Frontiers of Architectural Research, Elsevier, accepted version 1 Sept 2021

Enhancing the Sustainability and Energy Conservation in Heritage Buildings:

The Case of Nottingham Playhouse

Amin Al-Habaibeh[1], Allan Hawas[1,2], Lama Hamadeh[1], Benachir Medjdoub[1] , Julian Marsh[3] and Arijit Sen[1]

[1]Product Innovation Centre, School of Architecture, Design and The Built Environment
Nottingham Trent University
Nottingham, UK

[2] Mälardalen University, Sweden

[3] Sheffield Hallam University, UK

ABSTRACT

Today, there is a growing interest in developing energy efficient buildings since it is estimated that buildings account for about 40% of the total primary energy consumption in the world. In relation to existing buildings, energy efficiency retrofits have become an important opportunity to upgrade the energy performance of commercial, public and residential buildings that may reduce the energy consumption, demand and cost. In this paper we cover the energy efficiency deep retrofit process that has been carried out for Nottingham Playhouse theatre building for the aim of enhancing its environmental performance and analysing the energy efficiency gained after implementing certain proposed modifications. It is a nationally protected historic building, listed as Grade II* on The National Heritage List for England (NHLE). The building has had insulation enhancement, doors modifications, solar energy installations, energy-saving lights, in addition to improved heating and air conditioning system. The paper presents a novel methodology; and its results indicate significant improvements in the building's energy performance which is demonstrated using infrared thermographic images and data logger sensors where significant energy savings to the building's thermal performance are obtained. The energy saving measures have been completed while maintaining the heritage building's general appearance and architectural features, which have received a Commendation Certificate from The Nottingham Civic Society for this achievement.

Keywords: Deep Retrofitting, Energy, Buildings, Insulation, Heritage Buildings.

1. INTRODUCTION

The rapid growth of world energy consumption has already raised concerns over the exhaustion of energy resources, supply difficulties and heavy environmental impacts such as global warming, ozone layer depletion and climate change. The global contribution from buildings towards energy consumption, both residential and commercial, has greatly increased during recent decades, reaching Figures of between 20% and 40% in developed countries (Pérez-Lombard, et al., 2008) making it a priority in the environmental agenda. In the European Union, buildings are responsible for 40% of the energy consumption and 36% of the CO_2 emissions (Pérez-Lombard, et al., 2008). It is for this reason; major efforts are being made to reduce energy consumption in new and existing buildings by upgrading their energy efficiency. Because buildings are so numerous, even relatively small energy reductions on an individual-building basis can have a large impact globally (Ginley and Cahen, 2011; Elaiab 2014). Energy efficiency aims to develop cost-effective ways to reduce energy consumption through existing and improved technologies.. In the UK, the Climate Change Act adopted by royal assent in 2008 and revised in 2019 has targeted the reduction of total emissions by 100% by 2050. This makes the UK unique in being the only country in the world that has introduced a long-term legally binding framework to tackle the dangers of climate change. These targets will affect every industry in the country; indeed, the built environment will be scrutinised to tighten its energy consumption more than others due to its proportional impact on greenhouse gas emissions. Existing buildings are variously estimated to account for about 48% of all the UK's carbon emissions (Holguin and Roddan, 2011). Approximately, three quarters of the existing homes in 2050 have already been built. Therefore, by 2050, emissions from existing buildings need to be reduced substantially if we are to reach the target of 80% reduction (Energy Saving Trust, 2017). Consequently, it is evident that, for major reductions in energy consumption and carbon emissions in the building sector, the energy retrofitting of existing buildings must be addressed because the remaining years to 2050 will not be sufficient to replace the existing building stock with higher-efficiency new buildings rapidly enough to resolve the greenhouse-gas problem (Ginley and Cahen, 2011). A significant amount of research in energy efficiency retrofit projects on existing buildings have been broadly carried out in order to investigate different energy efficiency opportunities that lead to improve the energy performance of these buildings. The results have shown that implementing such projects in residential (Liu et al., 2014; Nik et al., 2016; Thomsen et al., 2016; Pombo et al., 2016), public (Chow et al., 2013; Chung and Rhee, 2014) and historic (Filippi, 2015; Mazzarella, 2015; Sahin et al., 2015; Ascione et al., 2015a) buildings around the world have great potential to achieve significant energy and cost savings. Specifically speaking, historic and culturally heritage-character buildings, and due to their significance, need particular attention when applying energy deep retrofit projects. Improving the energy efficiency of historic buildings is vitally important, not only as a means of protecting them from emptiness and dereliction, but also as an essential element of any emission reduction strategy in the built environment (Ascione et al., 2015b). Their essential character-defining features to their significance must be present after completing the retrofit project (Mazzarella, 2015). From thermal point of view, a building may be considered as a system that undergoes various indoor-outdoor temperature difference throughout the year. The building's insulation structure is a key factor to regulate the temperature in the building and to minimise the energy loss from the building to the outdoor as possible. Thus, any retrofit project must take into account the importance of this component and choose the proper energy efficiency technologies in order to enhance the building's insulation and achieve positive and satisfactory results. Significant research has been done to study the impact of different building retrofit options on the environmental performance of buildings. For instance, double-glazed windows (Hee et al., 2015), doors design (Mahajan et al., 2015), the wall insulation thickness (Özel et al., 2015; Dombayci, 2007), energy-efficient lighting (Ciampi, 2015) and photovoltaic panels (Nosrat, 2014; Piazza, 2013) have been analysed thoroughly and the results show that adopting the proper retrofit option that is compatible with the building's characteristics produces significant and promising outcomes.

Enhancing the sustainability and energy efficiency of heritage buildings is a challenging task in comparison to ordinary buildings, see for example Havinga and Colenbrander (2020). This is because the new energy-saving measures should be sympathetic to the key heritage characteristics, in case of heritage buildings, to maintain their appearance and nature. This includes the use of suitable materials and building features; and would require in many cases a formal approval process. Ordinary buildings, however, do not need an approval process and the owners could select any modern energy-saving measures that they find appropriate from energy and aesthetic aspects without the need to maintain the original characteristics of the building.

When reflecting on literature, see for example the case studies presented in (Silvero et al., 2018; Caro et al., 2020; Cho et al., 2020); the main key finding is that each heritage building is different in nature; and its location, materials, age and requirements of the retrofitting process also differ. For example (Silvero et al., 2018) presents a case study in hot-humid climate in Paraguay. Caro et al. (2020) explores the retrofitting process in a Mediterranean weather conditions in Seville, while Cho et al. (2020) explores the conservation and energy assessment of a university hall in Korea. Each case study seems to be different. However, there are general principles and methodologies that could be utilised, but it seems difficult to copy a specific solution; and hence this is one of the key challenges in introducing energy-saving measures in heritage buildings.

In this work we suggest a novel methodology and investigate the energy efficiency of Nottingham Playhouse, a Grade II* listed building, following an energy efficient deep retrofitting process during the period between December 2010 and December 2018. Infrared thermography (Asphaug et al., 2016; Al-Habaibeh et al., 2012; Al-Habaibeh et al., 2010, Litti et al., 2015), using FLIR E25 infrared camera, has been used as an energy analysis technique to evaluate the thermal insulation performance of the building before and after the building's improvement process is achieved. Also, temperature sensors are used to evaluate the performance of different parts of the structure before and after the deep renovation.

2. NOTTINGHAM PLAYHOUSE DESCRIPTION

The Nottingham Playhouse, as shown in Figure 1, is a top-class comedy, drama and music theatre in Nottingham city, UK. The current theatre was opened in 1964. It is Grade II* Listed Building. The architect was Peter Moro who had worked on the interior design of the Royal Festival Hall in London. The building received a Civic Trust Award in 1966, where the Neville Studio Extension designed by Marsh Grochowski LLP received a RIBA Award in 1995. Despite the cuboid general appearance and the cylindrical auditorium, the theatre has a traditional proscenium layout, seating an audience of 750 people.

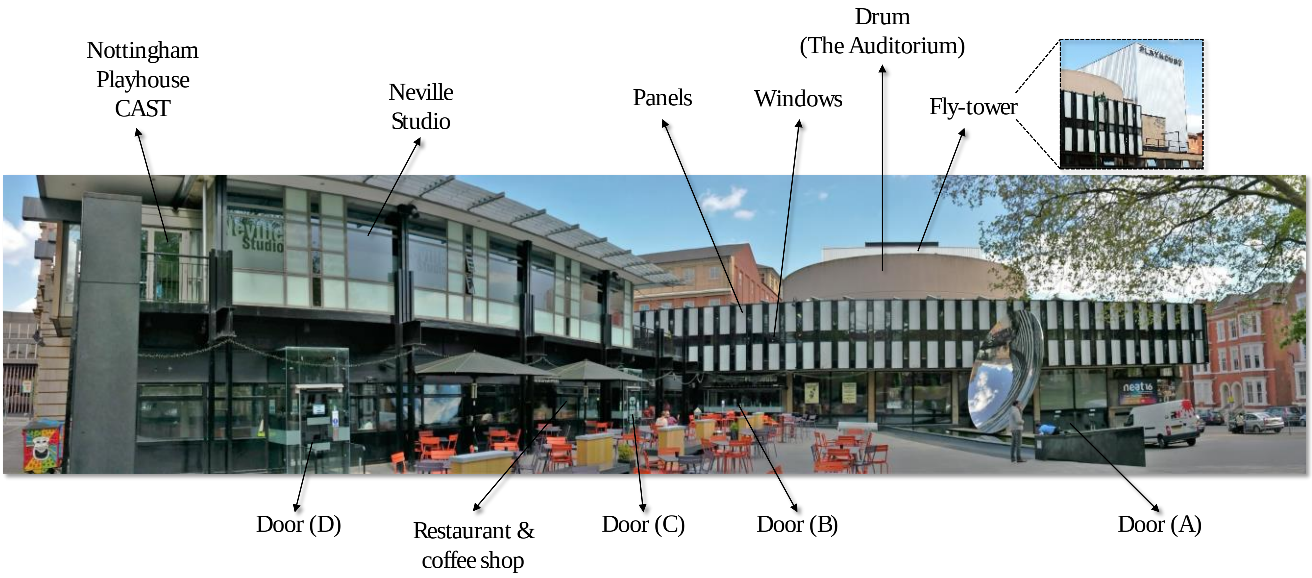


Figure 1: Nottingham Playhouse.

However, in recent years with the increase in energy prices, an enhancement to the energy performance of the building has become a necessity. It is important to mention that energy deep retrofit process to cultural heritage buildings is particularly demanding because these buildings are subject to special regulations that narrow the choice of applicable energy efficiency measures. The energy retrofit of cultural heritage buildings encompasses two very distinct areas: culture and sustainability. When it comes to energy improvements, cultural heritage buildings should be treated differently from contemporary ones (Sahin et al., 2015) where responsible and careful planning is required for the preservation of cultural heritage buildings to coincide with the application of energy efficiency measures (Blecich et al., 2016). Therefore, an energy efficiency upgrading procedure has been applied to certain parts of Nottingham Playhouse building between December 2010 and December 2018 which not only has improved the building's energy performance, but also it has maintained its original appearance and functionality while supporting public needs.

Most energy consumption in the UK in buildings is for heating applications and hence the focus of the work is to reduce the heating cost while maintaining the comfort temperature inside the building. In most cases, air conditioning will not be needed; and if cooling is needed, a simple ventilation in most cases would be adequate.

3. METHODOLOGY

The methodology of this work is schematically outlined in Figure 2. Nottingham Playhouse deep retrofit project has gone through three main stages during seven years of the program; pre-retrofit, retrofit and post-retrofit. Each of which includes certain activities that make up the project's framework.

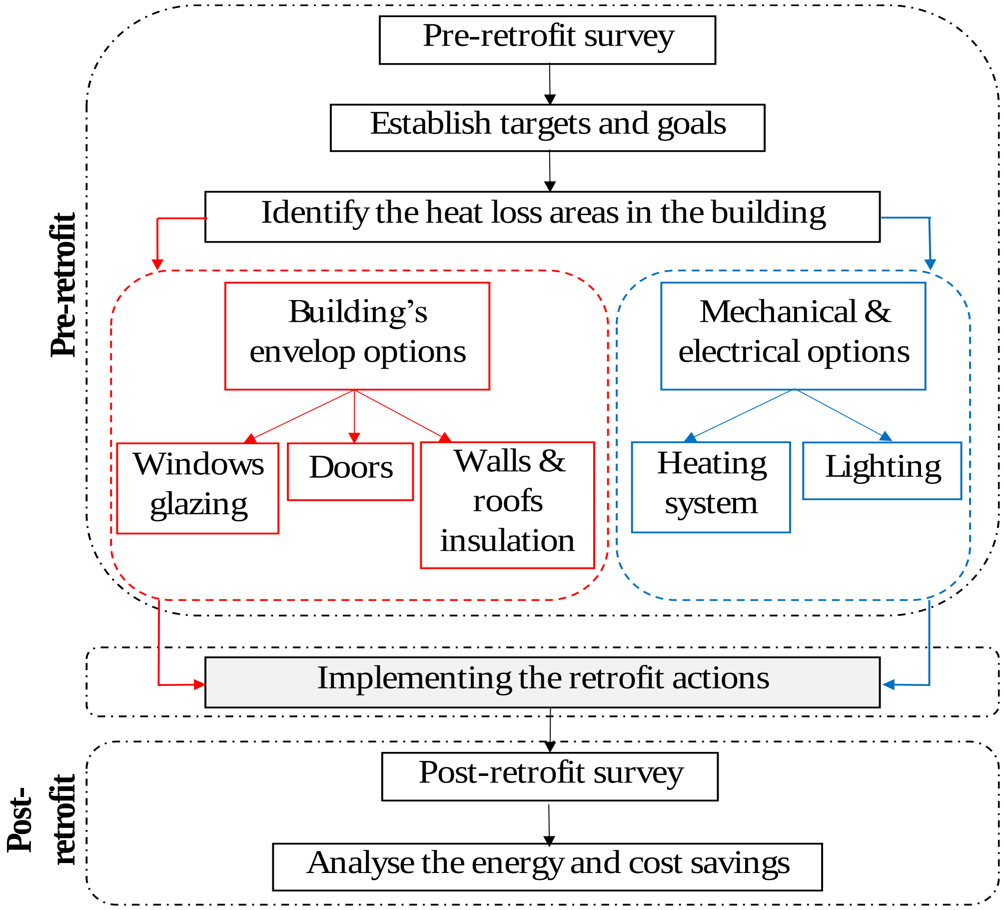


Figure 2: A schematic diagram of the novel methodology for the retrofit project of Nottingham Playhouse theatre.

