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RESEARCH ARTICLE

Enhancing the sustainability and energy conservation in heritage buildings: The case of Nottingham Playhouse

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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.

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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 CO₂ 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; Dombaycı, 2007), energy-efficient lighting (Ciampi, 2015) and photovoltaic panels (Nosrat et al., 2014; Piazza et al., 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; 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. (2021) 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., 2010, 2012; 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 Fig. 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.

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 Fig. 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.

3.1. 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.

3.2. 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.



Fig. 1 Nottingham Playhouse.

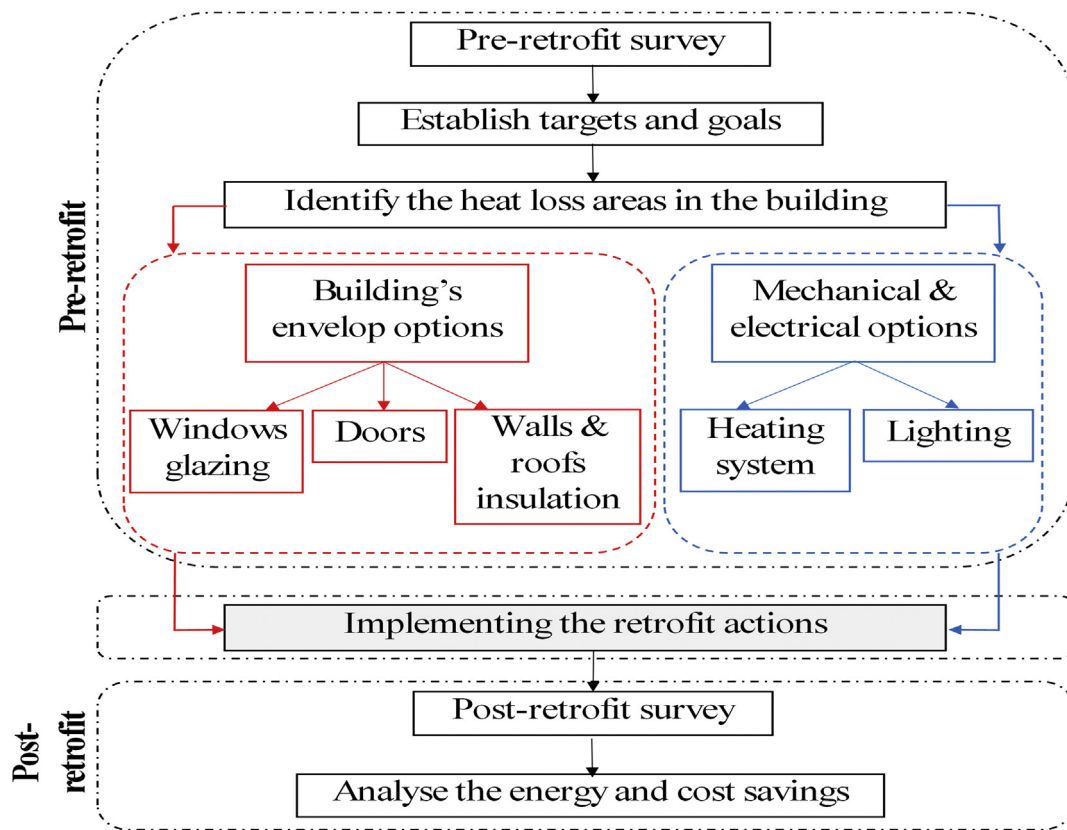


Fig. 2 A schematic diagram of the novel methodology for the retrofit project of Nottingham Playhouse theatre.

3.3. 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*:

$$q_{Cond} = -kA \frac{\Delta T}{\Delta x} \quad (1)$$

where:

q_{Cond} is the condition heat transfer (watts).

k is the thermal conductivity (watts·K⁻¹·m⁻¹).

A is the cross-sectional area normal to the direction of the transfer (m²).

$\frac{\Delta T}{\Delta x}$ is the temperature gradient (K·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:

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

where:

q_{Conv} is the convection heat transfer (watts).
 h is the convection heat transfer coefficient (watts·K⁻¹·m⁻²).
 $T_{HotWall} - T_{ColdWall}$ 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 et al., 2004):

$$q_{Rad} = \sigma A \varepsilon T^4 \quad (3)$$

where:

q_{Rad} is the radiation heat transfer (watts).
 σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ watt·K⁻⁴·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 16 mm, to create an insulating barrier that keeps heat in. The heat loss Q (watt) through a window with an area $A = 0.5$ m² as a function of the temperature difference between the external and internal temperatures ΔT (°C) for two glazing types; single-glazing with a U-value of 4.8 Watt/m²·°C, in blue solid line, and double-glazing where the U-value is dropped down to 2.9 Watt/m²·°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 Dombaycı (2007):

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

where:

E is the annual heat loss (J·m⁻²).

DD is the degree days (°C·days).

R is the sum of thermal resistances of the layers that make up a building element (i.e., walls, floors, roofs etc.) (watt⁻¹·m²·K).

Δx is the insulation thickness (m).

k is the thermal conduction of insulation material (watt·m⁻¹·K⁻¹).

η is the efficiency of space heating system.

Fig. 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.

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 Fig. 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 Fig. 4-a. The disadvantage of such a configuration is that significant heat loss is expected. On the other hand, a revolving door, see Fig. 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 Fig. 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

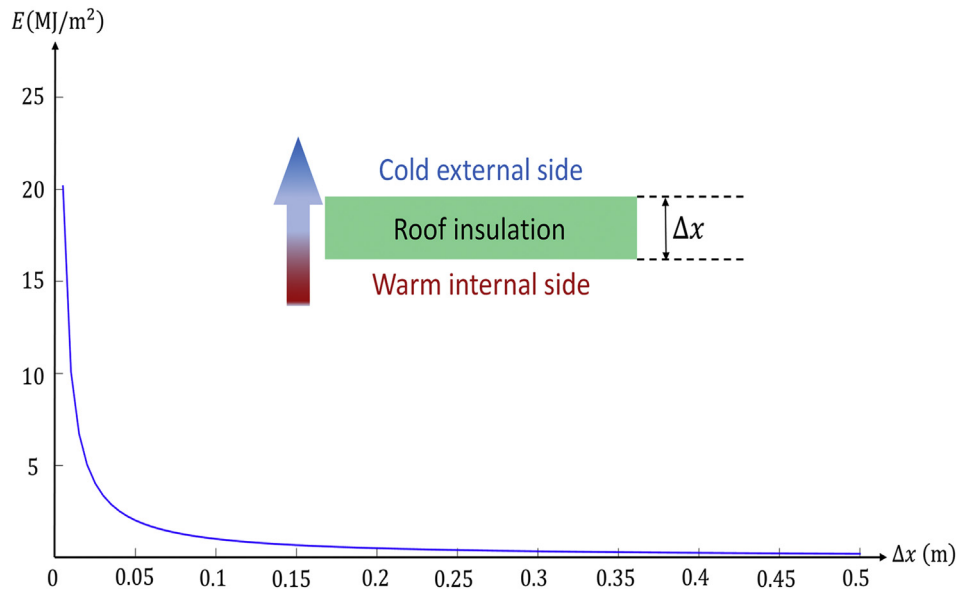


Fig. 3 The annual heat loss E (MJ/m^2) as a function of the insulation thickness Δx (m) of the ballasted insulation. The parameters values used in the calculations are: $DD = 2643$ for Nottingham city with a base temperature = 17°C , $R = 0.592 \text{ watt}^{-1} \cdot \text{m}^2 \cdot \text{K}$, $k =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

indoor climate. However, when the flow of people through the vestibule increases, the energy loss is expected to increase due to both doors being open.

