Resilience of Buildings to Extreme Weather Events

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Declaration of authorship

I, Athanasios Lykartsis, declare that this thesis entitled, ‘Resilience of buildings to extreme weather events’ and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

- Where I have consulted the published work of others, this is always clearly attributed.

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Abstract

Our climate is changing and the results of that are already visible. The two-month period of December 2013 and January 2014 was for England and Wales one of, if not the most, exceptional periods of winter rainfall in at least 248 years. In addition to that, on July 1st, 2015, at Heathrow, Greater London the highest July temperature on record for the UK was recorded.

Our buildings are already performing poorly under the current weather conditions. Even the buildings that are performing well now may become intolerable for the occupants by 2080. It is therefore important to find ways to increase the resilience of the current building stock and to identify master planning principles for the new buildings.

The scope of this research was to study the resilience of three different types of buildings (high-, medium- and low risk) under extreme weather conditions. The extreme events that were investigated are extreme hot and heavy rain. EDSL TAS, XP SWMM and MicroDrainage simulation software packages were used in order to estimate the thermal and energy performance of the buildings and investigate the effects of heavy rainfall.

There is clear evidence to show that climate change is happening. According to the UK Climate Projections (UKCP09), we can expect warmer and wetter winters, hotter and drier summers, rising sea levels, and more extreme weather events. These extreme weather events in the UK are likely to increase with rising temperatures, causing among others more substantial rainfall events with an increased risk of flooding. Flooding is currently identified as one of the greatest threats to the UK posed by climate change. In addition to that, the UKCP09 show that means daily temperatures will increase everywhere in the United Kingdom. This will significantly affect the thermal and energy performance of the current building stock.

This study presents four case studies where the resilience of the examined buildings is investigated under extreme hot weather events. It looks into the risk of overheating of a school building in 14 locations in the United Kingdom using the overheating criteria defined in Building Bulletin 101 (BB101). It examines three different ventilation modes and quantifies the required amount of cooling loads to achieve thermal comfort conditions. Furthermore, it considers the effect of relative humidity for an office building in London and for the same building, it examines the effect of the window-to-wall ratio on thermal comfort and energy consumption.

This study also evaluates the effect of extreme rainfall events on the resilience of buildings and presents two case studies on this. The first one examines the effect of building development on

the risk of flooding under extreme rainfall for an area that has a very low chance of flooding by modelling two different scenarios of building development. The second case study investigates the effects of sustainable drainage systems on residential developments under extreme rainfall events.

The outcomes of this research present practical approaches of mitigating the effects of extreme hot weather and extreme rainfall events. The research has demonstrated that lower window to wall ratios result in more comfortable conditions and has also shown that a relative humidity control will result in improved thermal comfort conditions for most of the occupied hours during the summer months. This study has also examined a school building and quantified the amount of cooling loads required to comply with the BB101 criteria and presented a comparison between the current and future weather conditions. Additionally, the research results demonstrated that automated control of the opening of the windows results in reduced operative temperatures and improved thermal comfort conditions. This study has also investigated the effects of sustainable drainage systems (SuDS) during extreme rainfall and has quantified the effect of three different types of SuDS (permeable water, rainwater harvesting, and attenuation basins) for a new build residential development. It has also shown that building development will increase the risk of flooding from surface water, even for areas with a low chance of flooding.

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List of publications resulting from this Thesis

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- Lykartsis A, Jahromi B.A, Mylona A, Fadejeva L, Coombs P., (2017), Effect of Building Development on the Risk of Flooding under Extreme Rainfall, 8th International Conference on Complexity, Informatics and Cybernetics, Orlando, USA, 21-24 March 2017, Florida, International Institute of Informatics and Systemics.