Pre-retrofit stage

This stage started in 2010 when the first survey of the building was carried out using mainly infrared thermography techniques (Kirimtat and Krejcar, 2018) and temperature monitoring. The purpose of this survey was to gain a better understanding of the building's architecture and the quality of the building's construction in terms of energy efficiency and its operational problems. Then, the main objectives and deadlines of the project were set which were primarily to upgrade the building's energy and environmental performance and reduce its energy demands and costs. Afterwards, two main groups were identified as the major heat loss areas in the building and ultimately, they form the leading retrofit options: building's envelope options (windows glazing, doors, walls and roof insulation) and mechanical and electrical options (lighting and heating system). Additionally, it was advised to add photovoltaic panels to the building's roof in order to generate electricity. This identification of the retrofit options is very useful to understand their potential costs, impacts involved and the payback period.

Retrofit stage

This stage aimed at implementing the retrofit process recommended modifications, mentioned above, that consisted of different types of actions, which will be explained in detail later on.

Post-retrofit stage

After applying the retrofit changes to all the proposed building's options, a post-retrofit survey and monitoring were carried out between 2014 and 2018 in order to estimate and analyse the overall energy savings associated with the renovation program. The resulting calculations show that although each individual change represents only limited energy savings to the building, but by adding up the savings from all the other building's options has led to considerable energy and cost reductions. In the following, we explain in more detail each step.

4. THEORETICAL ANALYSIS

When developing strategies to minimise energy consumption within buildings it is crucial to understand the dynamics and the physics behind outdoor-indoor heat transfer mechanisms through the building. This understanding is the key to not only know how the building's insulation works (in walls, roofs, windows, etc.), but also is a guide to enhance the performance of the next generation of energy efficiency technologies.

4.1 Heat transfer mechanisms

In principle, Heat transfer is energy in transit due to a temperature difference (Moran et al., 2003). Heat transfer across a building's exterior side results in energy loss during the winter from the warm interior to cold exterior. The insulation must reduce heat transfer due to three primary heat transfer mechanisms: conduction, convection, and radiation (Ginley and Cahen, 2011). In **conduction,** the heat is transferred across the material due to its molecular interaction. When the thickness of a homogenous material is much smaller than its other two dimensions, then conductivity can be considered as one-dimensional and thus it can be expressed by *Fourier's rate equation*:

$$q_{Cond} = -k\,A\,\frac{\Delta T}{\Delta x} \tag{1}$$

Where:

q_{Con} is the condition heat transfer (watts).
k is the thermal conductivity $(\text{watts}.\,\text{K}^{-1}.\,\text{m}^{-1})$.
A is the cross-sectional area normal to the direction of the transfer (m^2).
$\frac{\Delta T}{\Delta x}$ is the temperature gradient $(\text{K}.\,\text{m}^{-1})$.

Convection, on the other hand, is the heat transfer that takes place in gases and liquids and is the combination of conduction and fluid motion. To explain this mode, consider a wall cavity during the winter. The interior surface is warm, while the exterior surface can be much colder. Air in the cavity close to the cold wall will be much denser than the air close to the warm wall. The cold air will tend to move down under gravity, while the warm air rises. This sets up an energy exchange due to the fluid circulation, which substantially augments the exchange due solely to molecular motion. The convection heat transfer process can be expressed by *Newton's law of cooling rate equation* which is given by:

$$q_{\text{Conv}} = h\,A\,(T_{\text{HotWall}} - T_{\text{ColdWall}}) \tag{2}$$

Where:

q_{Conv} is the convection heat transfer (watts).
h is the convection heat transfer coefficient $(\text{watts}.\,\text{K}^{-1}.\,\text{m}^{-2})$.

$T_{\text{HotWall}} - T_{\text{ColdWall}}$ is the temperature difference (K).

The third heat transfer mechanism is **Radiation** which consists of electromagnetic waves emitted from a body by virtue of its temperature level. While the transfer of energy by conduction or convection requires the presence of a material medium, radiation does not. When the radiation hits a surface, it may either be absorbed, reflected or transmitted. An ideal thermal radiator is called a “black body” where it absorbs and emits energy at all electromagnetic wavelengths. The radiant heat rate emitted by a real surface is less than that of a blackbody at the same temperature and is given by *Stefan-Boltzmann law* (Ocana, 2004):

$$q_{\text{Rad}} = \sigma\, A\, \varepsilon\, T^4 \tag{3}$$

Where:

q_{Rad} is the radiation heat transfer (watts).

σ is the Stefan-Boltzmann constant $(\sigma = 5.67 \times 10^{-8}\ \text{watt}.\mathrm{K}^{-4}.\mathrm{m}^{-2})$.

ε is the emissivity which is the ratio of a surface’s ability to emit radiant energy compared with the ability of a perfect blackbody of the same area at the same temperature.

4.2 Heat transfer through windows

For the deep retrofitting of Nottingham playhouse to be efficient, one of the principles that needs to be achieved is to reduce convection, conduction and radiation between the internal side of the building and external environment. This can be done by selecting improved insulation materials. Double-glazed windows are usually a straightforward retrofit option for single-glazed windows due to their improved design to reduce heat loss through windows. Double glazing not only reduces heat loss but also condensation and noise, and therefore has a positive impact on occupant comfort levels (Ginks and Painter, 2017). Double-glazed windows have two sheets of glass with a gap in between which is sometimes filled with inert gas such as argon, xenon or krypton. The total heat transfer rate will be affected significantly by the emissivity (ε) of the glass material. Most energy-efficient type for double glazing has low emissivity. This lets in light and heat but blocks the amount of heat that can get out, thus improving heat gain during daytime and hence thermal efficiency. The gap between the two sheets of glass is usually about 16mm, to create an insulating barrier that keeps heat in. The heat loss Q (watt) through a window with an area A=0.5m^2 as a function of the temperature difference between the external and internal temperatures ΔT (^{0}C) for two glazing types; single-glazing with a U-value of 4.8 Watt/m^2. ^{0}C, in blue solid line, and double-glazing where the U-value is dropped down to 2.9 Watt/m^2. ^{0}C, in red dashed line.

4.3 Heat transfer through insulations

This can also be applied to walls and roofs where different insulations options can be assumed to reduce the heat loss through them. The insulation thickness is an important parameter when it comes to estimate the energy loss. To evaluate the annual energy consumption of the walls and roofs after applying the insulation as a function of the insulation thickness, we write based on Dombayci (2007):

$$E = \frac{86.400\, DD}{\left[R + \left(\frac{\Delta x}{k}\right)\right]\eta} \tag{4}$$

Where:

E is the annual heat loss $(\mathrm{J}.\mathrm{m}^{-2})$

DD is the degree days (^{0}C. days)

R is the sum of thermal resistances of the layers that make up a building element (i.e., walls, floors, roofs etc.) $(\mathrm{watt}^{-1}.\mathrm{m}^2.\mathrm{K})$.

Δx is the insulation thickness (m).

k is the thermal conduction of insulation material $(\mathrm{watt}.\mathrm{m}^{-1}.\mathrm{K}^{-1})$.

η is the efficiency of space heating system.

Figure 3 shows that the annual heat loss for the ballasted insulation (which is the same insulation that has been installed in the roofs and walls of Nottingham Playhouse building which is often termed an ‘upside down roof’) decreases with increasing the insulation thickness Δx. This is important especially during winter season when the indoor-outdoor temperature difference is at its peak.

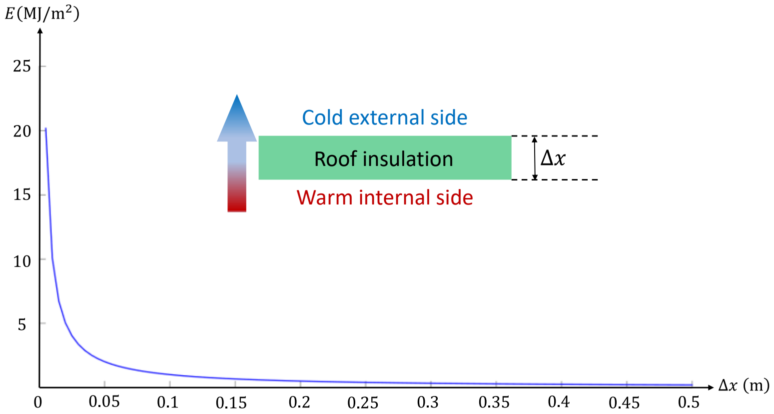


Figure 3: The annual heat loss E $(\mathrm{MJ/m^2})$ as a function of the insulation thickness $\Delta x(\mathrm{m})$ of the ballasted insulation. The parameters values used in the calculations are: DD = 2643 for Nottingham city with a base temperature =17^0C, $R = 0.592\ \mathrm{watt}^{-1}.\mathrm{m}^2.\mathrm{K}$, $k = 0.17\ \mathrm{watt}.\mathrm{m}^{-1}.\mathrm{K}^{-1}$ and $\eta = 0.65$.

4.4 Heat transfer through doors

One of the main issues to be addressed in the building is the external doors. A survey has been conducted in a cold winter to investigate the design of Nottingham Playhouse doors and their performance. The building has four main doors: Door A: for the main ticket counter of the theatre. Door B is in the same area serving the main theatre and the ticket office. Door C is for the main restaurant and coffee shop while Door D is mainly for a delicatessen. Doors A, B, C and D are illustrated in Figure 1.

Air infiltration through doors is considered to be an important factor when doors are used frequently such as in many public and commercial buildings including restaurants and theatres, either during operational hours or at certain duration during the day. Buildings could have different types of doors configurations such as pivot, sliding and revolving doors, which could influence the amount of energy lost or gained. The original doors at Nottingham Playhouse were pivot doors as shown in Figure 4-a. The disadvantage of such a configuration is that significant heat loss is expected. On the other hand, a revolving door, see Figure 4-b, is expected to save significant energy (Cho et al., 2010) as they decrease the air infiltration. Adding a second swinging door through a vestibule to high usage doors creates a double-swinging door system, as shown in Figure 4-c. The idea with a vestibule is that one door has a chance to be closed while the other one is open. In this way, a direct air exchange between the indoors and outdoors is reduced. By decreasing the direct air exchange with the outside environment results in decreased energy losses and a better indoor climate. However, when the flow of people though the vestibule increases, the energy loss is expected to increase due to both doors being open.

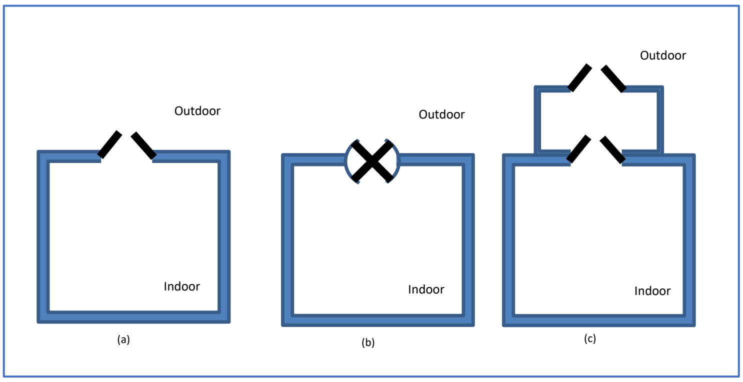


Figure 4: Current door systems: pivot (a), revolving (b) and a double-pivot system (c).

We can calculate the maximum possible air infiltration heat loss through one of the doors and see how it changes as the outdoor temperature varies throughout the year. For simplicity, and since swinging doors can be operated manually or with automatic openers, we will assume that we have an automatic swinging door. The main reason for this is that door opening pattern of manual doors is relatively difficult, i.e., depending on users' pattern, the door opening area and opening time can vary significantly. Because automatic doors often stay open longer with each use than manual doors, this assumption may result in over-estimates of infiltration rates (Cho et al., 2010). Let us take door (A) of the building as an example, therefore, the air infiltration through the automatic version of it is given in SI units (ASHRAE Handbook, 2009; AEPCA, 2004):

$$V = C_A \, A \, R_p \tag{6}$$

Where:

V is the volumetric airflow rate $(\mathrm{m}^3/\mathrm{s})$.

C_A is the airflow coefficient $\left(\mathrm{m}/\mathrm{s}.\sqrt{\mathrm{Pa}}\right)$.

A is the area of the door (m^2).

R_p is the pressure factor $\left(\sqrt{\mathrm{Pa}}\right)$.

Looking at Figure 5, it is clear that the air infiltration through a single-swinging door is noticeably larger comparing with the double-swinging door system, i.e., with a vestibule, and this is true throughout the year.

