.0,
- Frame PVC_u1.0,
- 40 mm external wall insulation level,
- Mechanical ventilation with heat recovery in Office A

Therefore, after implementing the combination of changes above, the following results were obtained:

Heading system	**Annual total final energy consumption (kWh)**	**Annual total primary energy consumption (kWh)**	**Annual total primary energy consumption (kWh/ m^2)**
Natural gas boiler	14518.2	19285.93	92.8
Air to air heat pump		3456.71	16.4
Air to water heat pump		4565.47	21.7
Biomass wood pellet boiler		15444.89	73.54

Table 37. Annual primary and final energy consumption for different heating systems.

It is clear that the heating energy consumption decreases if any of the alternative options is implemented. The reduction of the final energy consumption between the current situation natural gas boiler and the biomass wood pellet boiler is equal to 20%. In the case of the two heat pumps the final energy consumption is extremely reduced and the difference reaches up to 82 %. For that reason, replacing the heating system except from higher energy performance of the modelled office will lead to a number of benefits which are going to be analyzed later in this document.

10.5.2 Thermal comfort analysis – Solution to overheating

However, considering all these retrofit options would also affect the operational conditions of the modelled office. It was important to reassure that ideal indoor temperatures would exist after implementing these retrofit options. Implementing measures that would increase the air tightness of the building would also lead to increase of the indoor operative temperatures of the modelled office. An analysis was performed for summer conditions in order to investigate the comfort performance metrics. In Figure 36 on the left, it can be observed that when the windows were closed all the time the indoor operative temperatures could reach up to 31° C depending on the outdoor conditions (ambient temperature, wind speed, wind direction, solar irradiation etc.). One solution to avoid the effect of overheating and achieve comfort indoor conditions was to install a control loop that would allow the windows to open if the inside temperature of the modelled office rose higher than 23° C. In Figure 36 on the right it can be seen that opening the windows had as a result to significantly reduce the indoor operative temperatures by 5 – 6 ° C as the maximum observed temperature was found to be around 26 ° C.

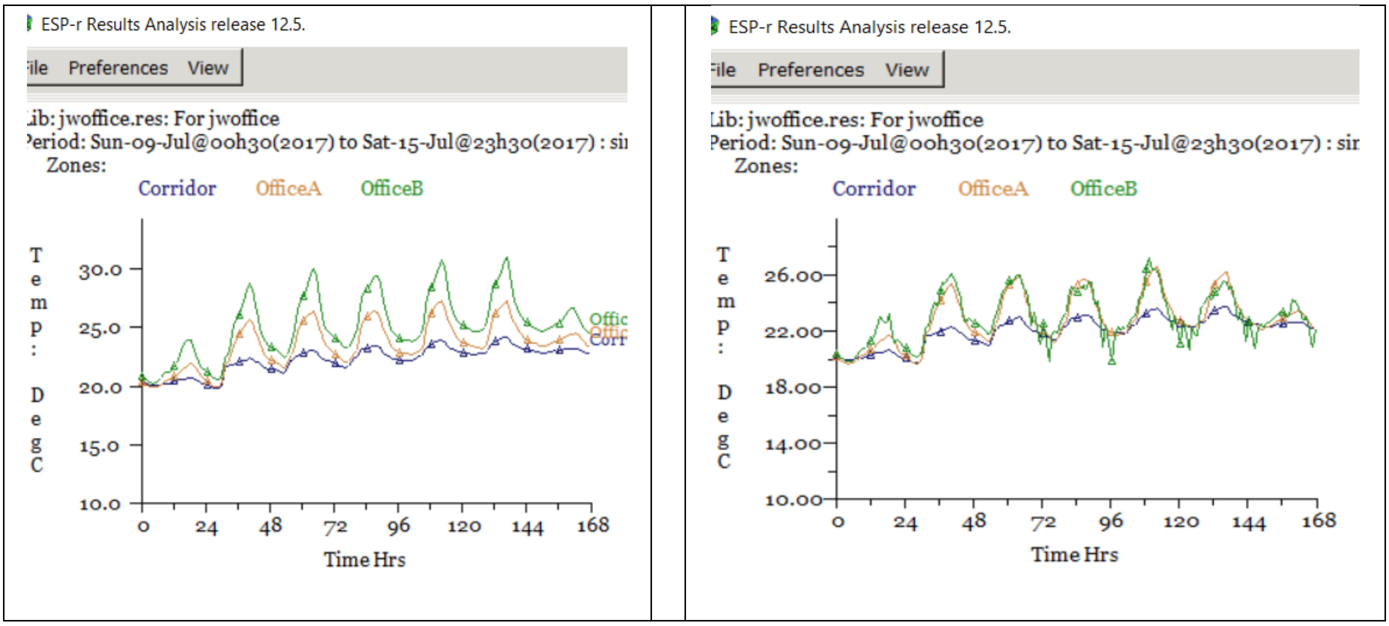


Figure 33. Operative temperatures of the modelled office areas with closed and openable windows respectively as presented in ESP-r.