- Lykartsis A., Jahromi B.A, Mylona A (2017) Investigating risk of overheating for school buildings under extreme hot weather conditions, Advances in Energy Research, An International Journal, Vol. 5, No. 4 (2017) 277-287 DOI: http://doi.org/10.12989/eri.2017.5.4.277

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Chapter 1. Introduction

1.1 Research background

Climate change is one of the major concerns the world currently faces (Ji, Lomas and Cook, 2009). Global temperatures are projected to continue to rise, bringing changes in weather patterns, rising sea levels and increased frequency and intensity of extreme weather for the UK (Defra, 2009a). Increasing evidence has shown that the accumulation of greenhouse gases such as CO2 in the atmosphere is the main reason behind global warming (Ji, Lomas, and Cook, 2009). It is very likely (over 90%) that the majority of the observed increase in global average temperatures since the middle of the twentieth century is a result of man-made greenhouse gas emissions. (IPCC, 2007).

The synthesis report of the Intergovernmental Panel on Climate Change (IPCC) from 2007 shows an increase of global mean temperatures and water levels and a decrease of global snow coverage over the last 50 years. One of the leading causes is the increased concentration of greenhouse gases in the atmosphere. The yearly emission of, for example, carbon dioxide increased from 21 to 38 gigatons in the period between 1970 and 2004 and represented 77% of the total greenhouse gas emissions. This surge is a direct result of burning more fossil fuels and deforestation. Global warming is mainly noticed in more fluctuations in global circulations, leading to more extreme and abnormal weather conditions in certain parts of the world, threatening the local ecosystems (Oosterlee, 2013).

Climate change is not only a challenge of the future. Past examples have shown that buildings are vulnerable to extreme weather conditions and that there is a lack of response mechanisms to deal with these conditions when they happen. We are already seeing changes in the UK climate, with average temperatures rise by around 1ºC over the last century. We see a movement towards warmer winters and hotter summers, sea levels around our coast are rising by around 3mm a year, and there is emerging proof of altering rainfall patterns. The heavy rainfall and flooding over the winter of 2015/16 – although they cannot yet be attributed to climate change – illustrate the costs and disruption that can be caused by extreme weather (Committee on Climate Change, 2016).

The memories of the catastrophic consequences of the heavy rainfall of winter 2013 in the UK are still fresh. Catastrophes connected to climate change and extreme weather events do not only cause losses of human lives, but they are also responsible for significant economic losses and long-term indirect impacts on health, education, and productivity.

Buildings are already performing poorly under the current weather conditions, resulting in less comfortable internal conditions for the occupants or higher energy consumption. Considering the projected climate changes, without the application of corrective measures, current building stock might become intolerable for the users in the future. People living in cities will mainly be at a higher risk during hot weather due to the urban heat island effect. Studies have revealed that prolonged exposure to hot conditions can have an adverse effect on human health. Humans, like all warm-blooded animals, must maintain their core temperature within a relatively narrow range for their bodies to function optimally. Exposure to prolonged periods of heat can cause the core temperature to increase, resulting in a decrease of thermal comfort and the onset of a variety of ailments such as the exacerbation of pre-existing respiratory issues, heat stroke, and, in the most severe circumstances, death (Lee, Voogt and Gillespie, 2018). Structural risks due to climate change will also arise, especially in the coastal areas, due to flooding. A substantial quantity of energy is often wasted in buildings because they fail to operate as intended. In addition to that, buildings account for over a third of the total greenhouse emissions in the UK (European Commission, 2015), which profoundly impacts the change in the climate and contributes to the overall warming of the planet.

Climate change is likely to cause an increase in energy demand, mainly for cooling purposes, resulting in escalating greenhouse emissions from the energy sector. Increased energy demand might also have a negative impact on the performance of the electricity grid. Fossil energy production can be adversely affected by air and water temperatures. Extreme weather conditions could result in reduced efficiencies and increased costs. Possible shortages in water supply will also hamper energy production. Increased frequency of extreme weather events will present further challenges in the production and transmission of energy.

Apart from the structural risks to buildings that result from flooding, flooding can also cause damage to the water supply systems and to sewerage and sewage disposal systems, which are crucial for the well-being of societies. Climate change will introduce new challenges in managing water, both when there is too much (floods) and when there is too little (droughts). Also, there is an established link between heavy rainfalls, flooding, and the subsequent outbreak of infectious diseases. Flooding of sanitation facilities can expose entire communities to health risks. According to the IPCC (2007) and based on several studies, higher water temperatures and changes in extremes, including floods and droughts, are predicted to influence water quality and exacerbate many forms of water pollution.