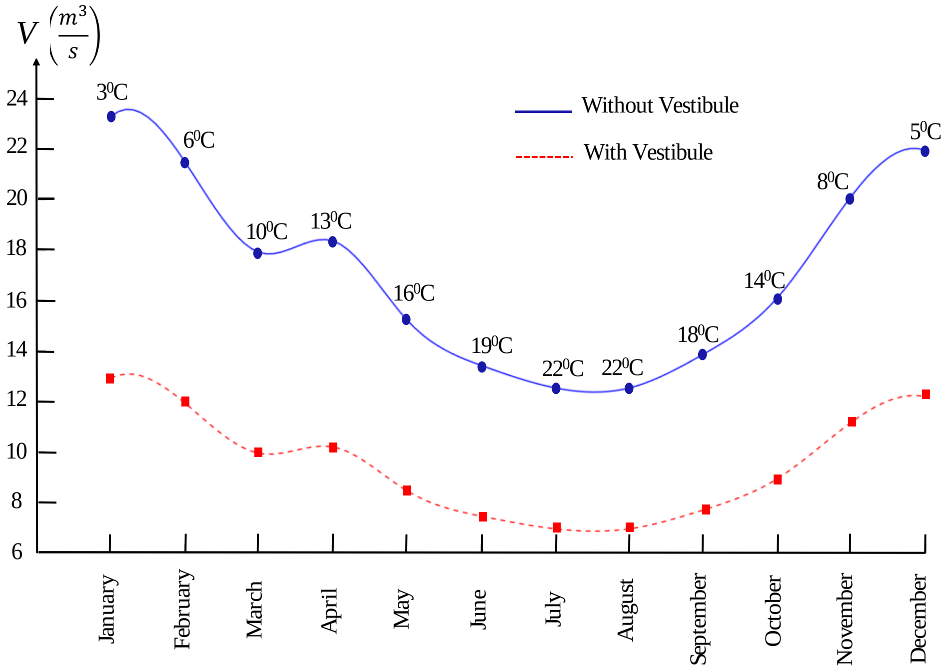


Figure 5: Air infiltration through door (A) as a function of the annual Nottingham average temperature. We have assumed the following: the people flow rate in off-peak times through door (A) is roughly 75 people per hour, the building height is 30 m and the door area is $2\ m^2$. The values of both parameters C_A and R_p have been extracted from ASHRAE Handbook (2009).

5. BUILDING'S ENERGY PERFORMANCE BEFORE AND AFTER THE RETROFITTING PROJECT

In this section, we introduce the pre- and post-retrofit conditions of key elements of Nottingham Playhouse theatre. Energy auditing and surveying can allow the understanding of quality and quantity of energy consumption and saving potentials (Ascione et al., 2015a). A qualitative and quantitative survey was conducted in 2010 to investigate the design and the environmental performance of Nottingham Playhouse building. This survey was made during a cold winter, with an ambient temperature of about -2°C in order to obtain a nearly accurate indoor-outdoor temperature difference. Following this survey, different main key drivers of energy consumption and potential upgrade options in the physical structure of the building were identified which were significantly related to its thermal performance, specifically heat loss through windows glazing, entrances, walls and roofs insulation. In addition, several mechanical and electrical options e.g., lighting and heating system were marked. This has lead to securing funding for the retrofitting process.

Following the implementation of the retrofitting project, two post-retrofit qualitative and quantitative surveys were carried out on the building after the energy efficiency modifications were implemented; the first was in December 2014 and the second was between November 2016 and March 2017. The main aims for these two surveys were to analyse the resulting environmental performance of the building, assess the amount of energy lost or gained as a consequence of the retrofit project and examine further potential changes for energy saving. For the first survey, the infrared thermography was used as an energy analysis technique to evaluate the thermal insulation of the building, primarily for windows glazing and entrances. However, for the second survey, several data logger sensors were installed in different locations in the building, as shown in Figure 6, to measure and keep track of energy consumption, internal and external temperature, internal humidity, energy efficiency of walls and window glasses and the operation of the main entrances. All monitoring data loggers were of the type OM-PL series that are multipurpose devices and can be used for a wide range of logging applications.

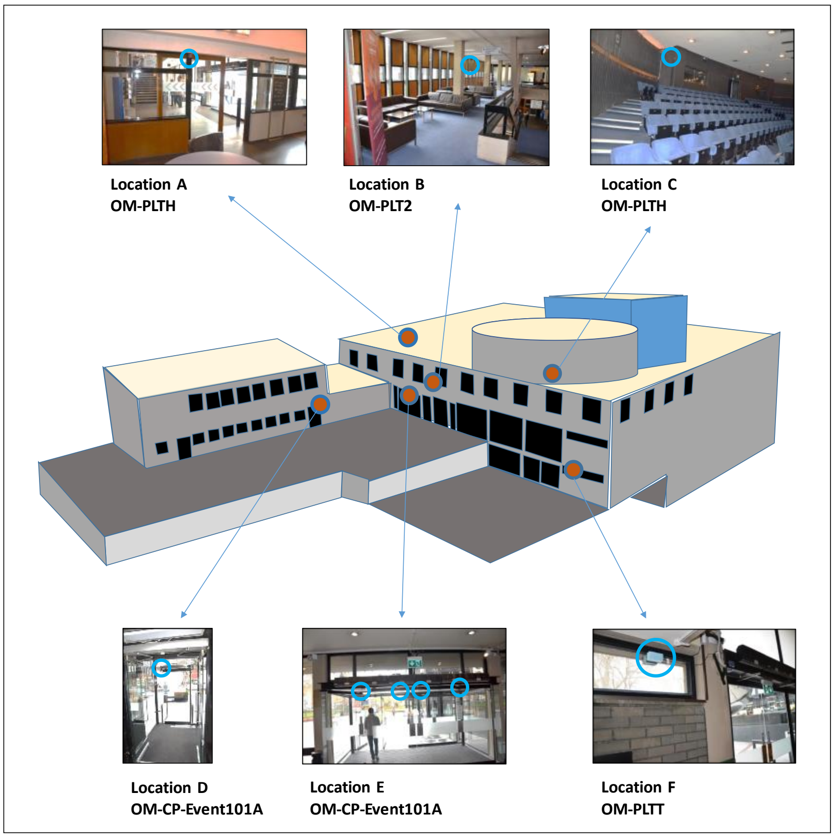
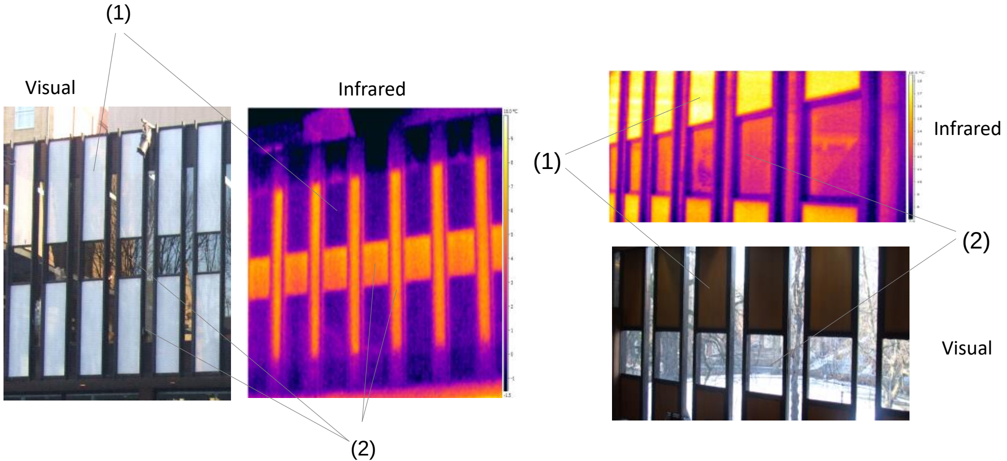


Figure 6. A schematic illustration of Nottingham Playhouse building combined with images of the locations of the data logger sensors that were installed as part of the survey that took place between November 2016 and March 2017.

5.1 Windows' Glazing

5.1.1 Pre-retrofit of windows' glazing

The exterior of the building has large-glazed areas with various window sizes (see Figure 1). The transparency of the façade not only provides a unique architectural effect but also creates a pleasant visual contact with outdoors, natural lighting and potential energy savings in terms of lighting, provided that the systems function properly (Ge and Fazio, 2004). However, the use of a fair amount of glass in the façade has resulted in certain problems as well (Goia et al., 2013) especially, and most importantly, when the windows were single glazed. Most of Nottingham Playhouse windows were single glazed using steel frame structure, and thus thermally very inefficient and one of the major contributors to heat loss. Also, windows metal framing is durable and has excellent structural characteristics, but it has very poor thermal performance (ASHRAE Handbook, 2009). Figure 7 presents the infrared images of the windows taken in 2010 before implementing the retrofit process. When comparing panels (1) with windows (2) in Figure 7-a, it becomes evident that there was about 8- to 10-degree centigrade difference which indicates significant heat loss and poor insulation. When examining the windows internally, as seen in Figure 7-b, it is obvious that the original frames acted as a thermal bridge to the outside temperature and that the windows were at a very low temperature in comparison to the panels.



(a) External view

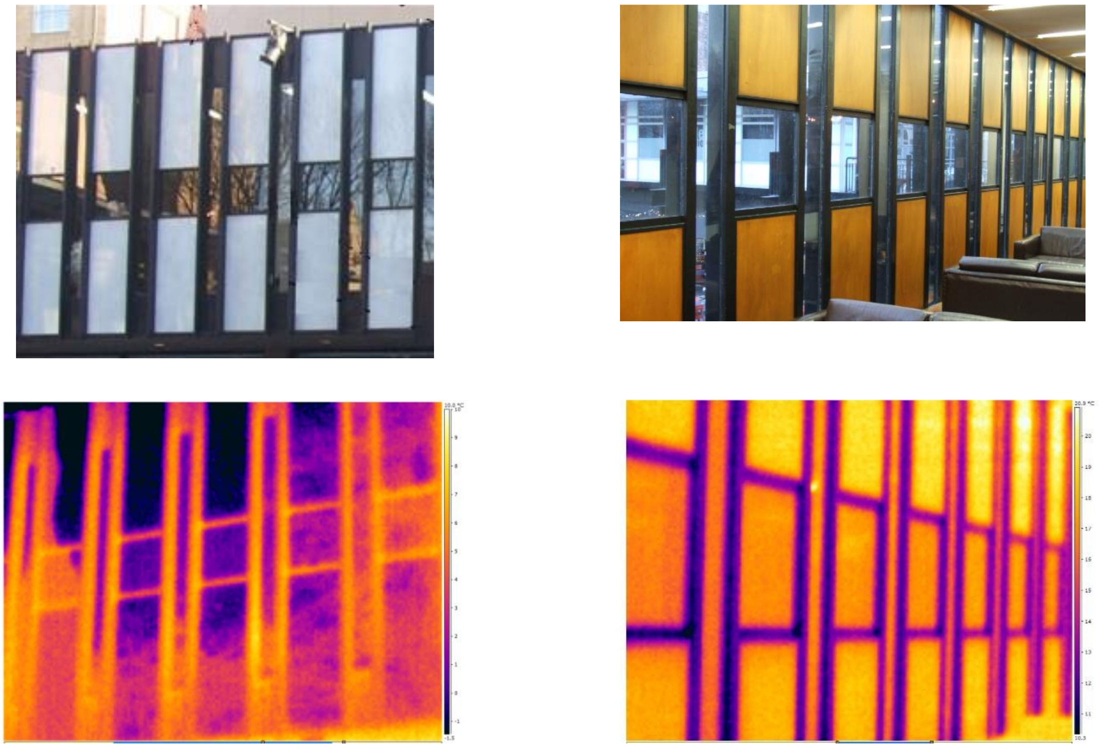
(b) Internal view

Figure 7: Pre-retrofit visual and infrared thermography images of the single-glazed windows: (a) exterior side and (b) interior side; which shows significant losses via the windows (2), in comparison to other panels (1). The frames around the windows also show significant heat losses.

5.1.2 Post-retrofit windows' glazing

The energy efficient change to the windows consists of replacing the single-glazed windows with double-glazed (insulated-glazed) ones. Additionally, since the poor thermal performance of metal-frame windows can be improved with a thermal break, i.e., a nonmetal component that separates the metal frame exposed to the outside from the surfaces exposed to the inside, it has been recommended to add aerogel insulation to the existing panels which has a major impact in reducing the heating load as it covers large area across the original building façade.

The thermography images, shown in Figure 8-a, were taken during the first survey in Dec 2014 after the implementation of the double-glazed windows on the building. They clearly illustrate that the external layer of the window glass is colder indicating that the double-glazed windows create a barrier that lets the sunlight and heat in but cuts the amount of heat that can get out again and this leads to a much better insulation. When examining the windows internally, and after the improvement, Figure 8-b shows that the internal layer of the glass is much warmer now indicating a much better insulation. However, the frames are still act as a thermal bridge.