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 overestimates 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; AEP-CA, 2004):

$$V = C_A A R_p \quad (5)$$

where:

V is the volumetric airflow rate (m^3/s).

C_A is the airflow coefficient ($\text{m}/\text{s} \cdot \sqrt{\text{Pa}}$).

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

R_p is the pressure factor ($\sqrt{\text{Pa}}$).

Looking at Fig. 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.

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

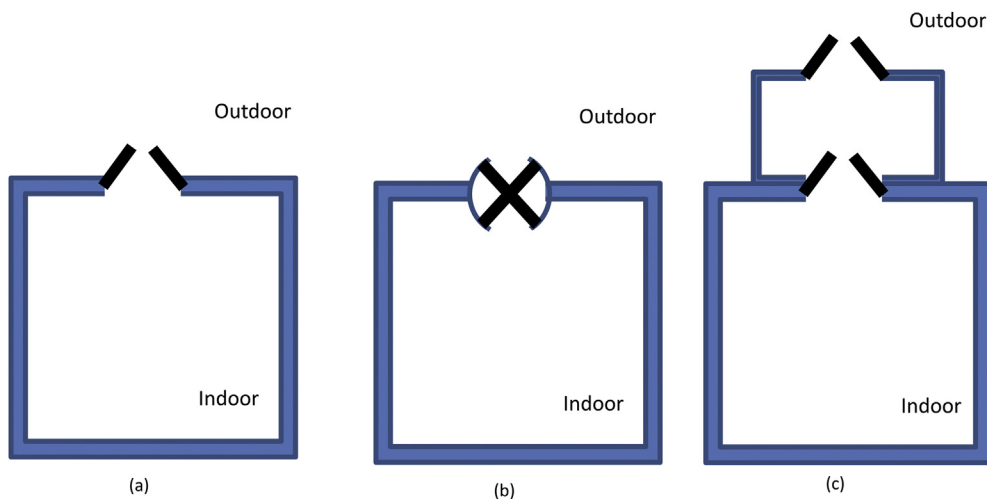


Fig. 4 Current door systems: pivot (a), revolving (b) and a double-pivot system (c).

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 $-2\text{ }^{\circ}\text{C}$ 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 Fig. 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.

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 Fig. 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). Fig. 7 presents the infrared images of the windows taken in 2010 before implementing the retrofit process. When comparing panels (1) with windows (2) in Fig. 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 Fig. 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.

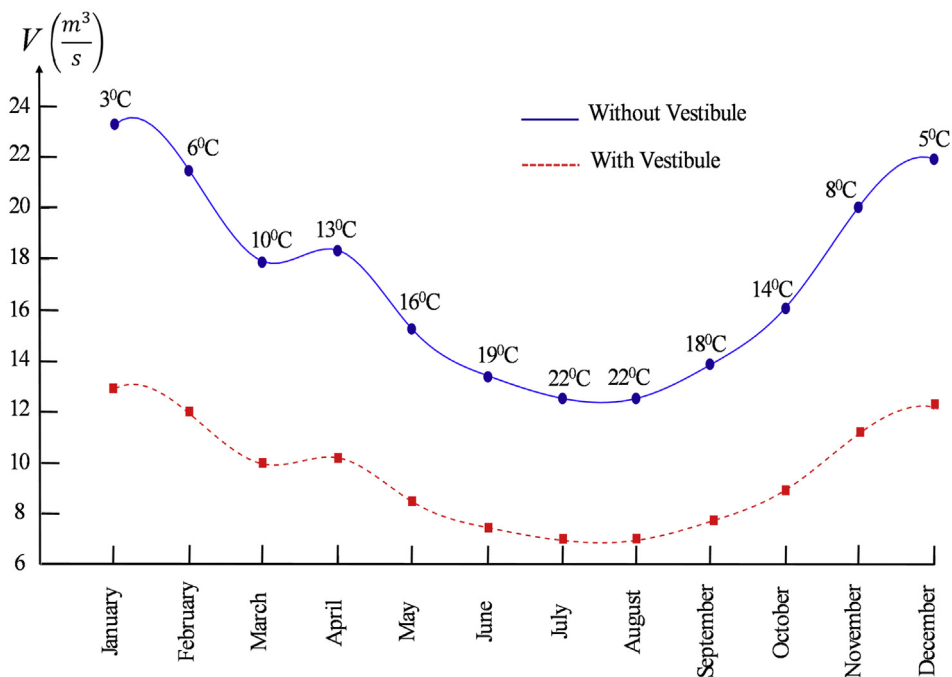


Fig. 5 Air infiltration through door (A) as a function of the annual Nottingham average temperature. We have assumed the following: the people flow rate in off-peak times through door (A) is roughly 75 people per hour, the building height is 30 m and the door area is 2 m^2 . The values of both parameters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