Considering how climate change and extreme weather events will affect the resilience of our buildings in many ways, it is very likely that the current building stock will face significant challenges in the future, in terms of structural stability, energy efficiency and thermal comfort. Challenges will be different for each type of building. Therefore, it is essential to identify solutions in order to enhance their resilience in the face of climate change, in order for them to be able to withstand the potential shocks caused by climate change and be ready to adapt to the new conditions.

1.2 Statement of research focus, objectives and research questions

1.2.1 Research focus

This research focuses on investigating the effect of extreme weather events on the performance of various types of buildings. More specifically, the weather conditions that are examined are extreme heat waves and heavy rainfall.
The three different types of buildings that are considered are:

- Low-risk building – Office
- Medium-risk building - Dwelling
- High-risk building – School

Buildings are classified into different risk categories based on the characteristics of their occupants and their ability to withstand the changes to the internal conditions caused by an extreme weather event. An office building is categorised as a low-risk building as it is likely to be occupied by healthy adults. A dwelling is considered as a medium-risk building since young children and elderly people are often among the occupants. Hospitals and schools are considered high-risk buildings as they house sensitive population groups, and the preservation of the ideal internal conditions is vital for their health and well-being.

1.2.2 Research objectives

The key objectives of this work are stated below:

1. Identify the effect of extreme hot weather on the resilience of buildings under the current and the projected weather conditions. This includes the effect on energy consumption and the thermal comfort conditions.
2. Investigate solutions that reduce the energy consumption of the buildings and improve their thermal comfort conditions and quantify their effect under the current and projected weather conditions.
3. Identify the effect of extreme rainfall on the resilience of buildings.
4. Examine solutions to enhance the resilience of buildings to extreme rainfall. This includes design considerations on a building level and structural flood defenses that influence the resilience of buildings of a greater area.

1.2.3 Research questions

As our climate is changing, we can expect warmer and wetter winters, hotter and drier summers, rising sea levels, and more extreme weather events. This change in the climate will affect the energy, environmental quality, and structural performance of the current building stock. Buildings will be required to consume more energy in order to maintain acceptable living conditions, and as a result, the amount of CO_2 emissions will be increased. Furthermore, buildings will also be more vulnerable to structural and flooding risks due to the increased likelihood of heavy rainfall.

Research questions:

– How is the thermal and energy performance of buildings affected when they are subjected to extreme hot weather conditions?
– Which are the most appropriate design and retrofit solutions to mitigate the effect of the examined extreme weather events, and increase the resilience of the building types examined?
– What is the influence of Sustainable Drainage Systems on the resilience of buildings when they are subjected to extreme rainfall events?

1.2.4 Research structure and chapter layout

The structure of this thesis is described below. The work is organised into eight chapters**.**

Chapter 1. Introduction

This chapter provides information on the background of the research. Furthermore, it states the research focus, research objectives, and research questions.

Chapter 2. Literature review

This chapter offers a literature review of the main issues that determine the objectives of this research. These include the resilience of buildings as a term and a resulting working definition adopted by this thesis, the UK Climate Projections, responses to extreme weather events, the definition of the extreme weather events examined and passive solutions to reduce the risk of overheating. Furthermore, it discusses the most common types of flooding in the UK, considerations to improve the resilience of buildings to flooding and structural and non-structural flood defenses.

Chapter 3. Methodology

This chapter discusses the methodology of this research, which is a quantitative methodology. This chapter provides information on the modeling process followed in the two software packages used by this thesis. Also, it presents the three examined buildings.

Chapter 4. Effect of window-to-wall ratio on thermal comfort and energy consumption

Large window areas allow more daylight into space, but they may also allow excessive heat gains or losses, which increases the air-conditioning cooling or heating load and consequently the energy consumption. This chapter examines the effect of the window-to-wall ratio on thermal comfort and energy demand for cooling and lighting for a university building. It investigates the difference between cooling and lighting loads between 8 different cases and examines the thermal comfort conditions for each of these cases. The results are presented for the current and the projected weather conditions of the 2050s**.**

Chapter 5. Effect of relative humidity on thermal comfort

This chapter examines the effect of relative humidity on thermal comfort for a university building. Simulations of the building were performed under the current and projected weather conditions of the 2050s, without relative humidity control, and the resulting thermal comfort conditions were investigated. In the following simulations of the building were performed under the projected weather conditions, with a relative humidity set point set at 40%. A comparison of the thermal comfort conditions between the three examined scenarios is presented for the hottest week of the year.