(a) Exterior View

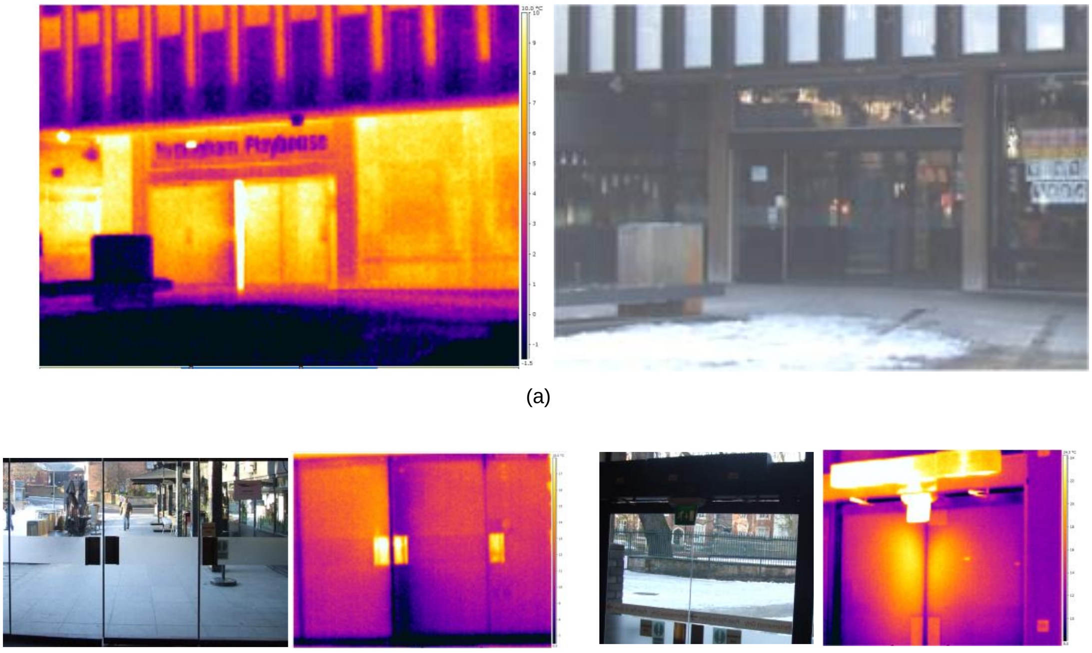
(b) Interior View

Figure 8. Post-retrofit infrared thermography images of the double-glazed windows taken during the survey in 2014 following the retrofitting of the double glazed windows, showing significant energy savings via the windows, but the metal frame still forms a thermal bridge .

5.2 Entrances

5.2.1 Pre-retrofit entrances

The building has four main doors: door A is for the main ticket counter of the theatre; door B is in the same area serving the main theatre and the ticket office; door C is for the main restaurant and coffee shop; and door D is mainly for a delicatessen, as presented in Figure 1. All of the building doors are of a swinging (pivot) type, or an open-type door, which is usually used as entrances for large buildings. Before applying any changes to the building doors, the main entrances were frameless glass doors, which were a poor fit and created a significant source of heat loss especially when the usage frequency is high either during operational hours or at certain times during the day or evening. Figure 9 presents visual and infrared images of door B; from outside as in Figure 9-a, and from inside the building as in Figure 9-b, where the air infiltration and poor insulation around the glass panels of the doors and through the single glazed glass is clearly noticeable. Figure 6-c presents door A from inside the building with similar characteristics as door B; see Figure1.

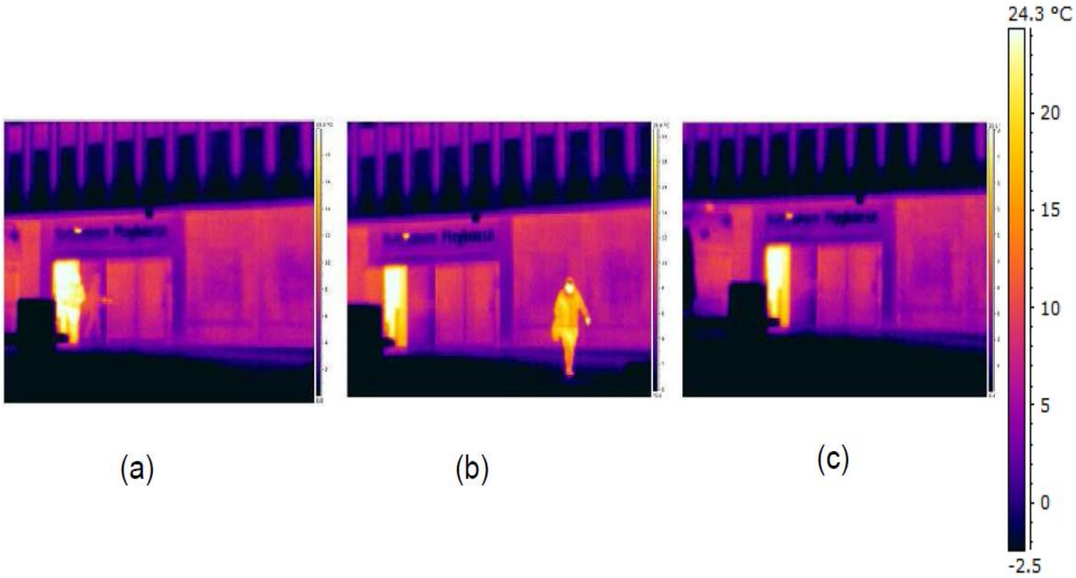

(a)

(b)

(c)

Figure 9: Pre-retrofit -Visual and infrared thermography images of the single-swinging door-B main entrance (a) and (b); and the second door-A main entrance (c).

In principle, these swinging doors can be designed to obtain good air tightness in their closed state. However, in their open state, ideally when people pass through, air exchange are free to occur (Karlsson, 2013) allowing cold outdoor air to enter into the building which makes them energetically inefficient due to a significant amount of energy losses, as illustrated in Figure 10.



(a)

(b)

(c)

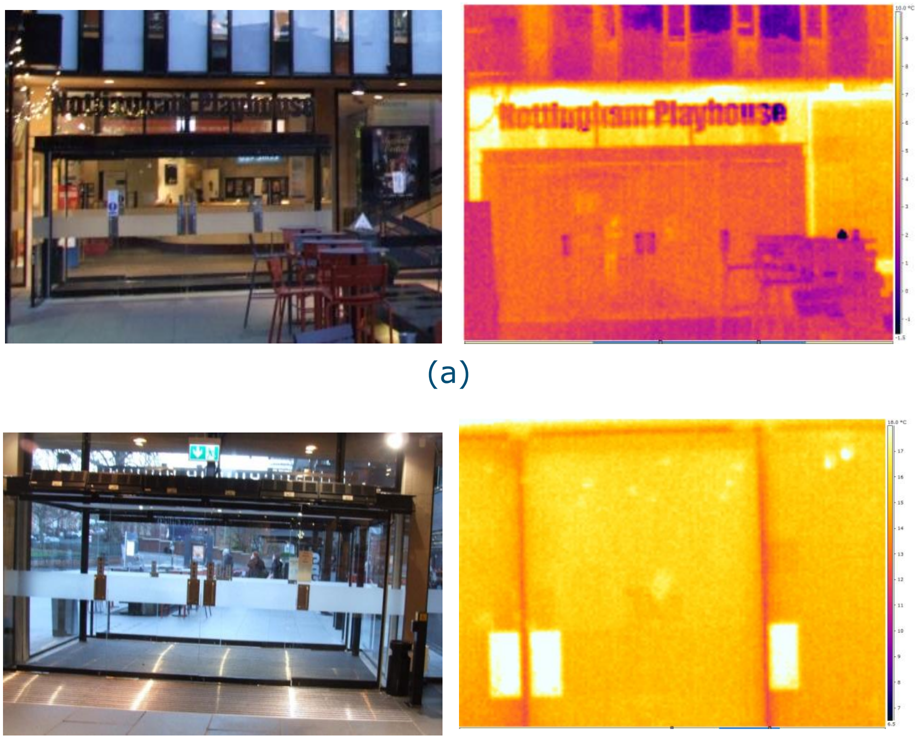
Figure 10: Pre-retrofit infrared images to the main entrance, door (B), that show qualitatively the heat loss when people enter, (a), or leave the building, (b) and (c).

5.2.2 Post-retrofit entrances

When the doors are continuously used throughout most of the day and until late evening, which is the normal situation for a public building like Nottingham Playhouse theatre, the air infiltration through door openings is considered to be an important and essential factor for energy loss. Consequently, an energy upgrading must be implemented. Two main modifications have been proposed to the existing doors:

- Adding a second swinging door through a vestibule to high usage doors creating a double-swinging system (see Figure 4-a and 4-c). The idea with a vestibule is that one door has a chance to be closed while the other one is open. In that way, a direct air exchange between the indoors and outdoors is prevented. By decreasing the direct air exchange with the outside environment results in decreased energy losses and a better indoor climate. However, when the flow of people though the vestibule increases the chance of having one door closed is decreased (Karlsson, 2013).
- Retaining the existing doors and fitting new draught seals across the original building.

Both of the proposed modifications for the building's doors have considerably improved the doors insulation. The thermography images, presented in Figure 11, exhibit the energy performance of door B externally and internally. It can be clearly seen, after comparing with Figure 9, that the insulation system has been significantly improved due to the double-swinging door system especially when the doors are in their closed status.



(a)

(b)

Figure 11: Post-retrofit visual and infrared thermography images of the double-swinging main entrance, door B.

As seen previously in Figure 5, adding a vestibule to a swinging door is considered as an effective design measure to decrease the air infiltration through door openings and ultimately to reduce the whole building energy consumption when doors are used frequently. Despite the improvement in doors' performance, the doors design could still be improved further to reduce air infiltration when doors are in use. For instance, swinging doors could be replaced by revolving doors. Revolving doors is a straightforward alternative to open-type doors. The operation of revolving doors is different from open-type doors in the way that they always maintain a physical separation between the indoor and outdoor climate and as a result they lead to a decrease in air infiltration through door openings and finally to reduce the whole building energy use when the doors are used frequently. Due to the restrictions that the Listed Building status placed on the design of retrofit, for instance a revolving door solution was not acceptable to English Heritage and they only accepted the Lobby solution when drawings showing Peter Moro's original design included a canopy over the door, removed as a cost saving during construction, of similar size to the proposed lobby.

5.2.3 Quantitative analysis of infrared thermography

Infrared images could be used for qualitative analysis as described above, but also could be used to estimate energy losses via quantitative analysis. The pixel-by-pixel temperature values from infrared images have been extracted and the average temperature of selected regions has been calculated using Matlab software. The average temperatures of selected regions on the infrared image of pre-retrofitted single glazed windows and panels and post-retrofitted double glazed windows and panels are compared in Figure 12. The average temperatures of the single glazed windows are 5.1 °C and 5.7 °C. On the other hand, the average temperatures of the double-glazed window are 0.5 °C and 2.2 °C. This difference in external temperatures can be translated to post-retrofit energy savings as discussed in the following paragraphs.

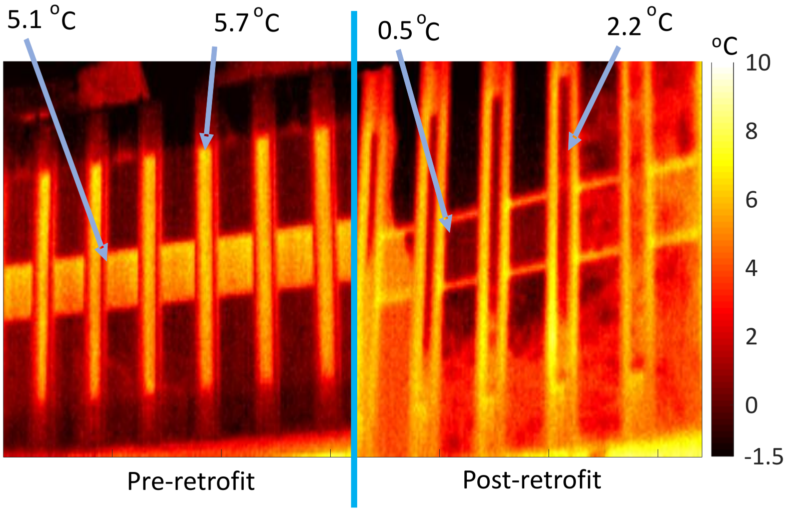
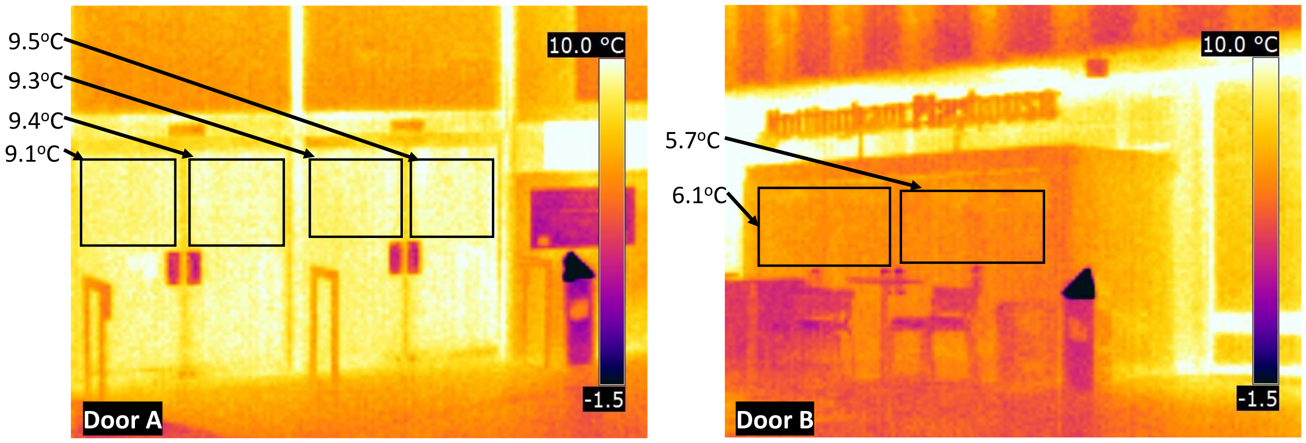


Figure 12: A comparison of average temperatures of windows pre- and post-retrofit; the external temperatures following the retrofit show much lower values indicating a much better insulation.