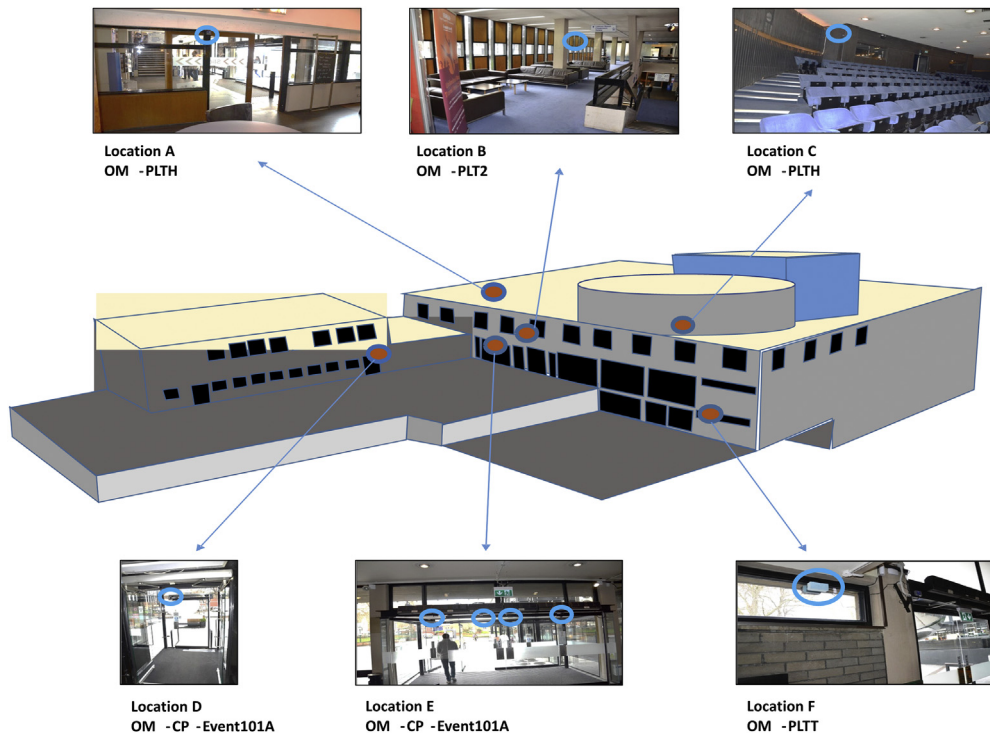


Fig. 6 A schematic illustration of Nottingham Playhouse building combined with images of the locations of the data logger sensors that were installed as part of the survey that took place between November 2016 and March 2017.

5.1.2. 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 Fig. 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

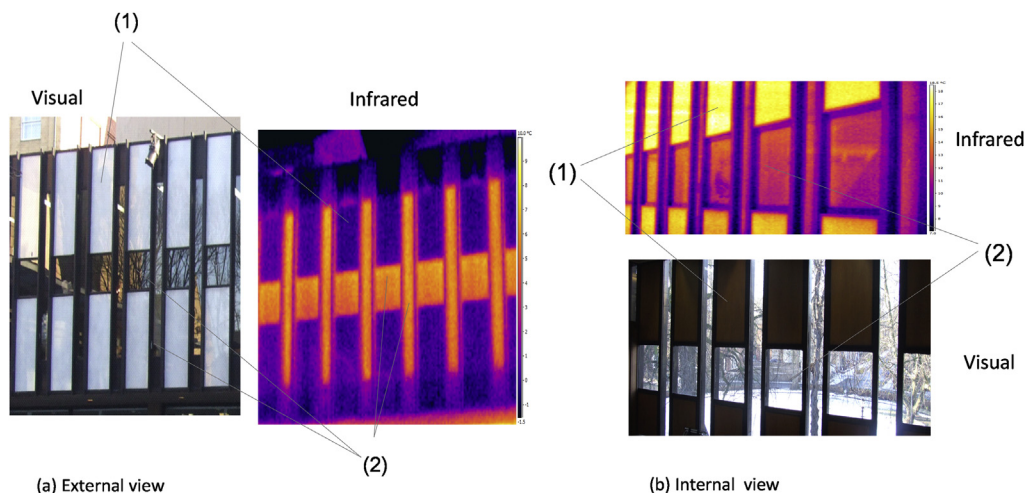


Fig. 7 Pre-retrofit visual and infrared thermography images of the single-glazed windows: (a) exterior side and (b) interior side; which shows significant losses via the windows (2), in comparison to other panels (1). The frames around the windows also show significant heat losses.

internally, and after the improvement, Fig. 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.

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 Fig. 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. Fig. 9 presents visual and infrared images of door B; from outside as in Fig. 9-a, and from inside the building as in Fig. 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. Fig. 6-c presents door A from inside the building with similar characteristics as door B; see Fig. 1.

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 Fig. 10.

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 Fig. 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 through 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 Fig. 11, exhibit the energy performance of door B externally and internally. It can be clearly seen, after comparing with Fig. 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.

As seen previously in Fig. 5, adding a vestibule to a swinging door is considered as an effective design measure

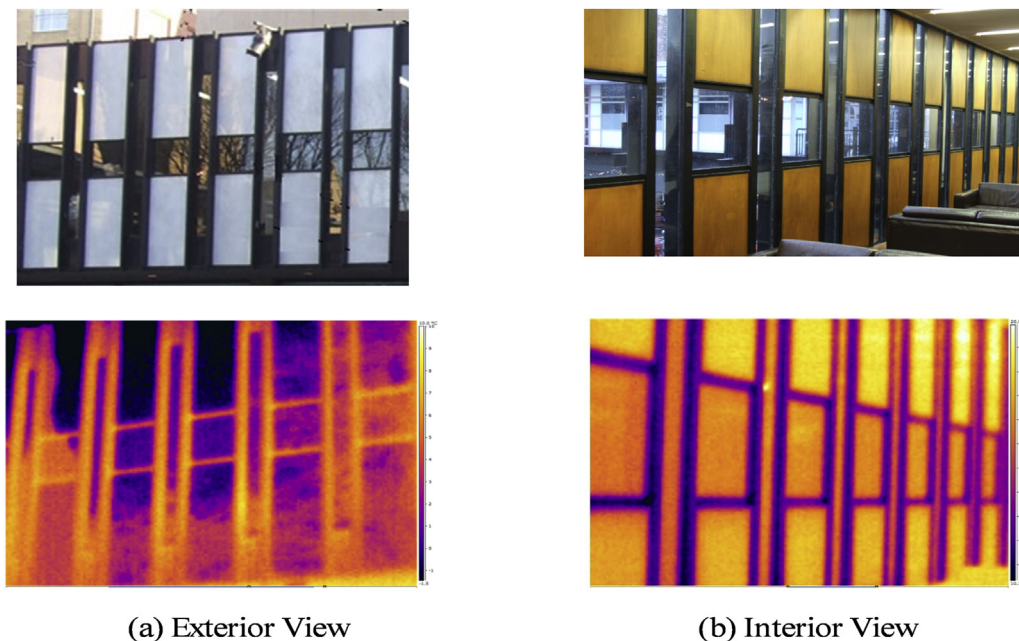


Fig. 8 Post-retrofit infrared thermography images of the double-glazed windows taken during the survey in 2014 following the retrofitting of the double glazed windows, showing significant energy savings via the windows, but the metal frame still forms a thermal bridge.