Therefore, the modelled office is suffering from overheating during some days in the summer period. Reducing the indoor environment temperatures would lead to achieving thermal comfort conditions. Working under suitable indoor conditions can increase the productivity and will reduce the health risks of the occupants. In Office B area of the modelled office there is no mechanical ventilation systems. However, during operational hours the occupants are capable of opening the windows and adjust their clothing level depending on the indoor conditions. Another measure that can be also taken in order to fight the overheating effect is to install blinds to the windows to reduce the incoming solar irradiation when required. Moreover, if it is necessary mechanical ventilation systems or air conditioning systems can also be installed.

10.6 Combination of retrofitting options to achieve the Passive House Standard Criteria

10.6.1 Results analysis

Another combination of retrofitting options was examined in order to investigate whether or not the modelled office would be able to satisfy the Passive House Standard Criteria. For this analysis the retrofitting options that comply with the Passive House Standard regarding the thermal building envelope and the ventilation systems have been selected in order to examine the heating energy performance.

These were:

- Triple glazing with U-Value of 0.831,
- Insulated aluminum frames with U-Value of 0.46,
- 300 mm of insulation to the exterior of the external wall plus 40 mm cavity filling insulation level which led to an external wall with a total U-Value of 0.109,
- Mechanical ventilation with heat recovery in Office A with an efficiency of 85%
- Mechanical ventilation with heat recovery in Office B with an efficiency of 85%
- Air tightness of 0.6 @ 50 Pa
- No thermal bridges

The Blower Door test is a method used to determine the airtightness of a building. A fan is mounted on an exterior door and pulls air out of the building with a pressure differential of 50 Pa. In ESP-r exist normal conditions and the easy way to find out the equivalent ach under normal conditions is (EnergyVanguard, 2017) (U.S.Department_of_Energy, 2017):

$$1\ ach_{normal} = \frac{1\ ach_{50\ Pa}}{20}$$

In reality to find out the ach under normal conditions is a bit more complicated but this equation has also very good accuracy. Therefore, in the case of the Passive House

Standard Criteria there is a limit of 0.6 ach @ 50 Pa which is equal to 0.03 ach under normal conditions.

After inserting all these parameters to ESP-r the following results had been obtained:

Heating system	**Annual total final energy consumption (kWh)**	**Annual total final energy consumption (kWh/ m^2)**	**Annual total primary energy consumption (kWh)**	**Annual total primary energy consumption (kWh/ m^2)**
Natural gas boiler	3094.1	14.6	4125.4	19.6
Air to air heat pump			736.69	3.6
Air to water heat pump			972.9	4.63
Biomass wood pellet boiler			3291.59	15.6

Table 38. Annual primary and final energy consumption for different heating systems

It can be observed that both the annual total final and primary heating energy consumption values are below the required limits in order to comply with the Passive House Standard. Especially in the case of implementing heat pumps as the heating system the consumption values are extremely low which indicates that the office barely needs energy for heating and hot water.

However, considering the retrofitting options which meet the Passive House Standard would also affect the operational conditions of the modelled office. It was important to reassure that ideal indoor temperatures would exist after implementing these retrofitting options. Implementing these measures would increase the air tightness of the building and would also lead to the increase of the indoor operative temperatures of the modelled office. An analysis was performed for summer conditions in order to investigate the comfort performance metrics.

10.6.2 Thermal comfort analysis – Solution to overheating

Currently, buildings in the UK face overheating issues (especially under summer conditions) due to the fact that there are no air conditioning systems installed. Existing buildings suffer from the impacts of climate change such as the higher ambient temperatures because these constructions were not designed to provide thermal comfort conditions under these circumstances. The number of hot days per year as well as the intensity and duration of heatwaves are increasing and the effect of overheating is taking place more frequently than before (Auzeby, et al., 2017) (Baborska-Narozny & Grudzinska, 2017) (Cleugh & Grimmond, 2012) (Pyrgou, et al., 2017) (Gourlis & Kovacic, 2017).

In this analysis, it was found that during summer conditions the operative temperatures of the modelled office could reach up to 37 ºC. This temperature level is unacceptable because it exceeds the thermal comfort conditions that are required in office environments. No human can effectively work under these conditions. As a result, during operational hours the occupants are capable of opening the windows and adjust their clothing level depending on the indoor conditions. Implementing a control loop in ESP-r that would allow the occupants to open the windows led to a significant reduction of the indoor operative temperatures.