(a) (b)

Figure 13: A comparison of average temperatures between door A (single swinging door without a vestibule) and door B (double swinging door through a vestibule); post retrofit.

Figure 13 shows the average temperatures of selected areas of door A and door B. The average temperatures of selected regions on door A ranges between 9.1°C to 9.5°C which represents high heat loss through the glasses of this door. On the other hand, the average temperature of the similar regions on door B ranges between 5.7°C to 6.1°C which signifies the benefits of double door (a second swinging door through a vestibule) in terms of limiting heat loss through the glass doors. Based on equations (2) and (3), infrared images shown in Figure 12 and 13 can be used to estimate heat loss through the glazing area with the help of equation (7).

$$P = 5.67\varepsilon_{tot}\left(\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_{out}}{100}\right)^4\right) + 3.8054v(T_i - T_{out}) \quad [\mathrm{W/m^2}] \qquad (7)$$

Here P is the total thermal power, ε_{tot} is the emissivity on the entire spectrum, ν is the wind speed, T_i is the wall surface temperature, T_{out} is the external environment temperature and ν is wind speed (Albatici and Tonelli, 2010). The emissivity of the glass has been taken as 0.88 (CIBSE, 2006). The external temperature and wind speed can be obtained from the local weather observation station and the surface temperature can be extracted from the infrared images. Heat loss for an hour at the constant power, obtained from equation 7, represents the loss of heating energy for that hour and by summing up the hourly heat energy losses the total heat loss for a year can be estimated using equation (8).

$$E = \sum_{D=0}^{365}\sum_{h=0}^{23} P_{h,d} \qquad (8)$$

The surface temperatures at different external temperatures can be estimated by interpolating through the curves shown in Figure 14. The external temperature at the time of capturing the infrared images has been recorded as -2°C and the average surface temperature of the single glazed area in Figure 12 is 5.4°C. Assuming the internal temperature is constant at 20°C, there will be no heat loss when the external temperature reaches at 20°C and consequently the surface temperature of the glazed area will be 20°C. For any external temperature, the surface temperature can be extracted from the curve joining these two points. Similar, temperature curve can be generated for double glazing surface area as well.

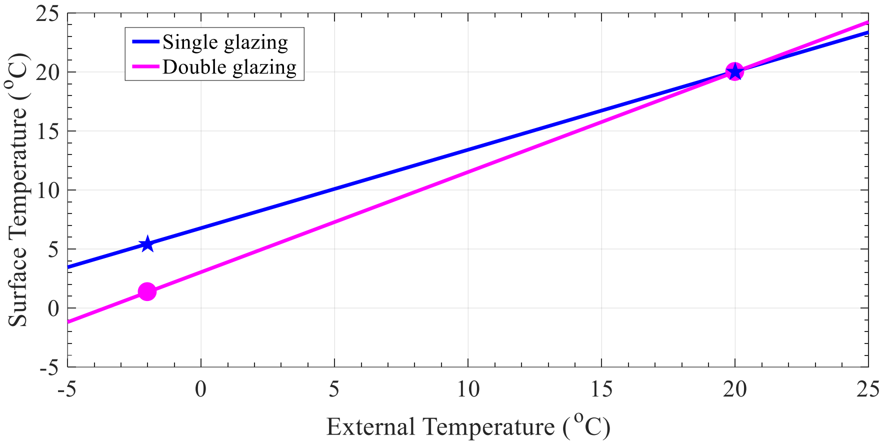


Figure 14: Curves showing the surface temperature of the glazed area with respect to external temperature (see Appendix A for the related equations).

The external temperature and wind speed data from the local weather observation station for the period 01/01/2014 to 31/12/2019 has been extracted from the database of the UK Met Office (Met Office, 2019). The heat losses per square meter through the single glazing and the double glazing areas have been estimated for these time periods. The Percentage reduction in heat loss is estimated by considering equation (9).

$$PR = \frac{E_{double\ glazed} - E_{single\ glazed}}{E_{single\ glazed}} \times 100 \qquad (9)$$

Similar analysis has been conducted with the infrared images of a single swinging door without a vestibule (door A) and double swinging door through a vestibule (door B). The results of these analysis are summarised in Table 1.

Table 1: Yearly heat loss and percentage reduction in heat loss due to retrofitting.

Year	**Yearly Energy Heat Loss (kWh/m²)**						Theoretical Estimated Energy Reduction (%)
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	
Single glazed window	356.45	371.23	336.38	340.69	363.18	328.89	
Double glazed window	158.95	165.61	150.05	151.92	162.05	146.69	55% (maximum)
Door A (single swinging door without a vestibule)	537.35	559.87	507.27	513.60	547.83	495.92	30% (maximum)
Door B (a second swinging door through a vestibule)	374.83	390.55	353.85	358.27	382.15	345.94	

It is noticed from Table 1 that double glazing could theoretically reduce the heat loss through the glazed area by a maximum of 55%. However, the energy savings could be much less than 55% as there would be higher heat loss through the other areas of the building's envelop. The use of double door could reduce the heat loss by a theoretical maximum of 30% based on the assumption that both doors are left closed for the same period of time. In reality, this is not possible to attain; however, the estimation of heat loss from infrared images gives a quick and fair approximation of the maximum potential theoretical savings due to the retrofitting. The above analysis does not also take into consideration people's behaviour and solar gain during day time.

5.3 Walls and roofs insulation

Due to numerous benefits of insulation as one of the easiest and most effective energy efficient technologies available today, including thermal performance, personal comfort, sound control, condensation control, fire protection and personnel protection (Elaiab, 2014), it was important to examine the building's insulation performance and analyse its efficiency. It is believed that a better insulating performance means a decrease of the heating demand (Ferrarini et. Al., 2016), but it turns out that this was not the case with Nottingham Playhouse.

5.3.1 Pre-retrofit walls and roof

The first survey to the building's roofs and walls indicated a poor insulation system throughout the building in addition to large exposed concrete frame structure that created cold bridges all over the building. Most of the cavity brickwork was unknot insulated, and there was little insulation on the roof and on/around the theatre drum that forms the Auditorium and the fly-tower. Thereby, the Auditorium's insulation performance and its temperature were studied to shed light on its overall efficiency. When examining the roof of the Auditorium with the infrared camera, the interface between the roof and the wall was found to be the least insulated, as shown in Figure 15. However, in general, the Auditorium was found relatively much better insulted in comparison with the rest of the building.

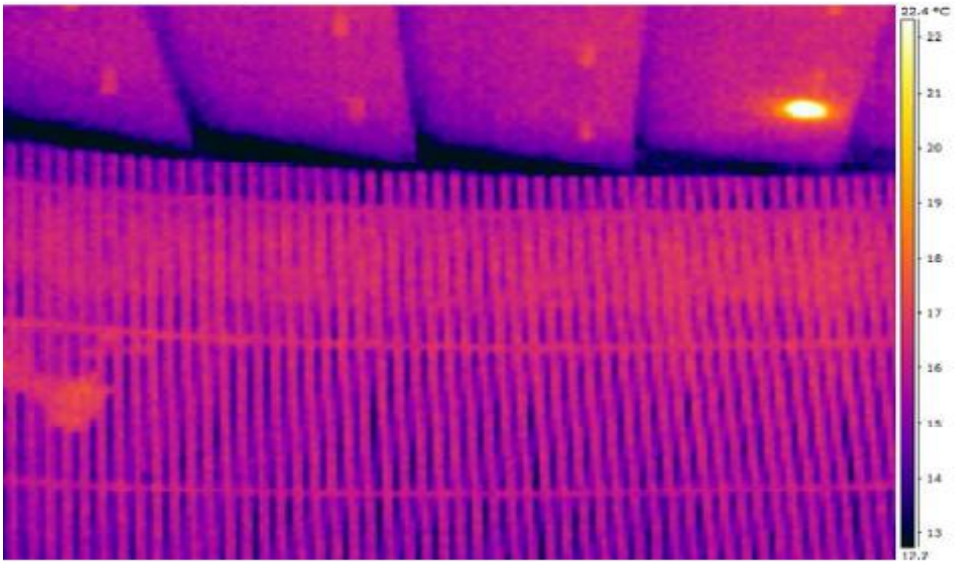


Figure 15: The Auditorium thermal performance pre-retrofit.

The Auditorium's temperature was also examined where a temperature sensor was used to capture the temperature in the lower part of the Auditorium between Friday, December 3, 2010 and Sunday, December 5, 2010, with an outside temperature between 0 ^{0}C (min) and 2 ^{0}C (max). Figure 16 presents the temperature change between 06:00 p.m. and midnight. Notice the fluctuations caused by the heating system and the gradual increase in temperature of 0.3^{0}C which is believed to be caused by the audience body temperature. Figure 17 shows one of the most important findings. When the heating system is off, the Auditorium temperature between 11:00 p.m. and 06:00 a.m. the following morning had been reduced by 1.4 ^{0}C only, which indicates a relatively good insulation characteristic.

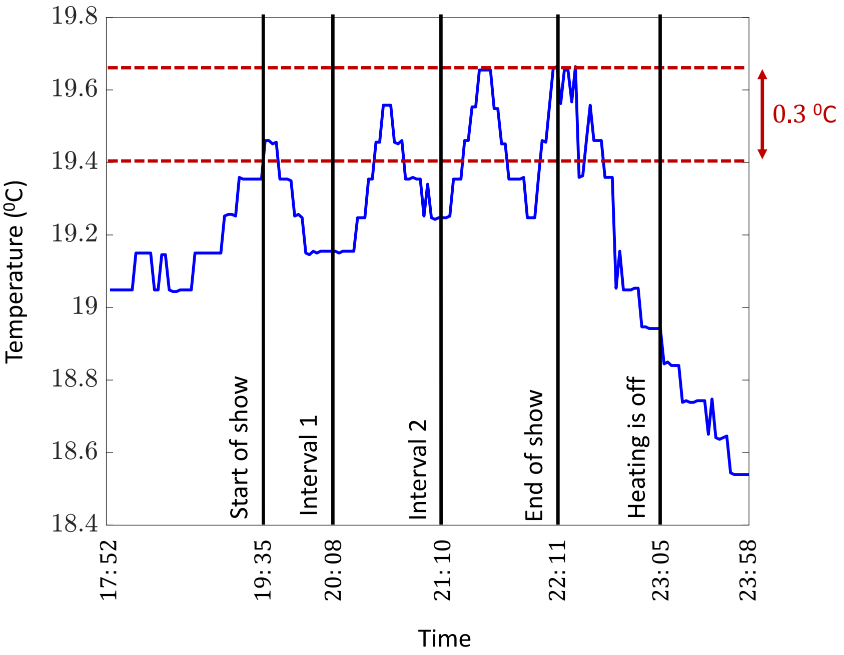


Figure 16: Temperature change in the Auditorium in the evening of December 3, 2010; pre-retrofit.

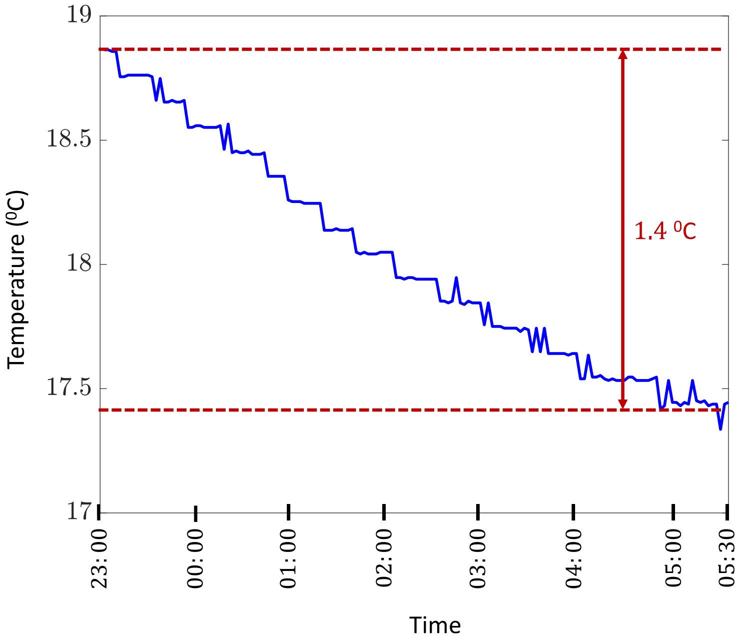


Figure 17: Heat loss in the Auditorium following switching the heating system off from 23:00 on 3rd until 05:30 on 4th Dec 2010; pre-retrofit.

Figure 18 illustrates the temperature fluctuations on Saturday, December 4, during two shows. Notice the change in temperature during the intervals of the shows. Figure 19 also presents the heat loss on Saturday night and Sunday morning as a result of switching the heating system off. A reduction of 0.6 ^{0}C had been measured. Figure 20 shows the change in temperature on Sunday and Monday morning. It is believed that the heating system was switched on in the building (but not in the Auditorium) between 06:00 a.m. and 11:00 p.m. Notice the temperature equilibrium of 16.5 ^{0}C on Sunday, December 5, 2010.