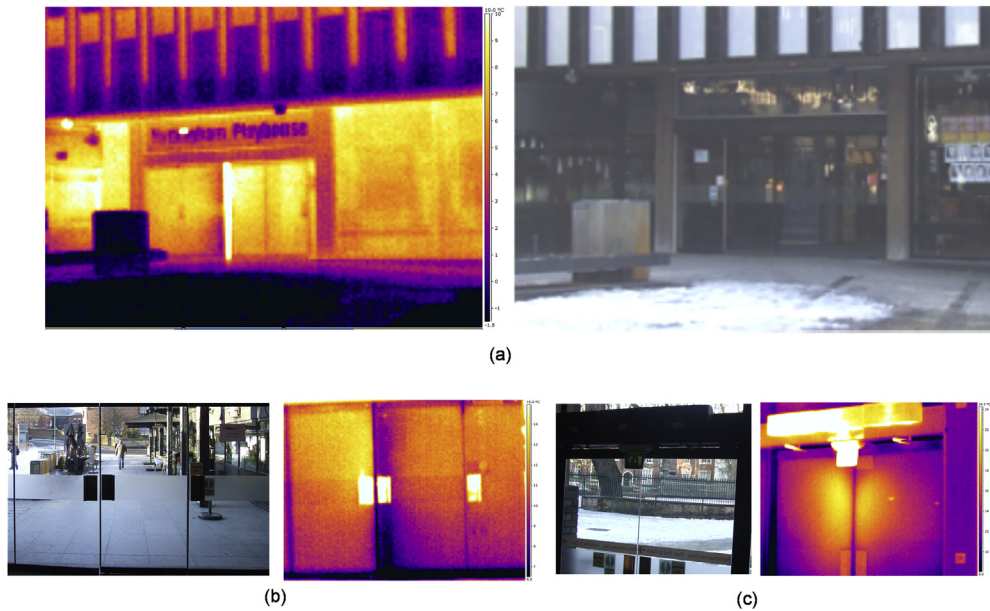


Fig. 9 Pre-retrofit -Visual and infrared thermography images of the single-swinging door-B main entrance (a) and (b); and the second door-A main entrance (c).

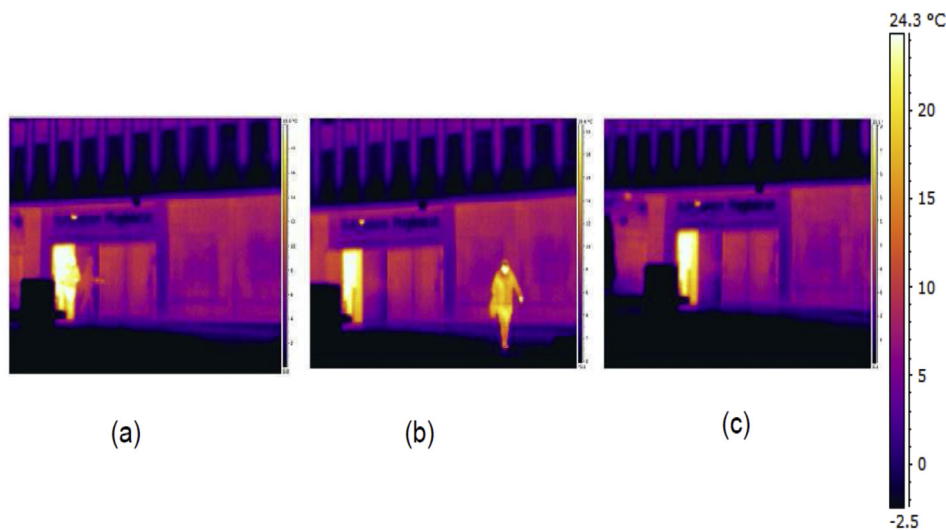


Fig. 10 Pre-retrofit infrared images to the main entrance, door (B), that show qualitatively the heat loss when people enter, (a), or leave the building, (b) and (c).

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

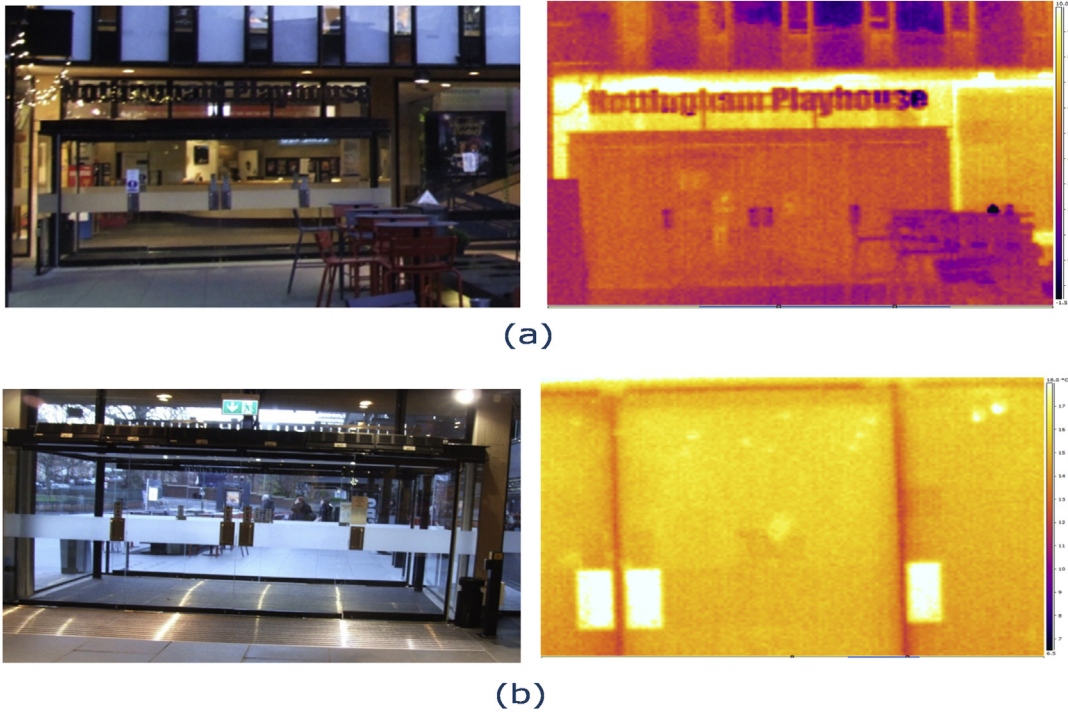


Fig. 11 Post-retrofit visual and infrared thermography images of the double-swinging main entrance, door B.

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 Fig. 12. The average temperatures of the single glazed windows are $5.1\text{ }^{\circ}\text{C}$ and $5.7\text{ }^{\circ}\text{C}$. On the other hand, the average temperatures of the double-glazed window are $0.5\text{ }^{\circ}\text{C}$ and $2.2\text{ }^{\circ}\text{C}$. This difference in external temperatures can be translated to post-retrofit energy savings as discussed in the following paragraphs.