Chapter 6. Ventilation techniques to reduce the risk of overheating for a school building

This study examined the risk of overheating of a school building, under extreme hot weather conditions, in 14 locations in the United Kingdom using the overheating criteria defined in Building Bulletin 101 (BB101). The building was modeled as naturally ventilated, mechanically ventilated and in mixed mode and was simulated both for the current and the projected weather conditions of the 2050s. Under the current weather conditions, the results of the simulations show that when naturally ventilated, the school building fulfills the BB101 criteria only in the areas of Edinburgh and Glasgow. In the simulations of the building as mechanically ventilated and mixed mode, mechanical cooling was provided in order for the building to comply with the overheating criteria. A comparison of the required cooling loads between the two scenarios shows that the application of mixed mode ventilation results in less cooling loads.

Chapter 7. Automated natural ventilation and lighting strategy for a residential building under extreme hot weather

Lighting systems are responsible for consuming large amounts of energy in buildings all around the world. Automated control systems, intelligent HVAC, and smart lighting can help reduce the energy consumption of buildings and improve the thermal comfort conditions of the occupants. This study considers a typical detached residential building in the United Kingdom and examines the effect of automated natural ventilation and lighting strategy on the energy consumption of the building and the thermal comfort of the occupants. For the purpose of this study, the windows of two bedrooms of the examined building were modeled with a temperature-based control function, and appropriate target illuminance levels were set to control the lighting. This chapter looks into the week with the higher external temperature and uses dynamic thermal simulations in order to assess the performance of the building. Simulations were performed with EDSL TAS software using the Design Summer Year (DSY) weather files from CIBSE. Results of the simulations show that an automated window opening system can reduce the operative temperatures up to 4°C, improve thermal comfort conditions, and reduce lighting gains by 49%.

Chapter 8. Effect of building development on the risk of flooding

There is clear evidence to show that climate change is happening. According to the UK Climate Projections (UKCP09) (Defra, 2009a), we can expect warmer and wetter winters, hotter and drier summers, rising sea levels, and more extreme weather events. These extreme weather events in the UK are likely to increase with rising temperatures, causing among others more substantial rainfall events with an increased risk of flooding. Flooding is currently identified as one of the greatest threats to the UK posed by climate change. In the UK, there is a continuous need for new housing. The UK government has set a goal of 1,000,000 new homes by 2020 in order to cover the country’s housing needs. This study examined the effect of building development on the risk of flooding under extreme rainfall, for an area that has a very low chance of flooding. Two different scenarios of building development were modeled using XP SWMM software. The results show that building development increases the maximum water depth and that newly-built houses will flood under extreme rainfall.

Chapter 9. The effects of sustainable drainage systems on residential developments during extreme rainfall

Flooding is identified as the most significant risk, currently and in the short term, across the UK. Climate change and increased urbanisation are likely to intensify the risk of flooding in the near future. Implementation of sustainable drainage systems (SuDS) in residential developments could help to control the quantity of runoff and reduce the risk of flooding. This case study examined a new build residential development in the south west of England and investigated the effect of three different types of sustainable drainage systems on the risk of flooding under a rainfall event with a return period of 1000 years.

The examined SuDS were rainwater harvesting, permeable paving, and attenuation basins. The MicroDrainage software package was used to perform the simulations. The results of the simulations show that for the examined development, implementation of attenuation basins provided a 94.8% reduction of the maximum flood volume and permeable paving and rainwater harvesting provided a 33.1% and a 40.3% reduction of the maximum flood volume respectively.

Chapter 10. Conclusions

This chapter highlights the main conclusions of the previous chapters and provides a summary of this work.