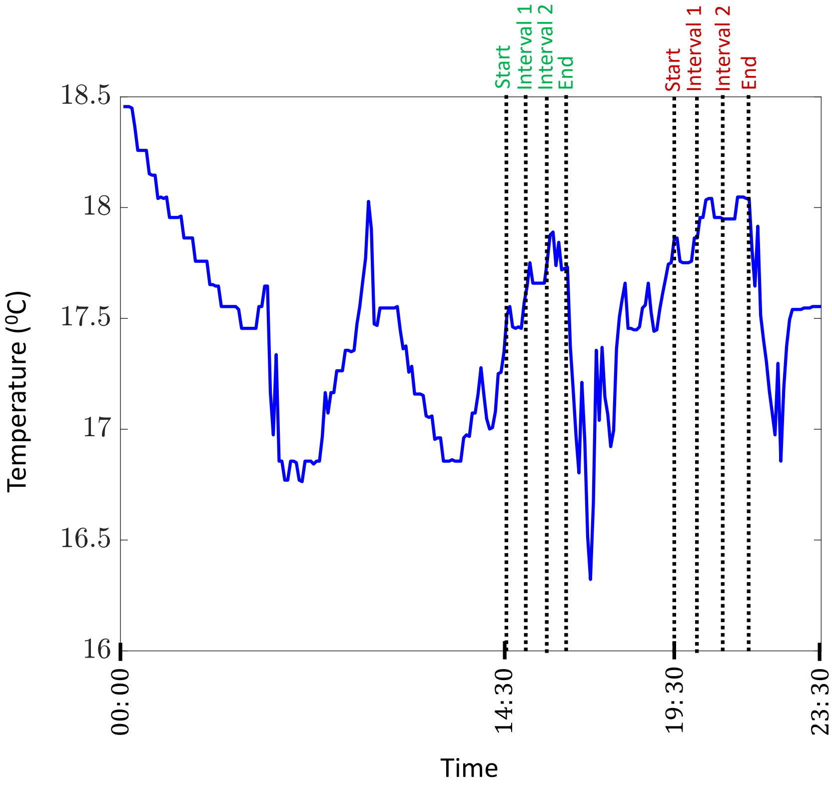


Figure 18: Temperature change in the Auditorium on 4th Dec 2010; pre-retrofit.

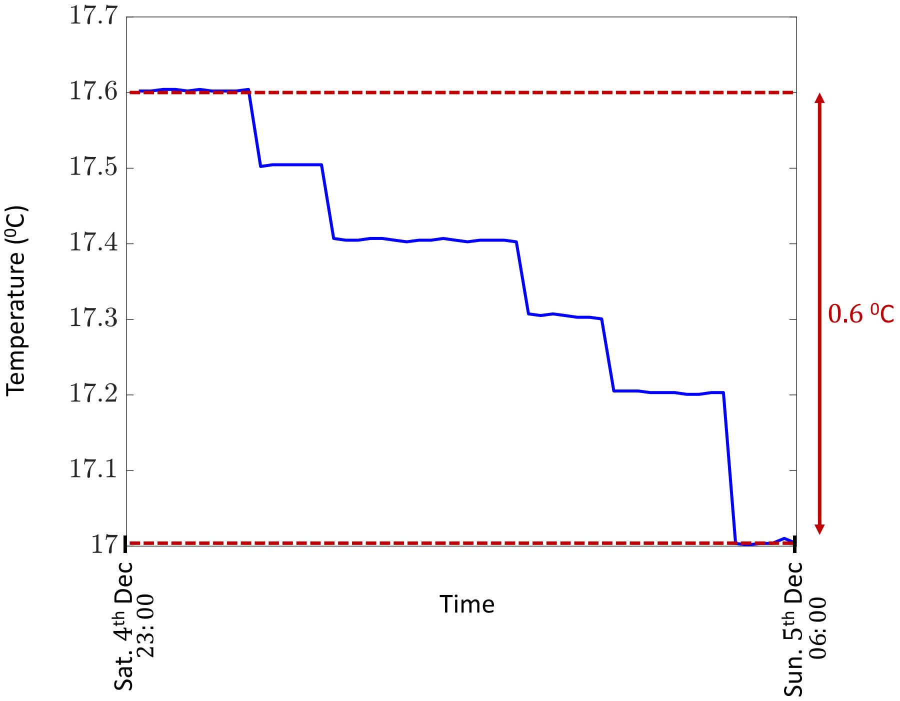


Figure 19: Heat loss in the Auditorium following the switching-off of the heating system on Saturday night, 4th Dec 2010, and Sunday morning, 5th Dec 2010; pre-retrofit.

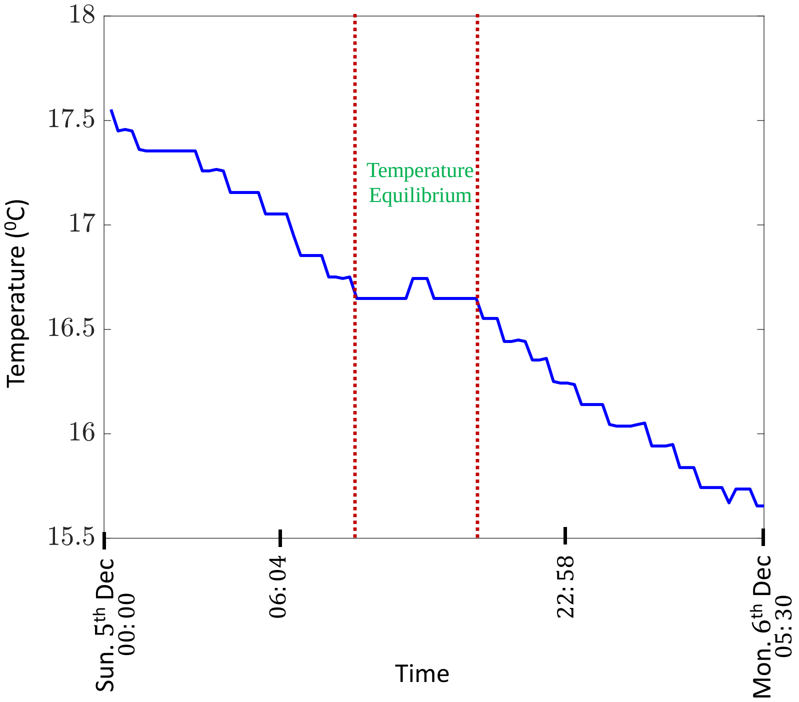


Figure 20: Temperature of the Auditorium during Sunday 5th Dec. and Monday 6th Dec. early morning; pre-retrofit.

5.3.2 Post- retrofit walls and roof

Due to the large exposed concrete surface area affected with respect to the whole building and because of the un-insulated, or minimal insulation, condition of much of the walls which created cold bridges throughout the building, therefore, insulating the exposed concrete of the drum and the fly-tower brickwork with ballasted insulation has the most significant effect on reducing the heating load of the building.

The Auditorium

The temperature of the auditorium has also been analysed from 08 Nov. 2016 to 28 Feb 2017. Figure 21 shows the temperature of the auditorium (see Figure 6, Location C) compared with the internal temperature at the first floor (see Figure 6, Location B) during the same recorded period. The graph illustrates a higher temperature in the auditorium compared with the first floor, although both follow mostly the same pattern.

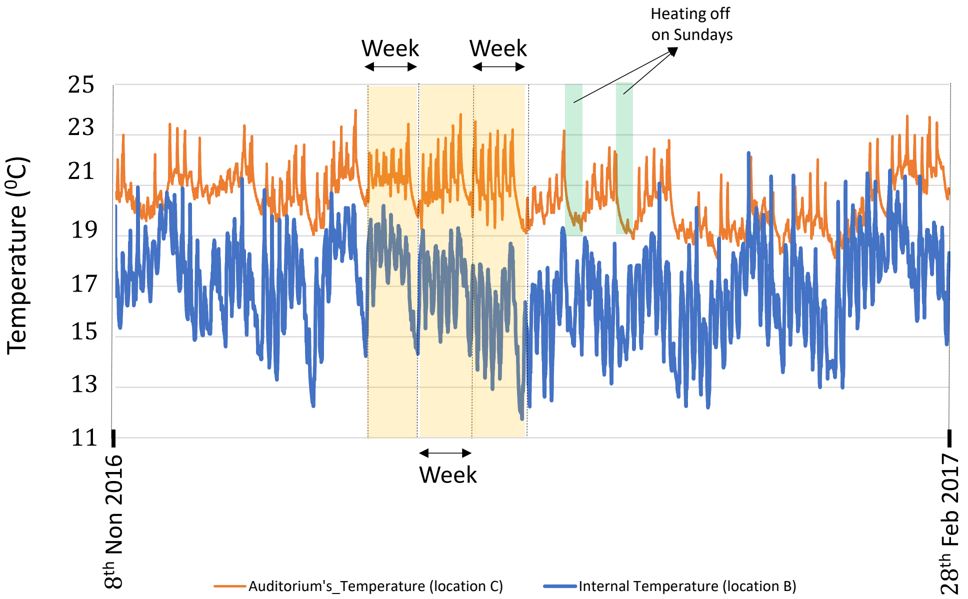


Figure 21: The temperature in the auditorium (Location C) compared with the temperature at first floor (Location B) during the time from 08/11/2016 to 28/02/2017; post-retrofit.

The audience factor and its effect on the building's temperature was also analysed. Interestingly, Figure 22 shows an interaction between the temperature of the auditorium (see Figure 6, Location C), temperature of the cafeteria (see Figure 6, Location A) and audience actions and existence in the building for one day. As shown in the Figure 22, the temperature of the cafeteria starts around 21.5 C° at 09:00 and that is when the heating system starts to operate and staff and visitors begin to occupy the place (body heat), particularly the audience that later moves to the auditorium where the shows take place. This temperature curve drops down many times through its path, mainly because of the opening of the main door for long periods and the leave of audience from the place, and even slightly because of weather change. The heating at the cafeteria, which is generated by audience present normally, starts raising before the shows, and followed by decreasing of the temperature when the audience leave the place and move to the auditorium at the showtimes resulting in increasing the temperature there instead. In this way, the audience work as portable heaters providing one of the most sustainable heating sources, not only saving the heating energy, but also leaving the place behind them heated for some time. The larger the number of the audience, the more heat is produced. Generally, when the number of audiences is low (e.g.,100) the produced heat is less than the cooling effect caused by the ventilation system and this results in decreasing of the temperature in the room by one degree Celsius. In contrast, high number of audience (e.g., 750) results in a significant heating (around 23.5 °C) overtaking the cooling effect.

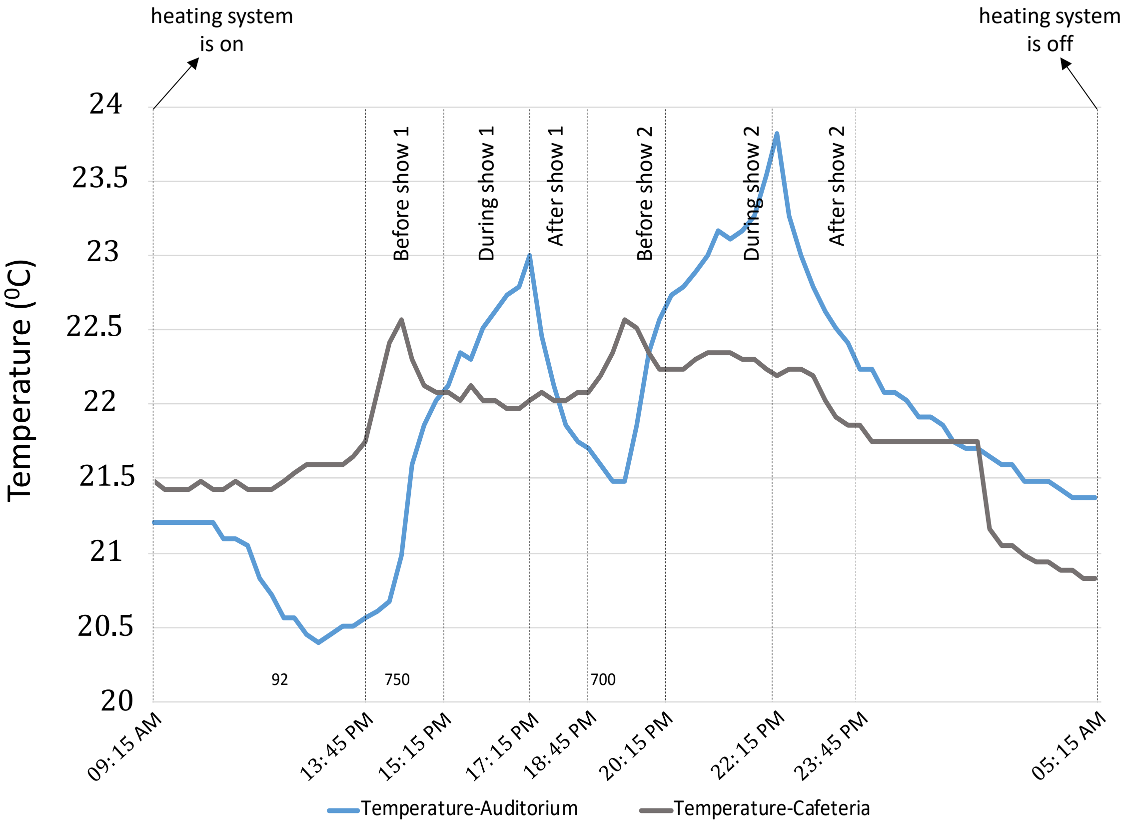


Figure 22: Temperature behaviour in the auditorium (location C) and Cafeteria (location A) in relation to audience present for one day; post-retrofit.