Fig. 13 shows the average temperatures of selected areas of door A and door B. The average temperatures of selected regions on door A ranges from $9.1\text{ }^{\circ}\text{C}$ to $9.5\text{ }^{\circ}\text{C}$ 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 $5.7\text{ }^{\circ}\text{C}$ to $6.1\text{ }^{\circ}\text{C}$ 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 Eqs. (2) and (3), infrared images shown in Figs. 12 and 13 can be used to

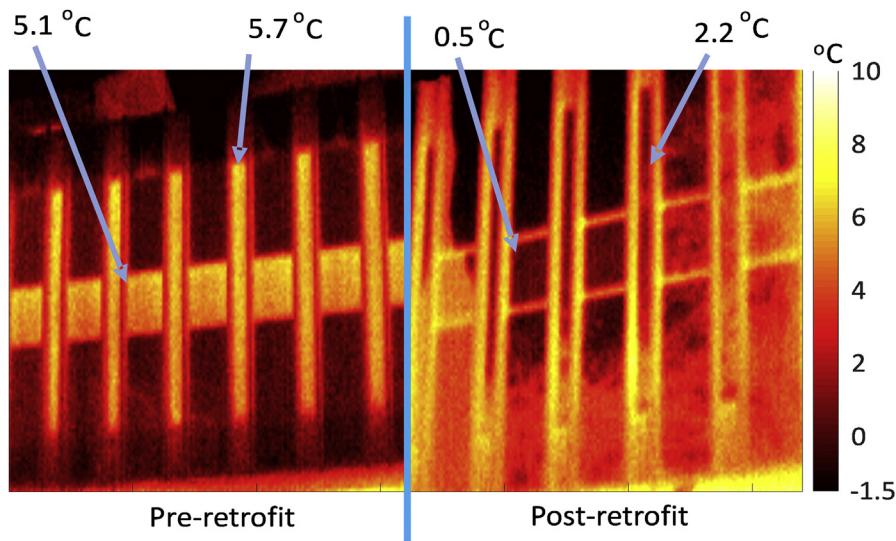


Fig. 12 A comparison of average temperatures of windows pre- and post-retrofit; the external temperatures following the retrofit show much lower values indicating a much better insulation.

estimate heat loss through the glazing area with the help of Eq. (6).

$$P = 5.67\varepsilon_{tot} \left(\left(\frac{T_i}{100} \right)^4 - \left(\frac{T_{out}}{100} \right)^4 \right) + 3.8054v(T_i - T_{out}) \quad [W/m^2] \quad (6)$$

Here P is the total thermal power, ε_{tot} is the emissivity on the entire spectrum, v is the wind speed, T_i is the wall surface temperature, T_{out} is the external environment temperature and v 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 Eq. (6), 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 Eq. (7).

$$E = \sum_{D=0}^{365} \sum_{h=0}^{23} P_{h,d} \quad (7)$$

The surface temperatures at different external temperatures can be estimated by interpolating through the curves shown in Fig. 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 Fig. 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.

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.

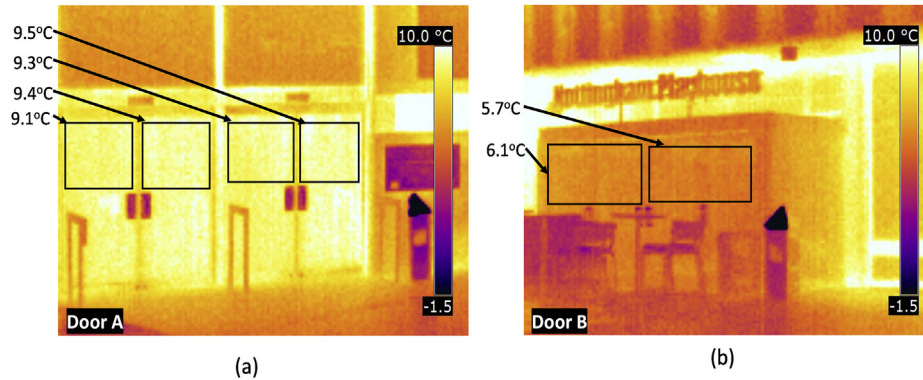


Fig. 13 A comparison of average temperatures between door A (single swinging door without a vestibule) and door B (double swinging door through a vestibule); post retrofit.

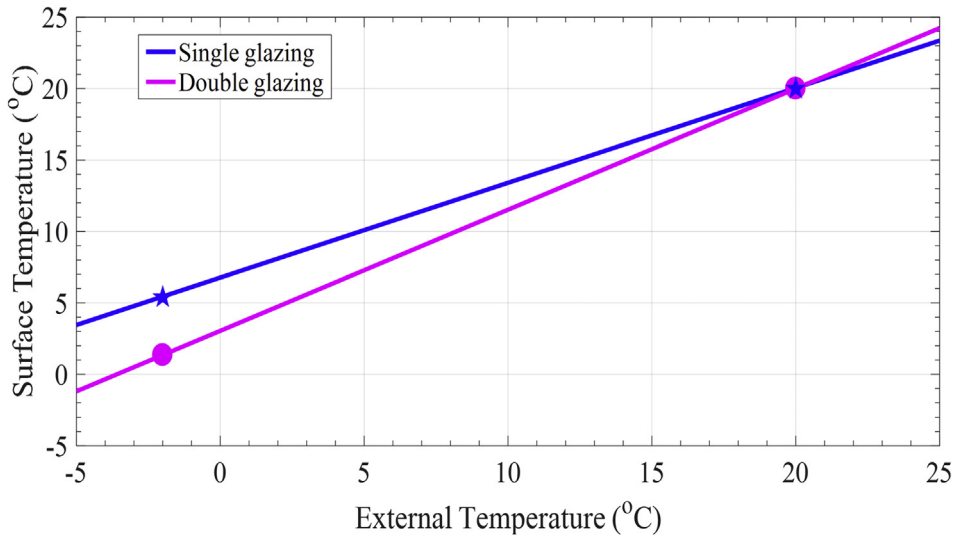


Fig. 14 Curves showing the surface temperature of the glazed area with respect to external temperature (see Appendix A for the related equations).

The Percentage reduction in heat loss is estimated by considering Eq. (8).

$$PR = \frac{E_{double\ glazed} - E_{single\ glazed}}{E_{single\ glazed}} \times 100 \quad (8)$$

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.

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 retrofiting. 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 unknotted 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 Fig. 15. However, in general, the Auditorium was found relatively much better insulated in comparison with the rest of the building.

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 °C (min) and 2 °C (max). Fig. 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 °C which is believed to be caused by the audience body temperature. Fig. 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 °C only, which indicates a relatively good insulation characteristic.