Chapter 2. Literature Review

2.1 Resilience of buildings

‘Resilience’ is a broad term with many definitions, being used in various scientific areas such as physical and ecological systems, disaster risk management, and engineering. Hassler and Kohler (2014) provide a table with the different context-specific definitions of resilience. Common in the definitions given is that the subject should have the ability to withstand potential shocks and adapt to new conditions. The Oxford English Dictionary gives the following definition of resilience: “The quality or fact of being able to recover quickly or easily from, or resist being affected by, a misfortune, shock, illness, etc.”. Carpenter *et al.*, 2001 introduced the term ‘specified resilience.’ Specified resilience arises from the answer to the question “resilience of what to what?” This means that in order to understand the resilience of a system, we must begin by clearly identifying the resilience of a part of the system against a specific threat. However, increasing the resilience of a system against specific disturbances might cause the system to lose resilience in other ways (Cifdaloz *et al.*, 2010). ‘General resilience,’ in contrast, does not define either the part of the system that might cross a threshold or the kinds of shocks that the system has to endure (Folke *et al.*, 2010). General resilience is about the whole system, and not only a part of it, being able to withstand any potential shock. Furthermore, when considering the resilience of a system, it is essential to specify the time scale (Folke et al., 2010).

The concept of resilience can be applied to the built environment. The built environment includes manmade buildings and infrastructure stocks that constitute the physical, natural, economic, social, and cultural capital. The concept of resilience offers a means to address the long-term evolution of the built environment and to explore the implications of changing conditions on the efficacy of different approaches to planning, design, operation, management, value and governance (Hassler and Kohler, 2014).

The Resilient Design Institute defines resilient design as the intentional design of buildings, landscapes, communities, and regions in order to respond to natural and manmade disasters and disturbances—as well as long-term changes resulting from climate change—including sea level rise, the increased frequency of heat waves, and regional drought (Resilient Design Institute, 2013).

Based on the above-given definitions of resilience, in order to define the resilience of a building, it is necessary to clearly identify the building with its components and any possible threats that the building itself or any of its parts might encounter. This also includes the occupants of the building and the resulting thermal comfort conditions when the building is subjected to extreme weather conditions.

A building can be defined as an enclosed structure intended for human occupancy. It includes the structure itself and non-structural components (e.g., cladding, roofing, interior walls and ceilings, HVAC systems, electrical systems) permanently attached to and supported by the structure (National Institute of Building Sciences, 2010). As it arises from the definition of the building, in order for it to be resilient, it should not only be able to withstand structural risks without collapsing, but it should also remain functional for the users.

Thermal comfort conditions within a building are usually achieved with the use of energy sources. Modern comfort options such as central heating and comfort cooling use energy in increasingly sophisticated ways. These changes greatly increase the range of climates we can inhabit comfortably. They also mean we may live in buildings that would not be habitable without using energy and provide acceptable thermal comfort conditions (CIBSE, 2013). Therefore, reducing the energy consumption of a building while maintaining or improving the thermal comfort conditions for the occupants will positively contribute towards the resilience of the building.

2.2 Extreme weather events

An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of ‘rare’ vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called extreme weather may vary from place to place (IPCC, 2001).

Extreme weather events can cause significant damage, not only immediate loss of lives and assets but also longer-term damage to livelihoods and economies (The Royal Society, 2014). On a global scale, annual material damage from significant weather and climate events has been found to have increased eight-fold between the 1960s and the 1990s.

Between 1980 and 2004, the total costs of extreme weather events 24 totaled US$ 1.4 trillion (IPCC, 2012).

A range of hypotheses exists concerning how extreme events might alter with climate change. These include the “no change,” “mean effect” (increase in mean but not variability), “variance effect” (increase in range) and “structural change” (increase in mean and skew of low probability events) hypotheses (World Health Organization, 2004, p.12). A representation of these methods is shown in Figure 1 below.