Post-retrofit insulation efficiency

During the second survey, the internal and external differential temperature of the windows at the lower floor (see Figure 6, Location F) of the building was monitored for a whole week, as shown in Figure 23. The selected location is less affected by the visitors and direct sunlight, which means a more stable reading of both weather temperature (outdoor) and heating temperature (indoor). It is clear that the internal temperature, in blue line, is noticeably higher than the external temperature, in green line, for the entire week indicating well-implemented energy-conserving measures. On the other hand, both graphs have similar pattern with a slight phase shift due to the heat transfer process; a convexity zone at the afternoon when the temperature reaches its highest levels and a concavity zone during the midnight and early morning when the temperature drops down to its lowest levels. However, Sundays show only a whole concavity as the building is closed and the temperature continues to decline.

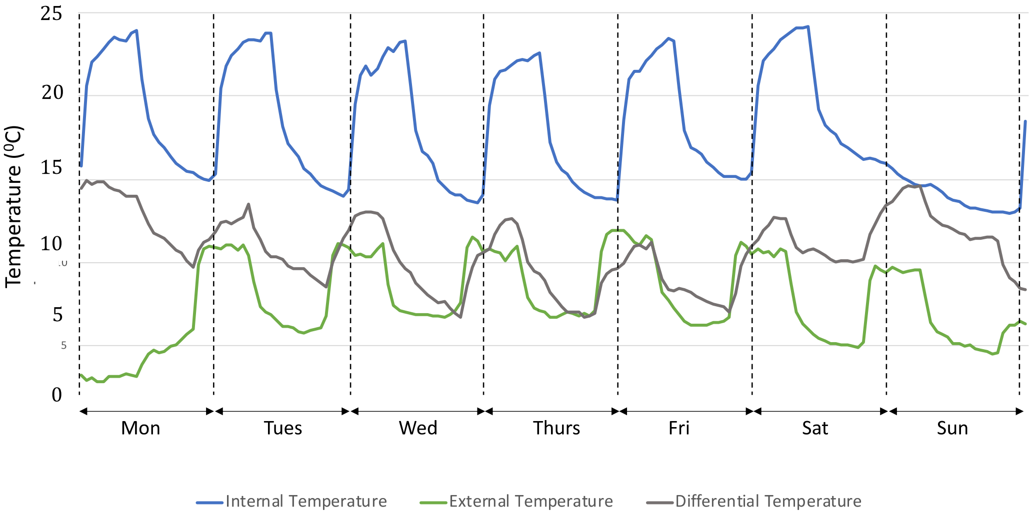


Figure 23: Internal, external and differential temperature of the windows at the lower floor (location F) for a whole week period; post-retrofit.

The internal, external and differential temperatures of the wall at the first floor (see Figure 6, Location B) of the building were also monitored from 24/01/2017 to 13/02/2017, as shown in Figure 24-a, and for the period 02/02 - 03/02/2017, as shown in Figure 24-b. As the location was affected by many factors such as heating system, the solar radiation, body temperature and audience behaviours, therefore the temperature behaviour has shown a clear irregular pattern. Despite the temperature difference, still the internal and external temperatures have mostly followed the same graph pattern, which indicates a clear interlinked relation.

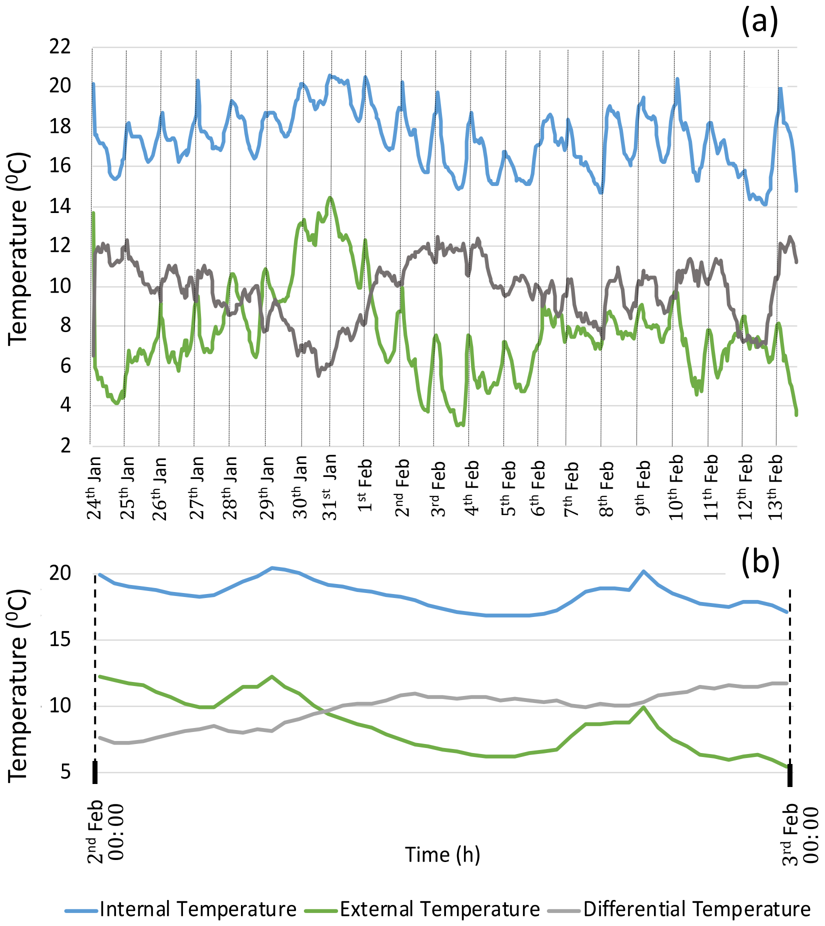


Figure 24: Internal, external and differential temperature of the wall (location B) were monitored. (a) for the period between 24/01 - 13/02/2017, and (b) for the period 02/02 - 03/02/2017; post-retrofit.

In comparison with the data collected of the windows in Location F in Figure 23 it is noticeable that the temperature graphs of the wall for Location B in Figure 24 have not shown a real convexity zone with a wide top. Instead, they only have a sharp slightly higher tops and lacking a clear lowest temperature zone. The differential temperature between the internal and external has an average of around 10°C, which is similar to the value of the window. The lowest differential value is around 6°C and the highest is over 12 °C.

5.4 The Heating System

5.4.1 Pre-retrofit heating system

The heating and cooling systems were for the most part fairly antiquated and ineffective at heating and cooling the building. Mainly, the building was heated by four Remeha Gas 210 Eco boilers – 2 for heating used in winter, 1 for heating used in summer, and 1 for hot water.

5.4.2 Post retrofitting Heating system

The main change for the heating system focuses on the replacement of boilers with more carbon efficient heat sources e.g., Combined Heat and Power (CHP)[1]. In addition, in order to make the existing system as efficient as possible, a more sophisticated new Building Energy Management System (BEMS or BMS)[2] to control existing heating could be installed. This would be computer controlled and would include zoning spaces that are used at different times of day to limit unnecessary heating, ensuring thermostatic control of systems and reducing this to 20 ^{0}C throughout. This indoor temperature provides a suitable thermal comfort climate for the building's occupants due to the fact that insufficient heat loss leads to overheating (hyperthermia), and excessive heat loss results in body cooling (hypothermia) (Cho et al., 2010).

5.5 Lighting

5.5.1 Pre-retrofit lighting

Most of the installed lighting fittings/ bulbs throughout the building were old-fashioned and highly energy-inefficient, e.g., incandescent light bulbs where they normally convert about 5% of the electricity they use into visible light; the rest is lost as waste heat (Ginley and Cahen, 2011).

5.5.2 Post retrofit Lighting

It has been suggested to replace 50% of the existing light fittings/bulbs in the occupied spaces in the building with low energy alternatives, i.e., low wattage light emitting diode (LED) which is currently considered as the most energy efficient technology for lighting applications (Pipattanasomporn, 2014). In addition to replacement of bulbs, an effective control strategy should be implemented. Where possible, movement or daylight sensors should be installed, especially in circulation spaces that are used sporadically. Therefore, effective management can help to reduce the occurrence of artificial lighting being switched on during daylight or unoccupied hours.

5.6 Photovoltaic panels

The choice of the area to install the photovoltaic has been selected in compliance to the building being listed (Grade II*). The roof of the building has been suggested since it is not apparent from the street level and offer enough space. After conducting the first survey, it has been recommended the installation of a 39kWp[3] system utilising 153 solar photovoltaic (PV) panels in order to generate electricity. As shown in Figure 25, the panels have the least overshadowing, specifically in the south facing roofs. This system will generate electricity, reduce energy bills, provide a measure of energy security and reduce the CO2 emissions of the building.

---

[1] Combined Heat and Power system (CHP) generates electricity whilst also capturing usable heat that is produced in this process. This contrasts with conventional ways of generating electricity where vast amounts of heat are simply wasted.

[2] Building Energy Management Systems (or BEMS) are computer-based systems that help to manage, control and monitor building technical services (HVAC, lighting etc.) and the energy consumption of devices used by the building.

[3] Solar electricity systems are given a rating in kilowatts peak (kWp). This is essentially the rate at which it generates energy at peak performance for example at noon on a sunny day.

Figure 25: Post-retrofit Nottingham Playhouse with the photovoltaic solar panels on the roof (Credit: Google Earth, under Geo Guidelines).

6. SUMMARY OF KEY CHARACTERISTICS AND ENERGY AND COST SAVINGS

A brief summary of the pre-retrofit status for the above elements is listed in Table 2. It indicates the original limitations of the windows, doors, walls and roof, heating system and lighting.

Table 2: A brief summary of the pre-retrofit status of the key heat loss sources in the building.

	Element	Pre-retrofit status
Fabrics of Building	Windows	i. Single glazed ii. Steel framed
	Doors	i. Single swinging doors ii. Frameless glass doors
	Walls & roofs insulation	i. Cavity Brickwork: un-insulated ii. Roof: little insulation iii. On/around the theatre drum: little insulation iv. Fly-tower: little insulation v. The roofs and the walls of Neville Studio: insulated below current standards.
Mechanical & Electrical	Heating system	antiquated and ineffective heating system
	Lighting	Outdated and energy-inefficient light fittings/bulbs

A brief list of the proposed modifications is presented in Table 3; which indicates the changes in addition to the use of photovoltaic solar panels to produce renewable energy to reduce carbon emission and enhance sustainability.

Table 3: A list of the of the proposed modifications for the building's heat loss elements.

	Element	**Proposed modifications (retrofit actions)**
Building' s envelope	doors	1. Adding a second swinging door through a vestibule which create a double-swinging door. 2. Retaining the existing doors and fitting new draught seals across the original building.
	windows	1. Changing the windows from single to double glazing. 2. Adding aerogel insulation to existing panels.
	Walls & roofs insulation	1. Insulate all roofs to the Original Building. 2. Insulating the exposed concrete in the theatre drum and the fly-tower brickwork.
Mechanical & electrical	lighting	1. Replacing 50% of the light bulbs with low energy alternatives. 2. Implement an effective control strategy. 3. Install movement or daylight sensors. 4. Effective management.
	Heating system	1. Replacement of boilers with Combined Heat and Power system (CHP). 2. Building Energy Management System (BEMS or BMS).
	PV Panels	Install 153 photovoltaic panels on the roof to generate electricity.

The post-retrofit status for each building's measure has helped in reducing the energy demand throughout the building every year and especially the insulation of the roofs and walls where the overall energy demand has decreased by 34.3%. Table 4 and Figure 26 show that the energy efficiency retrofit project has provided Nottingham Playhouse with a total energy savings that reaches approximately to 363,005 kwh/per year, in addition to a total cost savings which are approximately £26,080/ per annum. This is a solid proof that this project has made a very positive overall energy performance and environmental balance to the building.

Table 4: Summary of experimental energy and cost saving for both, building's fabric and mechanical & electrical measures after implementing the retrofit modifications.

	Element	**% Reduction in heat demand**	**Energy saving (kwh/per year approx.)**	**Cost saving (£/ per annum approx.)**
Building's fabric	Double-glazed windows	7.4%	28,900	£1,736
	Double-swinging doors	17.7%	68,800	£4,130
	Roof insulation	21.2%	82,500	£4,950
	Walls insulation	34.3%	133,700	£8,020
Mechanical & electrical	Lighting	n/a	35,800	£4,650
	Solar panel	n/a	13,305	£2,594

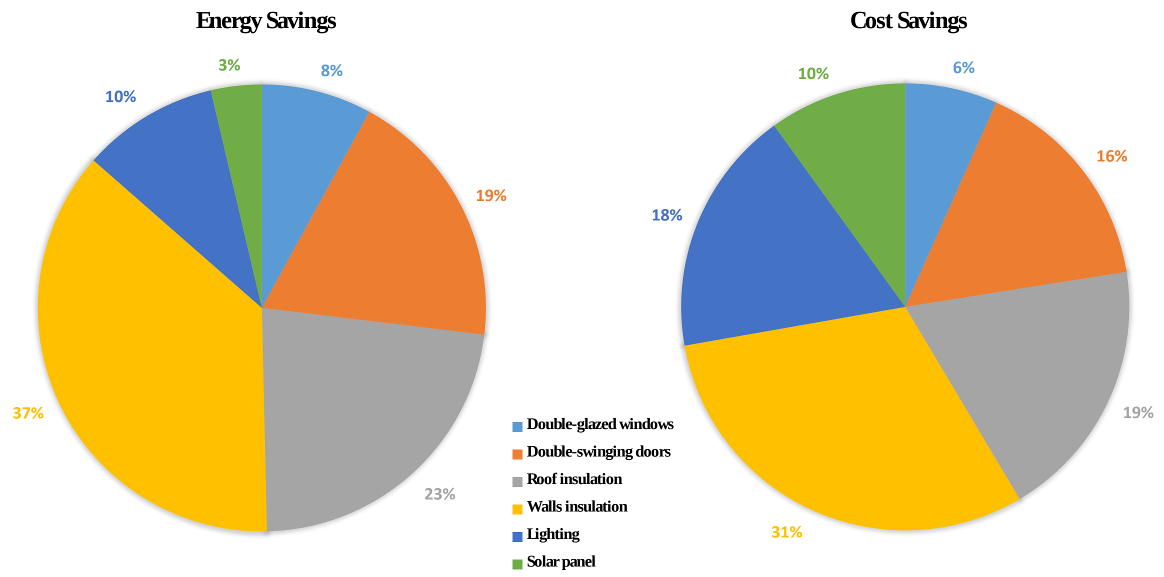


Figure 26: Experimental percentage of energy and cost savings attributed to each element.