Fig. 18 illustrates the temperature fluctuations on Saturday, December 4, during two shows. Notice the change in temperature during the intervals of the shows. Fig. 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 °C had been measured. Fig. 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 °C on Sunday, December 5, 2010.

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.

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

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

Year	Yearly Energy Heat Loss (kWh/m ²)						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	55% (maximum)
Double glazed window	158.95	165.61	150.05	151.92	162.05	146.69	
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	

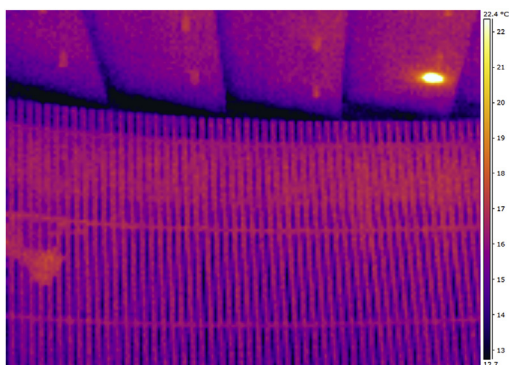


Fig. 15 The Auditorium thermal performance pre-retrofit.

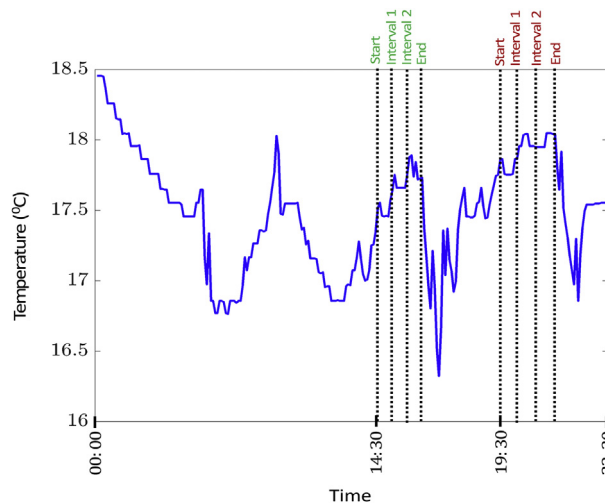


Fig. 18 Temperature change in the Auditorium on 4th Dec 2010; pre-retrofit.

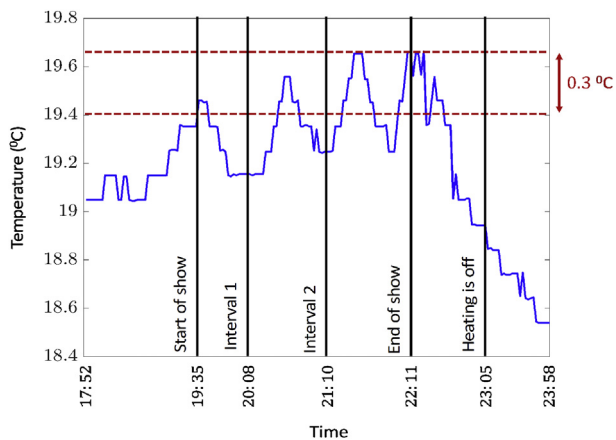


Fig. 16 Temperature change in the Auditorium in the evening of December 3, 2010; pre-retrofit.

temperature in the auditorium compared with the first floor, although both follow mostly the same pattern.

The audience factor and its effect on the building's temperature was also analysed. Interestingly, Fig. 22 shows an interaction between the temperature of the auditorium

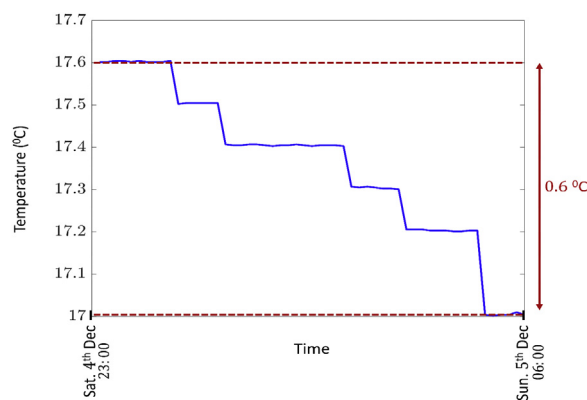


Fig. 19 Heat loss in the Auditorium following the switching-off of the heating system on Saturday night, 4th Dec 2010, and Sunday morning, 5th Dec 2010; pre-retrofit.

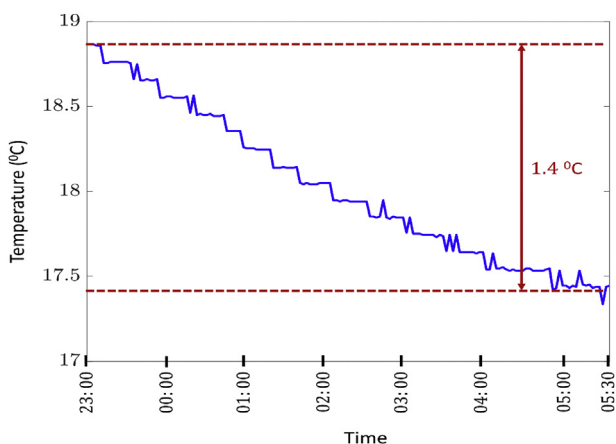


Fig. 17 Heat loss in the Auditorium following switching the heating system off from 23:00 on 3rd until 05:30 on 4th Dec 2010; pre-retrofit.

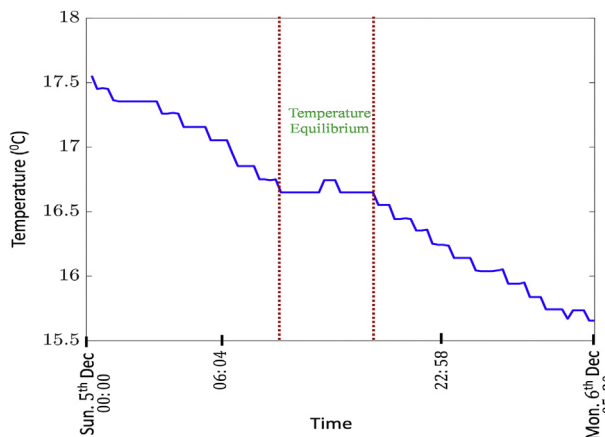


Fig. 20 Temperature of the Auditorium during Sunday 5th Dec. and Monday 6th Dec. early morning; pre-retrofit.