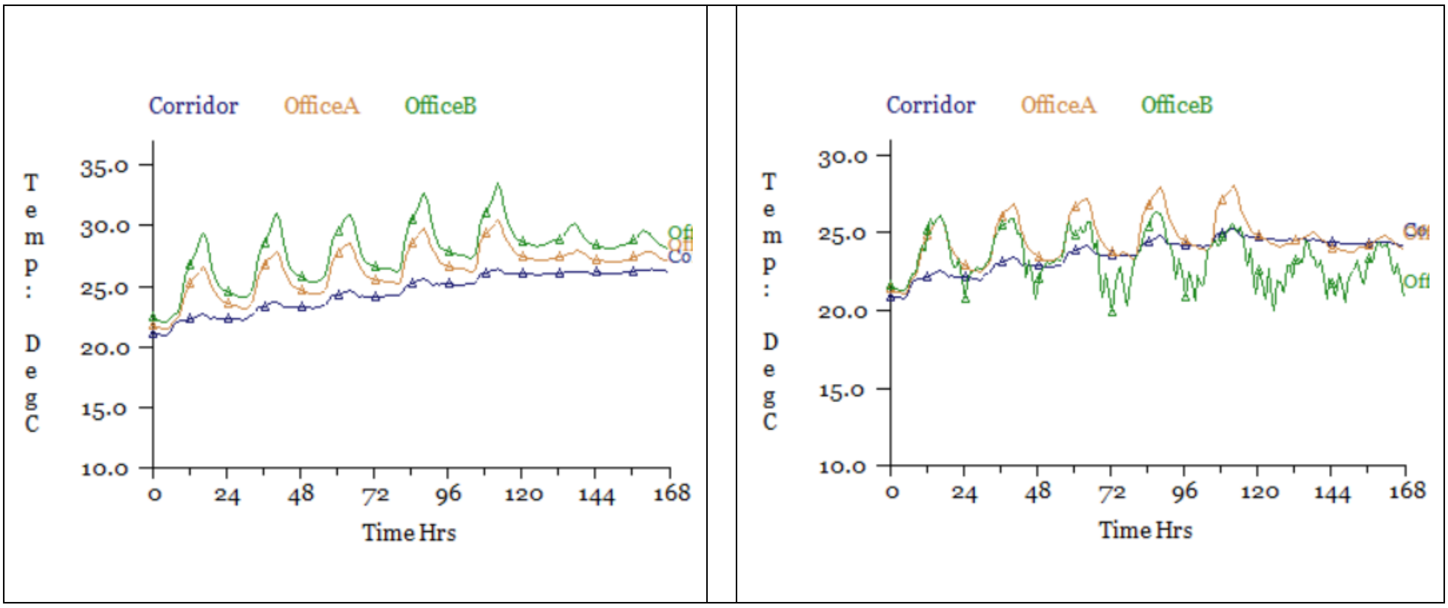


Figure 34. Operative temperatures of the modelled office areas with closed and openable windows respectively as presented in ESP-r (under Passive House Standard Criteria).

Another measure that can be also taken in order to fight the overheating effect is to install blinds to the windows to reduce the incoming solar irradiation when required. Lastly, if necessary, installing air condition systems would reassure that the indoor temperatures would never exceed the specified value and will always provide thermal comfort conditions to the building. However, installing air conditioning would lead to increase of the electricity consumption.

11. Environmental Impact Analysis

11.1 Introduction

The UK Government has as a target to reduce the carbon dioxide emissions of 1990 by 42% until 2020 and by 80% until 2050. Many strategies are implemented in order to achieve this target. Except from reduction in the primary or final annual energy consumption, the retrofit options lead also to benefits from environmental point of view. As it has been already stated, buildings are responsible for around one third of the global greenhouse gas emissions (Andrić, et al., 2017) (Peng, 2016) (Serrenho, et al., 2016). Retrofitting and upgrading options can contribute to the reduction of the pollutants emissions and mitigation of their environmental impact. Studies have shown that the operational stage of a building accounts for most (even 80-90%) of the total energy consumption and as a result of the CO_2 emissions over its lifetime (which in the UK it is considered to be 60 years for both commercial and residential buildings) (Malmqvist, et al., 2011) (Zabalza Bribián, et al., 2011). The carbon dioxide emissions from the operational stage are attributed to the heating/ cooling systems, the ventilation systems, the lighting, the office equipment such as the PCs, the printers and all the rest electromechanical equipment of the building.

11.2 Heating Systems

According to the UK Government the conversion factors for the greenhouse gas (GHG) reporting for year 2016 for natural gas, wood chips and electricity are presented in the Table below:

Fuel	Unit	kg CO_2	kg CH_4	kg N_2O
Natural gas	kWh	0.20405	0.000028	0.00011
Electricity	kWh	0.40957	0.00039	0.00209
Wood chips	kWh	0.01307	-	-

Table 39. Conversion factors for GHG reporting 2016.