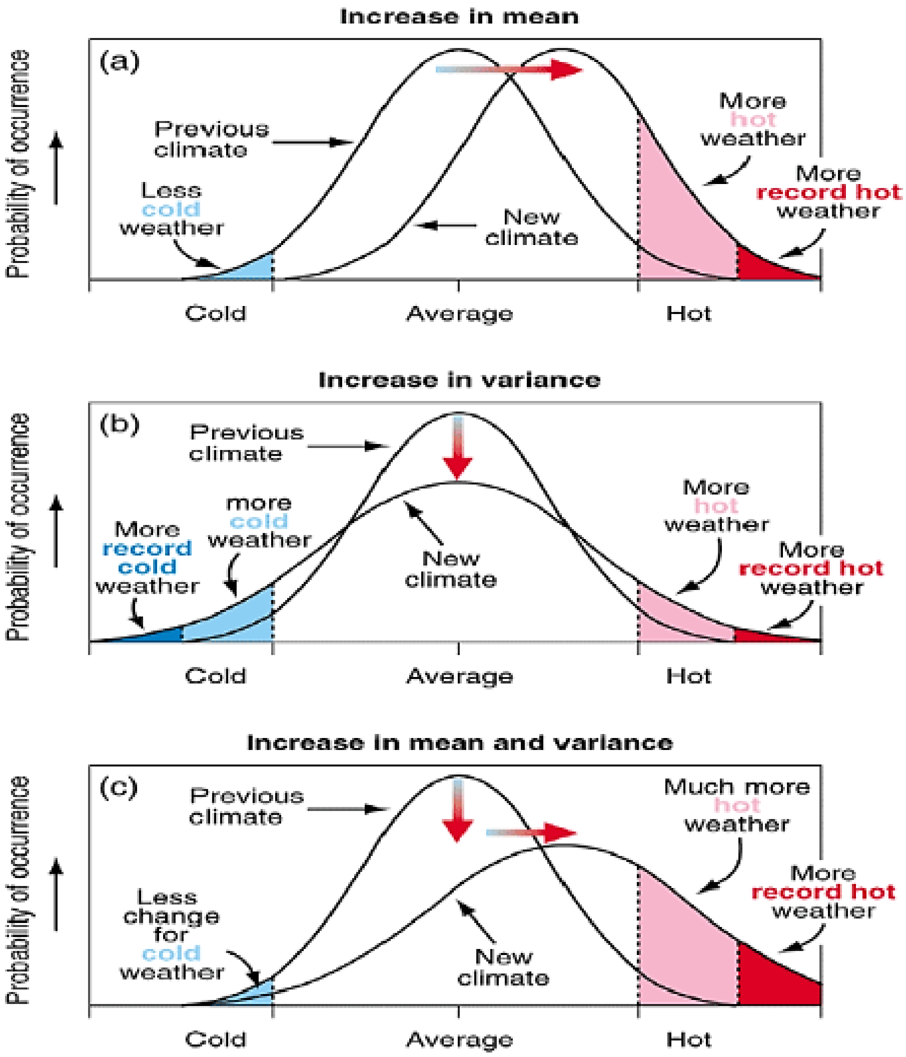


Figure 1 Change in the mean and variance of extreme weather events (Houghton et al., 2001)

Two broad approaches are taken to assess these hypotheses: statistical modeling using extreme value theory and modeling using General Circulation Models (GCMs) or Regional Climate Models (RCMs). Both approaches have projected the following outcomes for Europe, which in terms of scientific confidence are rated as ‘likely’ to ‘very likely’ (World

Health Organization, 2004):

1. More frequent extreme high temperatures and less frequent extreme low temperatures with an associated increase (decrease) in cooling (heating) degree days;
2. An increase in daily minimum temperatures in many regions that will exceed the increase for daytime maximum temperatures;
3. Daily temperature variability will decrease in winter but increase in summer;
4. There will be a general drying of mid-continental areas during summer; and
5. There will be an increase in precipitation intensity in some regions.

2.3 UK climate projections

The UK Climate Projections are the main source of climate change information on which research organisations, regulation, and policy-making bodies, and the insurance industry are basing their responses to changes in our climate. It must be remembered, however, that although there are limitations to the robustness of these projections, they represent our current best knowledge on the future UK climate (CIBSE, 2014).