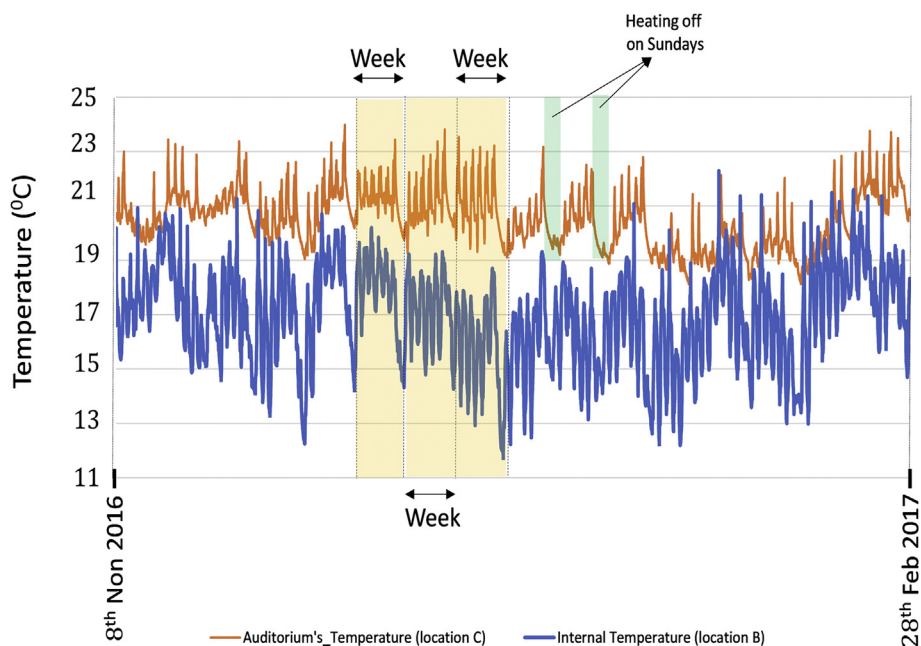


Fig. 21 The temperature in the auditorium (Location C) compared with the temperature at first floor (Location B) during the time from 08/11/2016 to 28/02/2017; post-retrofit.

(see Fig. 6, Location C), temperature of the cafeteria (see Fig. 6, Location A) and audience actions and existence in the building for one day. As shown in Fig. 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

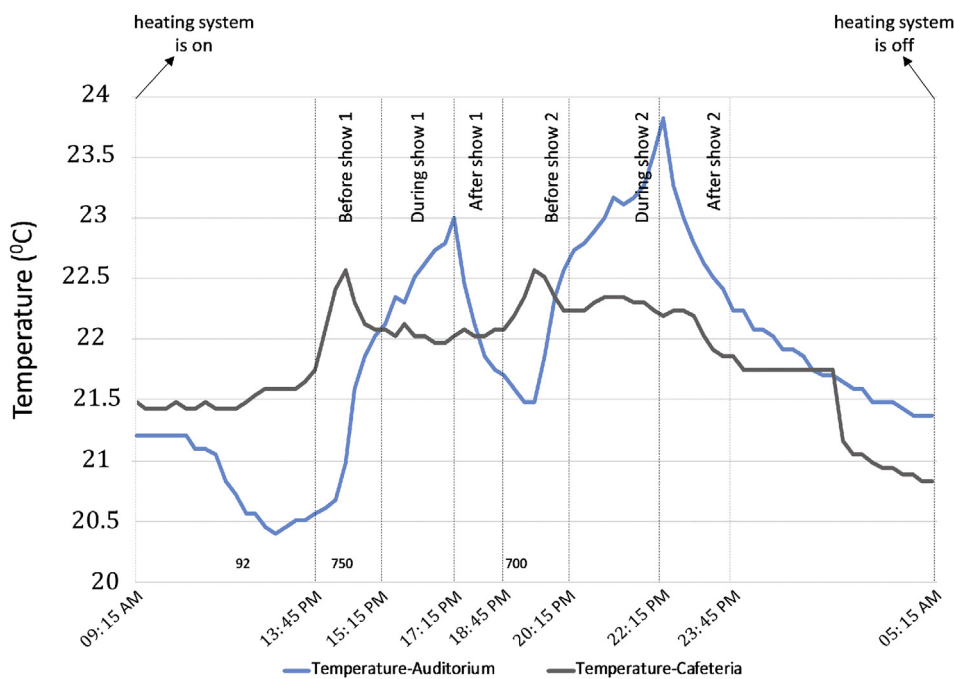


Fig. 22 Temperature behaviour in the auditorium (location C) and Cafeteria (location A) in relation to audience present for one day; post-retrofit.

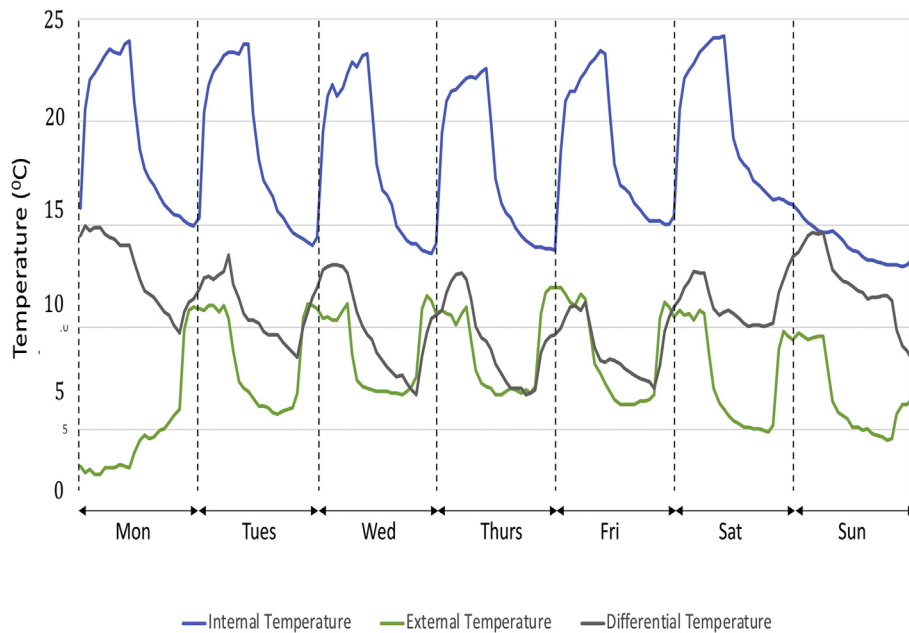


Fig. 23 Internal, external and differential temperature of the windows at the lower floor (location F) for a whole week period; post-retrofit.

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 1 °C. In contrast, high number of audience (e.g., 750) results in a significant heating (around 23.5 °C) overtaking the cooling effect.

5.3.2.2. Post-retrofit insulation efficiency. During the second survey, the internal and external differential temperature of the windows at the lower floor (see Fig. 6, Location F) of the building was monitored for a whole week, as shown in Fig. 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.