The emissions of CH_4 and N_2O in kg/ kWh are very low. Therefore, the analysis focuses on the CO_2 which is the most significant greenhouse gas emitted in Earth's atmosphere and the results are presented below:

Heating system	**Final annual energy consumption (kWh)**	**Primary annual energy consumption (kWh)**	**Total annual CO2 emissions (kg)**
Natural gas boiler	20053.25	26737.66	5455.81
Air to air heat pump		4774.5	1955.49
Air to water heat pump		6306.05	2583.76
Biomass wood chip boiler		21333.24	278.82

Table 40. Comparison of the primary, final and CO_2 emissions among different heating systems.

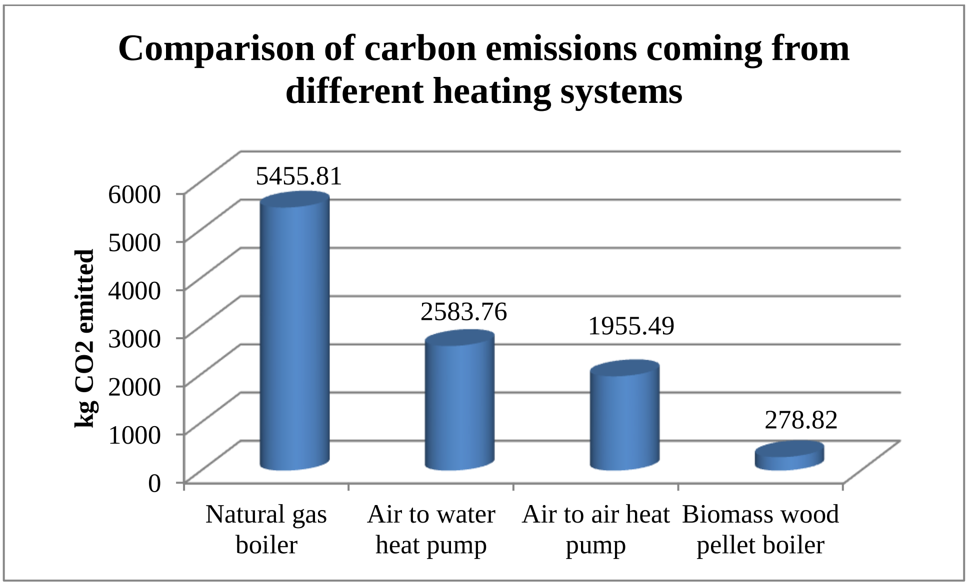


Figure 35. Comparison of CO_2 emissions coming from different heating systems.

The analysis resulted in valuable conclusions. The natural gas boiler represents the worst case regarding the annual carbon emissions. All the examined heating systems perform better in terms of CO$_2$ emissions. In the case of the heat pumps there is a difference in the results but this is attributed to the COP of the two kinds of heat pumps. It is not right to say that the air source heat pumps have less carbon emissions are for this analysis specific brands of heat pumps were analyzed. However, it is clear that the heat pumps can offer significant carbon savings compared to the natural gas boiler as they always perform better no matter how low is going to be the COP. In the case of the biomass wood pellet boiler it can be observed that the annual emission level is extremely lower than any other case. It should be noted that these calculations have been performed by taking into consideration the greenhouse gas conversion ratings of 2016 published by the UK Government. In reality, as it is previously explained biomass can be considered a renewable source of energy with no or very low carbon dioxide emissions under specific conditions.

11.3 Thermal Envelope

11.3.1 Windows

The different window types result in different annual carbon dioxide emissions. Selecting window types with lower U-Values reduces the total annual final energy consumption and the carbon emissions. The results are presented in the table below:

Window type	U – Value (W/m2K)	Frame type	U - Value (W/m2K)	Total annual final energy consumption (kWh)	Total annual primary energy consumption (kWh)	Annual CO2 emissions (kg)
double glazing	2.811	Aluminum	2.193	20053.25	26737.6	5455.82
		PVC	1.751	19965.3	26620.4	5431.89
		PVC	1.054	19806.97	26409.2	5388.81
triple glazing_u1.8	1.897	Aluminum	2.193	19749.54	26332.72	5373.19
		PVC	1.751	19674.5	26232.6	5352.77
		PVC	1.054	19516.72	26022.29	5309.84
triple glazing_u1.08	1.081	Aluminum	2.193	19390.61	25854.1	5275.53
		PVC	1.751	19297	25729.3	5250.07
		PVC	1.054	19019.65	25359.5	5174.61
Triple glazing_u0.831	0.831	Insulated Frame	0.46	18750.5	25000.66	5101.38

Table 41. Annual primary and final energy consumption and carbon emissions of different window types.

11.3.2 Insulation of the external walls

Implementing higher levels of insulation also reduces both total annual energy consumption and the carbon dioxide emissions. It can be concluded from the table below that filling the cavity of the external walls completely with insulation leads to the highest reduction of the carbon emissions.