The Projections provide data for three different (high, medium, low) future scenarios of greenhouse gases. These emission scenarios are constructed on different pathways showing how a range of factors, like population, economic growth, and energy usage, might change over time. For the next twenty to thirty years, there is little difference between the scenarios in terms of how they will impact global temperatures. After this point, the effect of different emissions levels becomes substantial, leading to a vast difference between low and high greenhouse gas emission scenarios by the 2080s (Defra, 2009a).

The graphs presented below show the global emissions of greenhouse gases of the three emission scenarios and the global mean temperature rise in each of these scenarios. The black dashed line represents the world stabilisation scenario, which is the emissions pathway needed to achieve the EU’s goal to limit global warming to 2°C (Defra, 2009a).

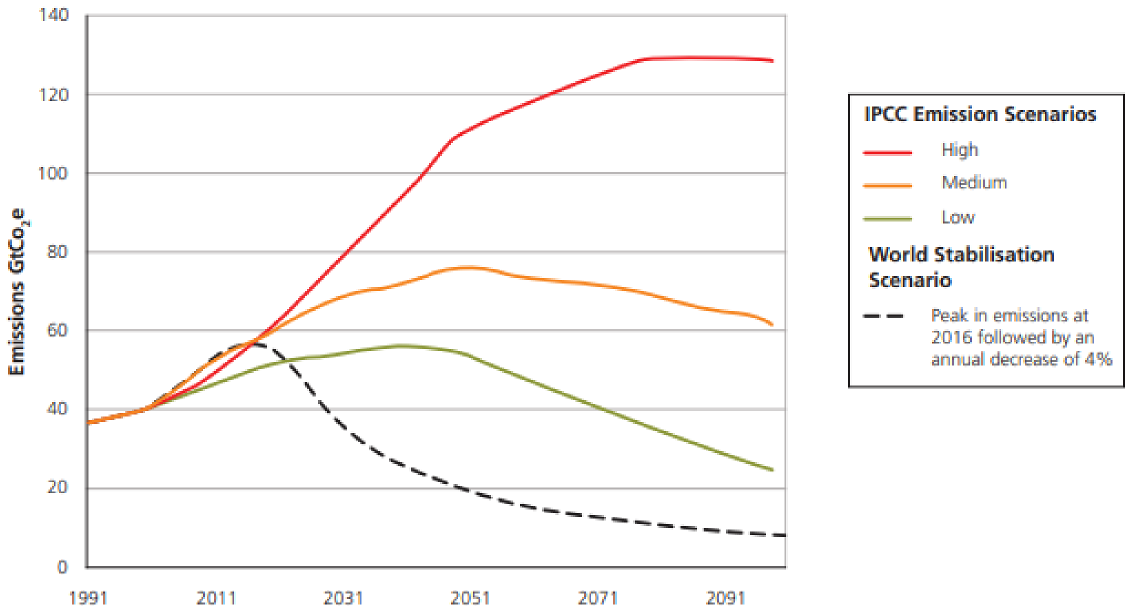


Figure 2 Global emissions of greenhouse gases (Defra, 2009a)