The effect of the shading devices on the energy performance of the building was not covered in this paper because the key objective is to save energy during the winter months, and the shadow is insignificant in winter due to the sun angle and the short daylight.

7. CONCLUSION

In conclusion, this paper has shown that the energy efficiency retrofit project on Nottingham Playhouse theatre has effectively enhanced the thermal performance of the building and has shaped a built environment that has a net positive environmental influence where high standards in terms of workplace and sustainability have been provided. In particular, we have comprehensively studied the energy efficient modifications that have been applied to certain building's elements fully complying with the listing of the building Grade II*, using primarily infrared thermography as an energy analysis technique to evaluate the thermal insulation performance and data logger devices to keep track of the resulting indoor temperature. The resulting energy and cost savings have been analysed where energy savings have been successfully achieved. It has been found that creating a better insulation system for the walls and roofs throughout the building has a major impact on its energy performance as is accounted for the highest reduction in heat demand in addition to the largest energy and cost savings. These proposed retrofit recommendations have given Nottingham Playhouse theatre the desired energy performance without spoiling its appearance or heritage character. This project provides an exemplary case study in relation to a generic methodology for implementing energy saving measures while maintaining key heritage characteristics of a building; which would provide international guidance for heritage architects and sustainability experts.

ACKNOWLEDGMENTS

The authors are deeply grateful to Future Factory, funded by Nottingham Trent University and the European Regional Development Fund for supporting this research work. We also, give a special thank to the Nottingham Civic Society for the award of Commendation Certificate for the project; and acknowledge the contribution of Suzy Hunt as project architect for the work at Marsh Grochowski LLP. Finally, we would like to thank Nottingham Playhouse team, especially Ms Stephanie Sirr and Mr Stewart Smith, for their collaboration and support in carrying out the energy monitoring of the case study.

REFERENCES

AEPCA, 2004. A Best Practice Guide to Measurement and Verification of Energy Savings, Australian Energy Performance Contracting Association, South Melbourne, Australia, 2004.

Albatici, R. and Tonelli, A. M., 2010. Infrared thermovision technique for the assessment of thermal transmittance value of opaque building elements on site, Energy and Buildings, 42(11), pp. 2177–2183.

Ascione, F., Bianco, N., De Masi,R. F., de'Rossi, F., and Vanoli, G.P., 2015a. Energy retrofit of an educational building in the ancient centre of Benevento. Feasibility study of energy savings and respect of the historical value, Energy and Buildings, Volume 95, Pages 172-183.

Ascione, F., Cheche, N., De Masi, R. F., Minichiello F., and Vanoli, G. P., 2015b. Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building. Energy and Buildings, Volume 99, Pages 162-176.

Al-Habaibeh, A., Damji, G. A. K., Jones, G., and Lam, K., 2010. Using Infrared Thermography for Monitoring Thermal Efficiency of Buildings- Case Studies from Nottingham Trent University. The 7th Jordanian International Mechanical Engineering Conference (JIMEC'7) 27 - 29 September 2010, Amman – Jordan

Al-Habaibeh, A., Medjdoub, B., and Pidduck, A., 2012. Investigating the Influence of Door Design on the Energy Consumption of Buildings Using Infrared Thermograph. 4th. JIIRCRAC 2012, Amman-Jordan, Sept. 10th – 12th.

ASHRAE Handbook, 2009. Fundamentals, American society of heating, refrigerating and air-conditioning engineers.

Asphaug, S. K., Jelle, B. P., Gullbrekken, L., and Uvsløkk, S., 2016, Accelerated ageing and durability of double-glazed sealed insulating window panes and impact on heating demand in buildings. Energy and Buildings, Volume 116, Pages 395–402.

Blecich, P., Franković, M. and Kristl, Ž., 2016. Energy retrofit of the Krsan Castle: From sustainable to responsible design—A case study. Energy and Buildings, Volume 122, Pages 23-33.

Caro, R., Sendra, J. J., González, C. M. M., 2021. The role of hybrid systems in the decarbonization of residential heritage buildings in Mediterranean climate. A case study in Seville, Spain, Energy and Buildings, Volume 250, 111302, ISSN 0378-7788.

Cho, H., Gowri, K., and Liu, B., 2010. Energy Saving Impact of ASHRAE 90.1 Vestibule Requirements: Modelling of Air Infiltration through Door Openings.

Cho, H. M., Yun, B. Y., Yang, S., Wi, S., Chang, S. J., Kim, S., 2020, Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building, Applied Energy, Volume 275, 115313, ISSN 0306-2619.

Chow, D.H.C., Li, Z., and Darkwa, J., 2013. The effectiveness of retrofitting existing public buildings in face of future climate change in the hot summer cold winter region of China. Energy and Buildings Volume 57, Pages 176–186.

Chung, M. H. and Rhee., E. K., 2014. Potential opportunities for energy conservation in existing buildings on university campus: A field survey in Korea. Energy and Buildings Volume 78, Pages 176–182.

Ciampi, G., Rosato, A., Scorpio, M., and Sibilio, S., 2015. Retrofitting Solutions for Energy Saving in a Historical Building Lighting System. Energy Procedia, Volume 78, Pages 2669–2674. 6th International Building Physics Conference, IBPC.

CIBSE, 2006. CIBSE Guide A: Environment Design'. Elsevier, pp. 1–323. CIBSE- Guide-A-Environmental-Design , Available at: hhttp://www.cibse.org/getattachment/Knowledge/CIBSE-Guide/CIBSE-Guide-A-Environmental-Design-NEW-2015/Guide-A-presentation.pdf.aspx.

Dombaycı, Ö. A., 2007. The environmental impact of optimum insulation thickness for external walls of buildings. Building and Environment, Volume 42, Issue 11, Pages 3855–3859.

Elaiab, F., Thermal comfort investigation of multi-storey residential buildings in Mediterranean climate with reference to Darnah, Libya. Ph.D thesis submitted to the University of Nottingham, United Kingdom. 2014.

Energy Saving Trust, 2017. The Clean Growth Plan: A "2050-ready" new-build homes policy. Report available on-line at https://www.energysavingtrust.org.uk/

Ferrarini, G., Bison, P., Bortolin, A., and Cadelano, G., 2016. Thermal response measurement of building insulating materials by infrared thermography, Energy and Buildings, Volume 133, Pages 559-564, 2016.

Filippi, M., 2015. Remarks on the green retrofitting of historic buildings in Italy. Energy and Buildings Volume 95, Pages 15–22.

Ge, H. and Fazio, P., Experimental investigation of cold draft induced by two different types of glazing panels in metal curtain walls. Building and Environment, Volume 39, Issue 2, Pages 115–125, 2004.

Ginks, N., and Painter, B., 2017. Energy retrofit interventions in historic building: Exploring guidance and attitudes of conservation professionals to slim double glazing in the UK”. Energy and Buildings, Volume 149, Pages 391 – 399.

Ginley, D. S., and Cahen, D., 2011. Fundamentals of Materials for Energy and Environmental Sustainability. Cambridge University Press.

Goia, F., Perino, M. and Serra, V., 2013. Improving thermal comfort conditions by means of PCM glazing system. Energy and Buildings, Volume 60, Pages 442–452.

Hee, W.J., Alghoul, M.A., Bakhtyar, B., Elayeb, O., Shameri, M.A., Alrubaih, M.S., and Sopian, K., 2015. The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews, Volume 42, Pages 323–343.

Holguin, P. M., Roddan, A. C., 2011. Factory built energy efficient sustainable building. United states Patent Application Publication. US 2011/0107689 A1.

Karlsson, N., 2013. Air infiltration through building entrances. Master’s thesis submitted to the Chalmers University of Technology, Sweden.

Kirimtat, A., and Krejcar, O., 2018. A review of infrared thermography for the investigation of building envelopes: Advances and prospects”. Energy and Buildings, Volume 176, Pages 390-406.

Litti, G., Khoshdel, S., Audenaert, A., and Braet, J., 2015. Hygrothermal performance evaluation of traditional brick masonry in historic buildings. Energy and Buildings, Volume 105, Pages 393-411.

Liu, L., Moshfegh, B., Akander, J., and Cehlin. M., 2014. Comprehensive investigation on energy retrofits in eleven multi-family buildings in Sweden. Energy and Buildings Volume 84, Pages 704–715.

Mahajan, G., Cho, H., Shanley, K., and Kang, D., 2015. Comprehensive modelling of airflow rate through automatic doors for low-rise buildings. Building and Environment, Volume 87, Pages 72–81.

Mazzarella, L., 2015. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energy and Buildings Volume 95, Pages 23–31.

Met Office, 2019. MIDAS Open: UK hourly weather observation data, v201901, Centre for Environmental Data Analysis, 01 March 2019. doi: 10.5285/c58c1af69b9745fda4cdf487a9547185.

Moran, M. J., Shapiro, H. N., Munson, B. R., and DeWitt, D. P., 2003. Introduction to thermal systems engineering: Thermodynamics, fluid mechanics, and heat transfer. John Wiley & Sons, Inc.

Nik, V. M., Mata, E., Kalagasidis A. S., and Scartezzini, J.,2016. Effective and robust energy retrofitting measures for future climatic conditions—Reduced heating demand of Swedish households. Energy and Buildings Volume 121, Pages 176–187.

Nosrat, A. H., Swan, L. G., and Pearce, J. M., 2014. Simulations of greenhouse gas emission reductions from low-cost hybrid solar photovoltaic and cogeneration systems for new communities”. Sustainable Energy Technologies and Assessments, Volume 8, Pages 34–4.

Ocana, S. M., Guerrero, I. C., and Requena, I. G., 2004. Thermographic survey of two rural buildings in Spain. Energy and Buildings, Volume 36, Pages 515-523.

Özel, G., Açıkkalp, E., Görgün, B., Yamık, H., and Caner, N., 2015. Optimum insulation thickness determination using the environmental and life cycle cost analyses based entransy approach. Sustainable Energy Technologies and Assessments, Volume 11, Pages 87–91.

Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review on buildings energy consumption information”. Energy and Buildings, Volume 40, Issue 3, Pages 394–398.

Pombo, O., Allacker, K., Rivela, B., and Neila, J., 2016. Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock”. Energy and Buildings Volume 116, Pages 384–394.

Piazza, M. C., Pucci, M., and Vitale, G., 2013. Intelligent power conversion system management for photovoltaic generation”. Sustainable Energy Technologies and Assessments, Volume 2, Pages 19–30.

Pipattanasomporn, M., Rahman, S., Flory, I., and Teklu, Y., 2014. “Engineering design and assessment of a demand-sensitive LED streetlighting system”. Sustainable Energy Technologies and Assessments, Volume 7, Pages 136–146.

Sahin, C. D., Arsan, Z. D., Tuncoku, S. S., Broström, T., Akkurt, G. G., 2015. A transdisciplinary approach on the energy efficient retrofitting of a historic building in the Aegean Region of Turkey, Energy and Buildings, Volume 96, 1 June 2015, Pages 128-139.

Silvero, F., Montelpare, S., Rodrigues, F., Spacone, E., Varum, H., 2018, Energy retrofit solutions for heritage buildings located in hot-humid climates, Procedia Structural Integrity, Volume 11, Pages 52-59,ISSN 2452-3216.

Thomsen, K. E., Rose, J., Mørck, O., Jensen, S. Ø., Østergaard, I., Knudsen H. N., and Bergsøe, N. C. 2016. Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting. Energy and Buildings Volume 123, Pages 8–16.

Havinga, L. Colenbrander,B., 2020. Henk Schellen, Heritage attributes of post-war housing in Amsterdam, Frontiers of Architectural Research, Volume 9, Issue 1, Pages 1-19, ISSN 2095-2635'

Appendix A

Equation used to draw the straight lines in Figure 14:

$$\frac{x - x_0}{x_1 - x_0} = \frac{y - y_0}{y_1 - y_0}$$

$$or, \frac{x - (-2)}{20 - (-2)} = \frac{y - 5.4}{20 - 5.4}$$

$$or, \frac{x + 2}{22} = \frac{y - 5.4}{14.6}$$

$$14.6x + 29.2 = 22y - 118.8 \;\; or, 22y = 14.6x + 148$$

$$or, y = 0.664x + 6.727$$

$$\frac{x - x_0}{x_1 - x_0} = \frac{y - y_0}{y_1 - y_0}$$

$$or, \frac{x - (-2)}{20 - (-2)} = \frac{y - 1.35}{20 - 1.35}$$

$$or, \frac{x + 2}{22} = \frac{y - 1.35}{18.65}$$

$$18.65x + 37.3 = 22y - 29.7 \;\; or, 22y = 18.65x + 67$$

$$or, y = 0.848x + 3.045$$