Cavity filling insulation

Insulation type	Thickness (mm)	U - Value (W/m2K)	Total annual final heating energy consumption (KWh)	Total annual primary heating energy consumption (KWh)	Annual CO2 emissions (kg)
mineral fiber	10	1.19	20053.25	26737.67	5455.82
mineral fiber	20	0.874	19673.57	26231.43	5352.52
mineral fiber	30	0.717	19419.50	25892.67	5283.40
mineral fiber	40	0.618	19194.80	25593.07	5222.27

Table 42. Annual primary and final energy consumption and carbon emissions of different insulation levels.

11.4 Ventilation systems

11.4.1 Mechanical ventilation with heat recovery systems

Implementing a mechanical ventilation system with heat recovery reduces significantly the annual primary and final energy consumption. However, installing heat recovery system means electricity consumption in order for the fans to operate. The annual carbon dioxide emissions were calculated by taking into account both the conversion factors of 2016 for the greenhouse gas reporting for natural gas and electricity and presented below:

Ventilation type	**Annual final energy consumption (kWh)**	**Annual primary energy consumption (kWh)**	**Annual CO2 emissions (kg)**
Mechanical ventilation with heat recovery in Office A and B	13361.1 natural gas + 504.42 electricity	17814.8 + 504.42	3841.6

Table 43. Annual primary and final energy consumption and carbon emissions of the modelled office after implementing mechanical ventilation with heat recovery to Office A and B.

11.5 Combination of retrofitting options

Simulations were also run after combining many different retrofit options. For this analysis the best retrofit options regarding the thermal building envelope and the ventilation systems have been selected in order to examine the possible carbon emissions savings.

These were:

- Triple glazing_u1.0,
- Frame PVC_u1.0,
- 40 mm external wall insulation level,
- Mechanical ventilation with heat recovery in Office A

Therefore, after implementing the combination of changes above, the following results were obtained:

Heating system	**Annual total final energy consumption (kWh)**	**Annual total primary energy consumption (kWh)**	**Annual CO_2 emissions (kg)**
Natural gas boiler	14518.2	19285.93	3935.29
Air to air heat pump		3456.71	1415.76
Air to water heat pump		4565.47	1869.87
Biomass wood pellet boiler		15444.89	201.86

Table 44. Primary and final energy consumption and carbon emissions for different heating systems.

Regarding the environmental point of view, all the considered alternative heating system options are performing better. The carbon emissions are significantly reduced compared to the current situation in a great extent. The air to air heat pump Panasonic CU-5Z90TBE reduces the emissions by 64 % and the air to water heat pump NIBE F2300 by 52.4 %. The best heating system option is definitely the biomass wood pellet boiler as it leads to an annual carbon emissions reduction of 94.8 %.

11.6 Combination of retrofitting options to achieve the Passive House Standard Criteria

An analysis was also performed to investigate the carbon dioxide savings after considering the retrofitting options that comply with the Passive House Standard Criteria. The results are summarized in the following table:

Heading system	Annual total final energy consumption (kWh)	Annual total primary energy consumption (kWh)	Annual CO_2 emissions (kg)
Natural gas boiler	3094.1	4125.4	841.78
Air to air heat pump		736.69	301.72
Air to water heat pump		972.9	398.4
Biomass wood pellet boiler		3291.59	43.02

Table 45. Primary and final energy consumption and carbon emissions for different heating systems in Passive House case.

As it was expected, implementing retrofitting options that comply to the Passive House Standard would have the highest carbon dioxide savings compared to the rest cases that were examined. Currently, the heating system of the modelled office is natural gas boiler and the annual carbon emissions were found to be 5455.81 kg. From Table 45, it can be observed that the annual CO_2 emissions after achieving the Passive House Standard and without changing the heating system are 841.78 kg which indicates a reduction of 84%. Of course, considering alternative heating systems lead to higher carbon savings.

12. Discussion

Firstly, it is clear that Europe is moving towards a new sustainable era with lower carbon emissions. There are a number of policies and green buildings rating systems that promote energy efficiency and environmental protection.

After analyzing the actual energy consumption data of James Weir Building and the expected energy consumption data provided by the EPC rating, it is clear that there is a significant discrepancy. Comparing these data led to the conclusion that the actual energy consumption is underestimated by 65 kWh/ m^2 or 31.4 % compared to the EPC. As it has been already explained, the EPC rating comes from a process which is based on a predictive method. The EPC does not take into account the electrical appliance use which means that the electricity consumption is lower than the actual one. There are also many uncertainties and assumptions made while estimating the building performance that can lead to variances to the input and output data. Moreover, the thermal bridging effect plays a considerable role in calculating the actual thermal losses and it is difficult to predict and model. Of course information regarding occupancy patterns and operation hours have significant effect on the energy performance of a building and can contribute to false calculations as these values are usually estimated. Thus, the real building energy rating class is worse than C that is attributed by the EPC.