The internal, external and differential temperatures of the wall at the first floor (see Fig. 6, Location B) of the building were also monitored from 24/01/2017 to 13/02/2017, as shown in Fig. 24-a, and for the period 02/02–03/02/2017, as shown in Fig. 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.

In comparison with the data collected of the windows in Location F in Fig. 23 it is noticeable that the temperature graphs of the wall for Location B in Fig. 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

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

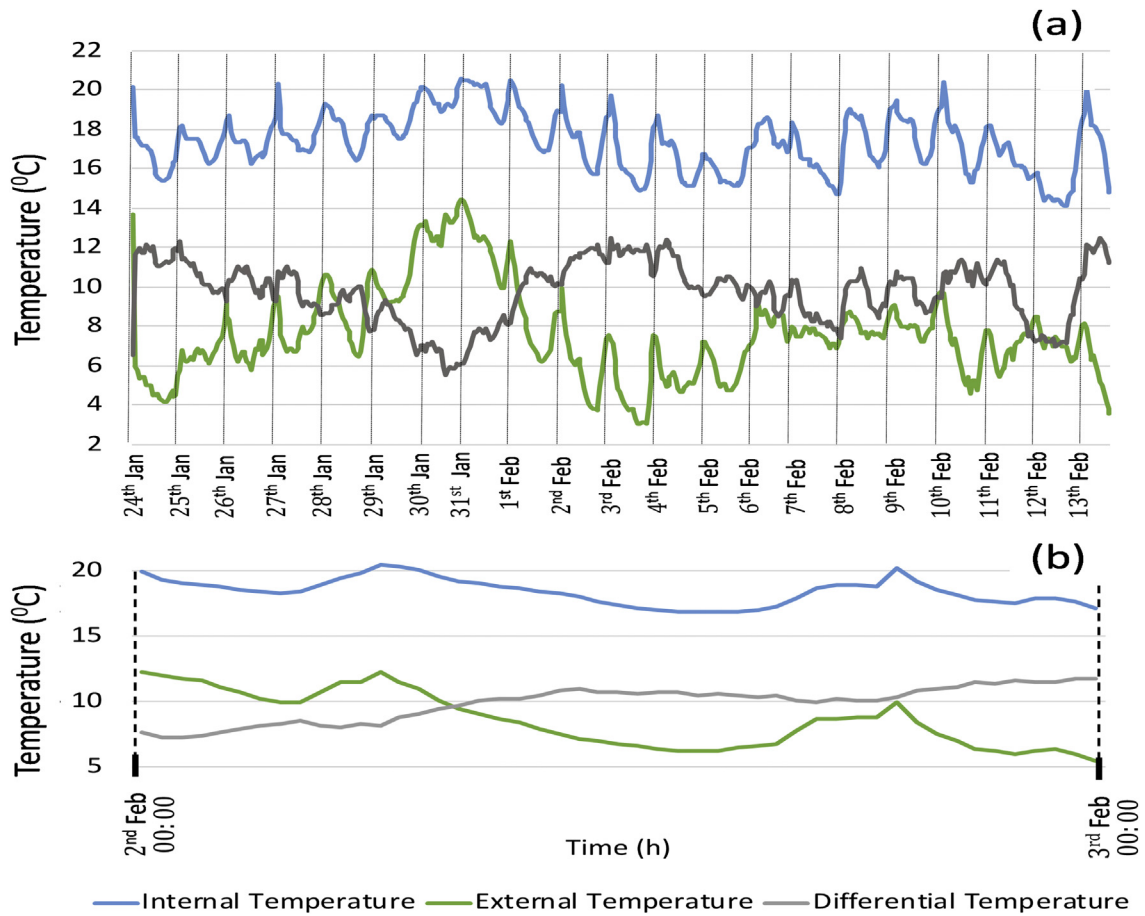


Fig. 24 Internal, external and differential temperature of the wall (location B) were monitored. (a) for the period between 24/01–13/02/2017, and (b) for the period 02/02–03/02/2017; post-retrofit.



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

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 °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 et al., 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 39kWp³ system utilising 153 solar photovoltaic (PV) panels in order to generate electricity. As shown in Fig. 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.

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.

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

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.

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.

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 Fig. 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.

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.

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.

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	£1736
	Double-swinging doors	17.7%	68,800	£4130
	Roof insulation	21.2%	82,500	£4950
	Walls insulation	34.3%	133,700	£8020
	Lighting	n/a	35,800	£4650
Mechanical & electrical	Solar panel	n/a	13,305	£2594

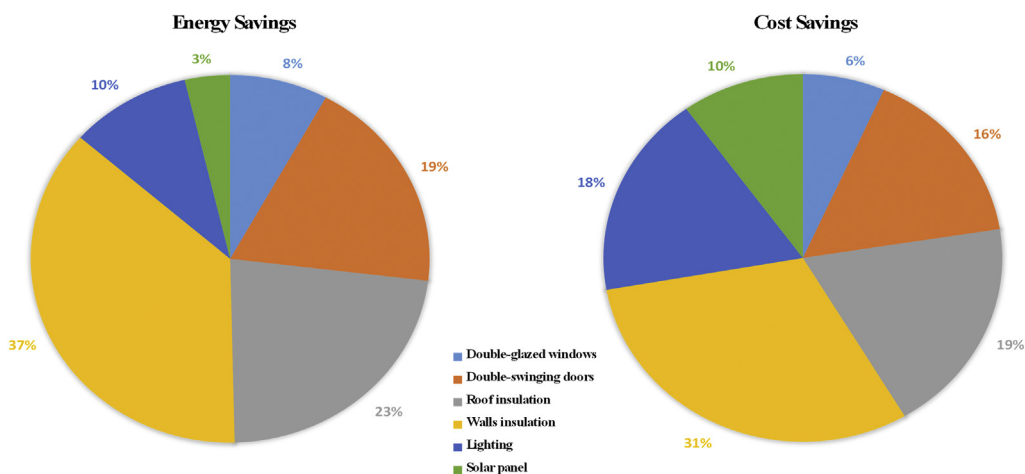


Fig. 26 Experimental percentage of energy and cost savings attributed to each element.

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.

Declaration of competing interest

The authors would like to declare that there is no conflict of interest including any financial, personal or other relationships with other people or that could inappropriately influence, or be perceived to influence, their work.

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Appendix A

Equation used to draw the straight lines in Fig. 14:

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

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

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

$$14.6x + 29.2 = 22y - 118.8 \text{ or, } 22y = 14.6x + 148$$

$$\text{or, } y = 0.664x + 6.727$$

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

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

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

$$18.65x + 37.3 = 22y - 29.7 \text{ or, } 22y = 18.65x + 67$$

$$\text{or, } y = 0.848x + 3.045$$

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