Due to these discrepancies, the use of dynamic simulation tools can contribute to a more accurate calculation of the energy performance of a building. Using, ESP-r made it possible to model the office and observe that the energy consumption of the modelled office was just 7% lower than the actual one. This difference was reasonable due to all the uncertainties that exist and that have been discussed in all the previous sections and chapters. Therefore, the results of the verification of the modelled office, based on the assumptions made and the inserted input data, revealed that the model's behavior is very similar to the real's one and that the energy performance of the built model is extremely accurate. Hence, dynamic simulation tools can constitute a reliable way of calculating the energy performance of buildings.

Consequently, the next step was to investigate and examine a variety of retrofitting options which would lead to possible reduction of the energy use and the carbon dioxide emissions. Different options were considered and the results have already been analyzed.

Replacing the double glazing windows along with the aluminum frames with triple glazing windows (U-Value of 1.08) and PVC frames (U-Value of 1.054) led to 5% reduction of the annual energy consumption of the modelled office.

Implementing 40 mm of insulation into the cavity brick wall also had an influence on the annual energy consumption presenting a reduction of 4.2%. Here it is also important to be stated that this percentage is going to be higher in reality as changing the insulation of the whole building would affect the heat losses coming from other areas which are in contact with the internal walls of the modelled office.

Another important parameter that should be taken into account as a retrofit option is selecting the ideal lighting equipment. Especially commercial buildings and as an extent educational buildings require high levels of illuminance to cover the needs of the occupants and significant energy savings can be achieved by installing lighting with high efficacy such as LED or specific types of Fluorescent lamps.

Alternative heating systems present the greatest opportunity in energy and carbon dioxide savings. However, in some cases lower energy consumption does not automatically mean lower carbon emissions. The results showed that instead of using the natural gas boiler with typical efficiency of 75%, installing heat pumps can lead to great energy savings. A comparison between the chosen air to air heat pump and the current situation’s natural gas heating system demonstrated a reduction of 79% to the annual primary energy consumption. Of course the carbon emissions were also remarkably lower. In the case of biomass wood pellet boiler the results are different. Having an efficiency of 94% meant that it consumes less amount of primary energy compared to the currently installed natural gas boiler but significantly more energy compared to the heat pumps. However, the carbon dioxide emissions are the lowest from all the examined options. Assuming that biomass is a renewable source of energy, meaning that the amount of carbon dioxide released during the combustion process of the boiler is equal to the amount of carbon dioxide which is absorbed by the plants during their growth. Then, by all means, there are emissions due to the cultivation and the transportation of biomass. If this hypothetical scenario is considered then the conversion factors of greenhouse gas reporting of wood pellet are very small leading to extremely low carbon dioxide emissions.

The last retrofitting option which was analyzed was to the ventilation systems. In Office A and Office B areas of the modelled office mechanical ventilation systems with heat recovery were implemented. This led to a reduction of 34% to the annual final energy consumption in the modelled office compared to the current situation.

Implementing the selected retrofitting options of section 11.5 in Chapter 11 had as a consequence much lower annual energy consumption values (both final and primary) and lower CO_2 emissions. In the case of installing also the air to air heat pump the annual final heating energy consumption decreases to 16 kWh/ m^2 instead of 93 kWh/ m^2 that is the current value.

One important part of the study was to examine possible retrofitting options which would lead to achieving the Passive House Standard. It was found that this is possible as all the criteria with reference to the thermal envelope, the ventilation systems, the air tightness and the heating energy consumption were met. However, before concluding that the Passive House Certification can be awarded an analysis regarding the electricity consumption due to the lighting and small equipment should also be executed. After completing this, if the total annual final and primary energy consumption criteria are being met then the Passive House Standard will have been achieved.

Finally, problems such as overheating can appear after implementing retrofitting options as the building’s air tightness is improved. In summer conditions, opening the windows or installing blinds can definitely reduce the indoor operative temperatures, fight the overheating effect and improve the indoor thermal comfort conditions for the occupants.

14. Limitations

The project was executed in the best possible way based on the available time. However, there are noteworthy limitations that have affected the results and they have to be noted. Hence, a further work analysis can become even better and more accurate.

Assumptions have been made regarding many different parameters. The occupancy levels and the lighting equipment have significant effect on the casual gains. Collecting more accurate information will result in better results. Moreover, based on the literature the heating set points are usually set to 22º C during winter. The heating was selected to be switched on from 06:00 to 18:00 and outside of these hours free floating conditions existed due to lack of real information. Lastly, the infiltration and ventilation systems are difficult to predict and model and they were modelled independently of the weather profile. In reality the infiltration levels are based on the weather details such as the wind speed, direction and etc. Therefore, creating a flow network in ESP-r can lead to higher accuracy.

To conclude, in order to eliminate the assumptions in a further work analysis, deeper investigation can be performed and more accurate information regarding all these parameters can be gathered.

15. Further Work

The project scope was limited to all the sections that have been analyzed in this document. Of course further work can arise which will lead to more conclusions.

Due to time restriction it was not performed a financial analysis regarding the retrofitting options in order to investigate whether or not each one of them is cost effective and to find out the running costs and the needed amount of time for balancing the capital costs.

Another analysis that can be executed is the investigation, feasibility and affordability of implementing renewable energy systems on top of the building such as PV panels. Storage can also be added and an effort of optimizing the dispachability of the electricity coming from the renewable energy systems can be attempted.

16. Conclusions

After the completion of this study, the main conclusions that have been arose are summarized in this section.

First of all, it is evident to promote the energy efficiency in buildings in order to achieve lower fuel consumption and as and extend lower environmental destruction and lower carbon dioxide emissions.

The comparison between the actual total annual energy consumption of the case study with the expected one ended in a significant discrepancy as the expected one overestimates the energy performance of the building. The use of dynamic simulation tools can close the performance gap and predict with higher accuracy the energy performance of a building during the design stage because more detailed input data lead to more accurate calculations. Therefore, in order to limit or avoid erroneous and deceptive results it is strongly recommended to perform and double-check the building energy performance calculations by using dynamic simulation tools because of their higher accuracy.

The implementation of retrofitting options resulted in higher energy performance of the modelled office. The use of materials or components with lower U-Values reduced the heat losses of the building envelope. Replacing the natural gas boiler with alternative heating systems decreased significantly the primary energy consumption. Especially in the case of installing heat pumps it was reduced up to 79% based on the examined options. Furthermore, adding mechanical ventilation with heat recovery to the modelled office indicated a reduction of the total final heating energy consumption by 34%.

The aim of accomplishing the Passive House Standard Criteria was achieved. The selection of retrofitting options to the building envelope and the ventilation systems that would satisfy the requirements resulted in accomplishing an annual final heating energy consumption of 14.6 kWh /m^2 which is below the limit of 15 kWh /m^2. In the case that the heating system was also replaced with an alternative the annual final energy consumption was reduced significantly reaching a value of even 3.6 kWh /m^2. Therefore, it is clear that a well-designed building even in cold climates can barely need heating.

On the topic of the environmental impact analysis, it was concluded that all the investigated retrofitting options would result in lower carbon dioxide emissions. Heat pumps have great performance and minimize significantly the annual final heating energy consumption. As a result, the carbon emissions follow the same pattern. In the case of installing a biomass wood pellet boiler, the carbon emissions were extremely reduced and were almost eliminated. However, as it has been already explained there is controversy about the sustainability of biomass and whether it is a renewable source of energy or not.

The improvement of the air tightness of the building caused overheating problems. Especially, in the case that the Passive House Criteria were met the overheating effect was even more intense. Then, measures to tackle this effect have to be taken and if necessary cooling systems have to be installed. Thus, it is important to have in mind possible side-effects that can occur while implementing retrofitting options and be prepared to face them.

Lastly, one of the most important conclusions is that the application of retrofitting options demands high capital costs. Hence, a careful financial analysis should be executed before taking any action in order to reassure the cost effectiveness and the expected outcome of the project.

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Appendix I

Geometry Details

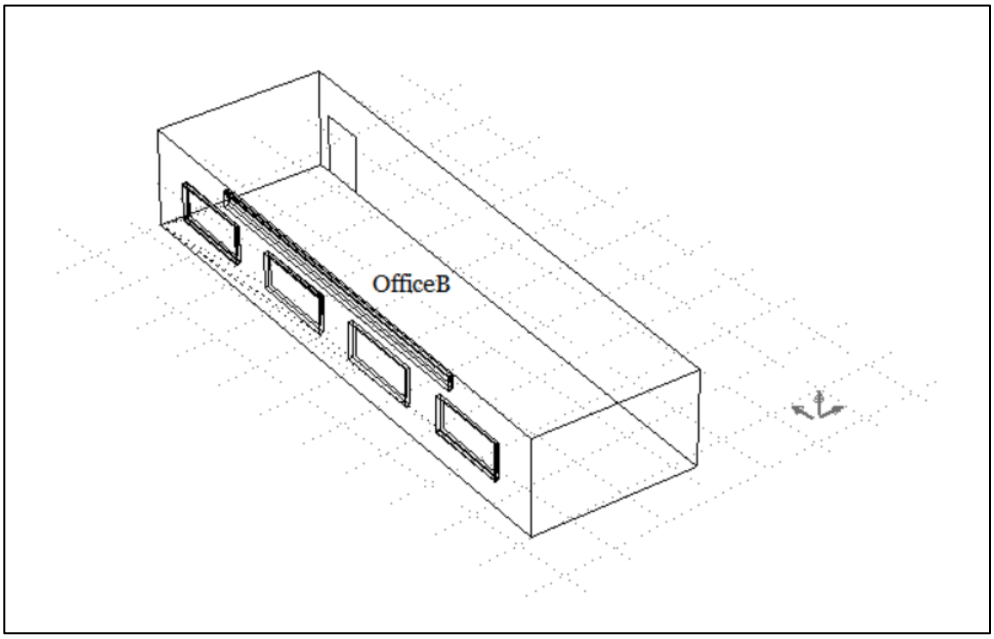

Figure 36. Office B model

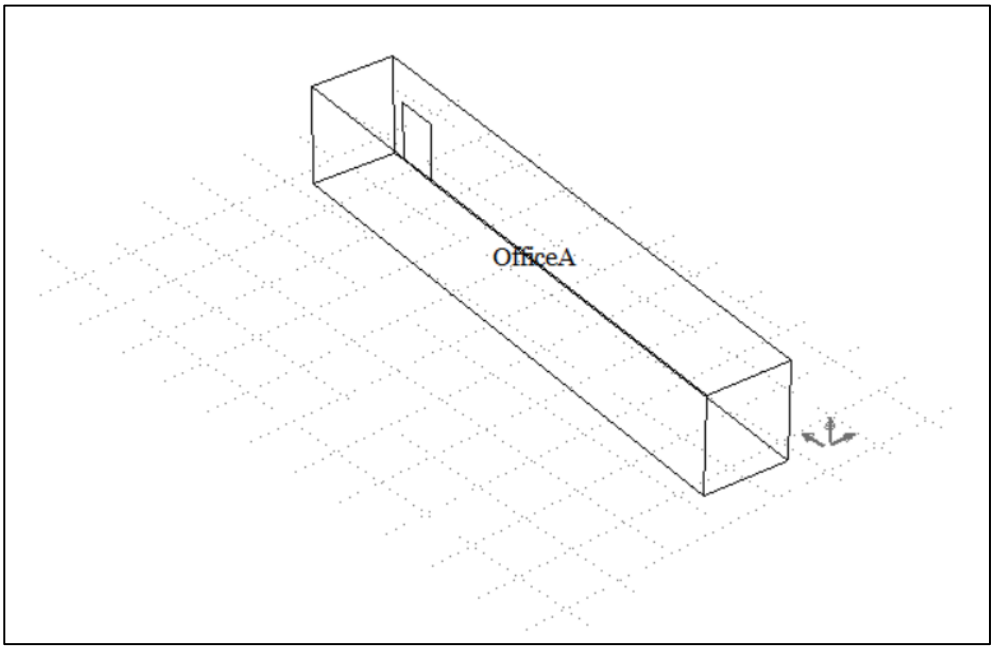

Figure 37. Office A model

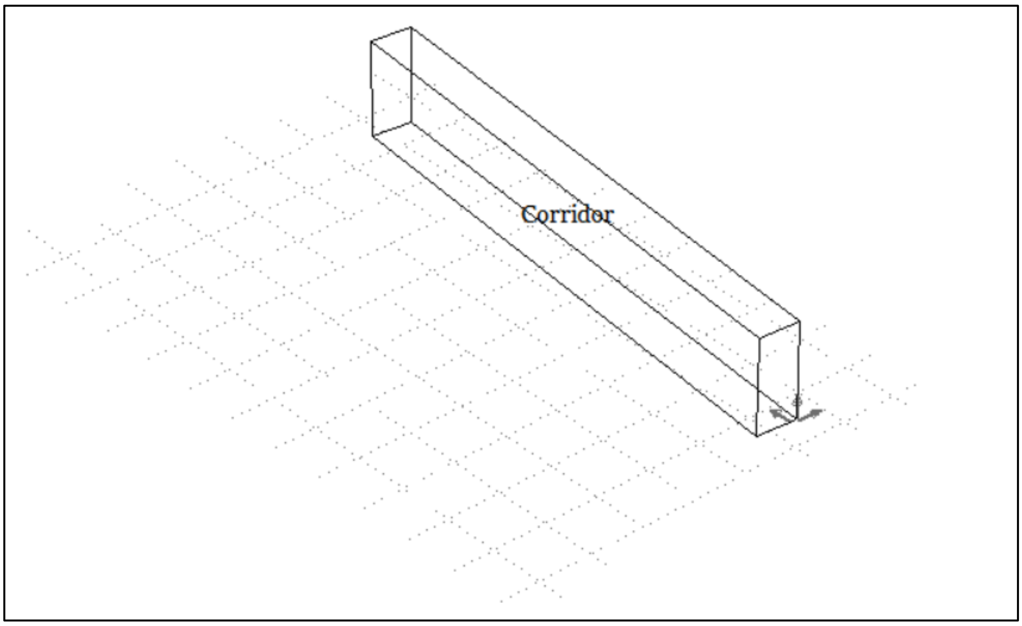

Figure 38. Corridor model