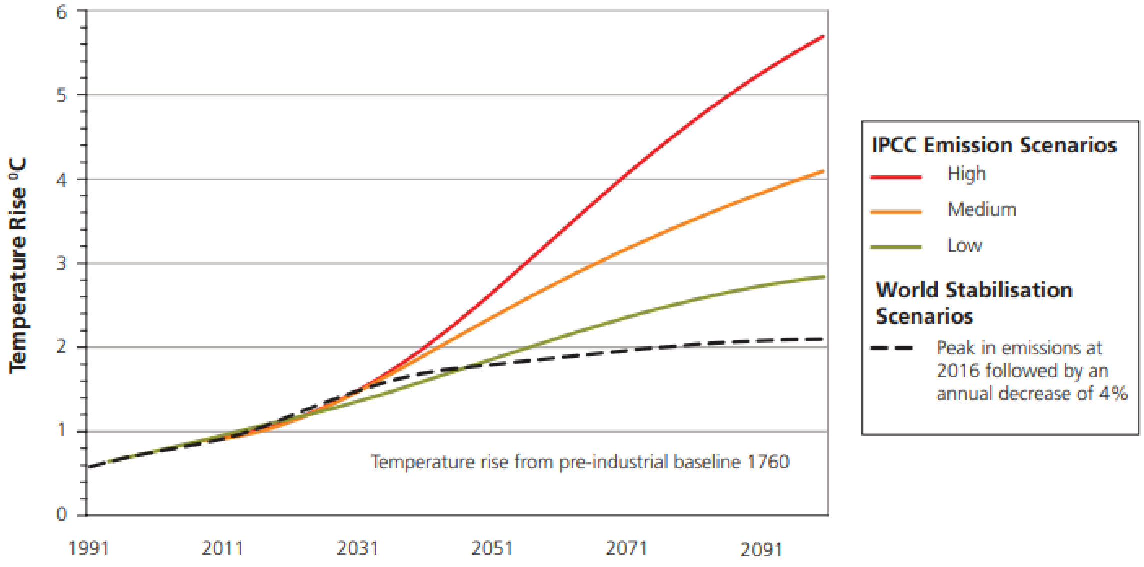


Figure 3 Global emissions mean temperature changes (Defra, 2009a)

The key findings of the UKCP09 show that all areas of the UK will get warmer, more so in summer than in winter. Summer precipitation tends to decrease across the UK, while winter precipitation tends to increase. Also, we can expect rising sea levels and storm surges.

Figure 4 presented below shows the 10, 50, and 90% probability levels of changes to mean daily temperature in summer by the 2080s, under the medium emissions scenario, averaged over administrative regions. It can be observed that the temperature rise will be more significant in the south than in the north of the country.

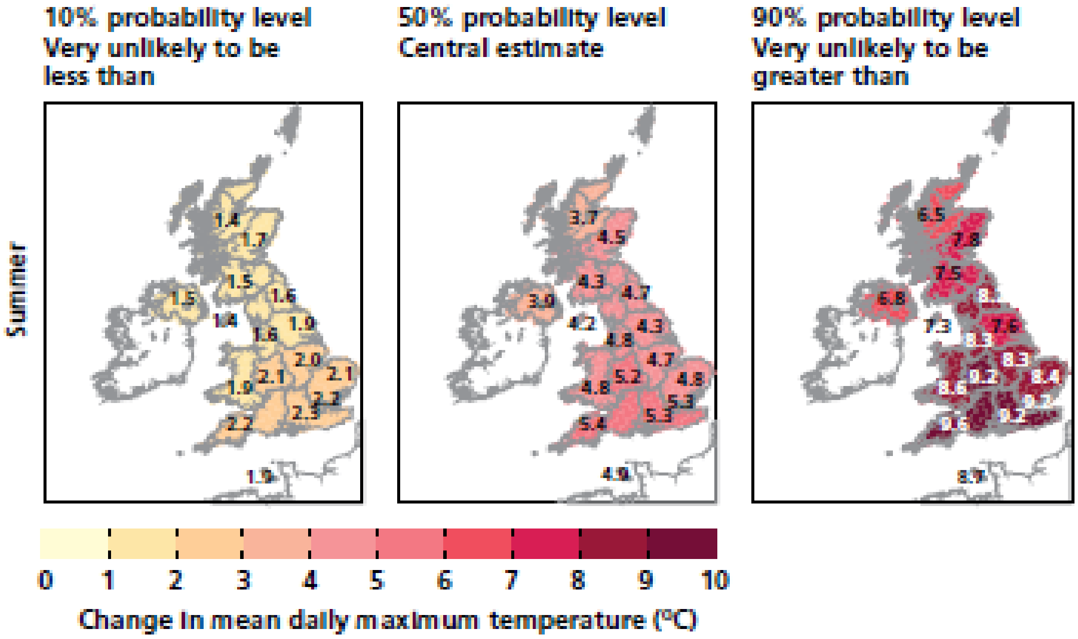


Figure 4 Changes in mean daily maximum temperatures (Defra, 2009b)

Figure 5 shows the percentage change in winter mean precipitation at the 10, 50, and 90% probability for the 2080s under the medium emissions scenario. In winter, precipitation increases are in the range of +10 to +30% over the majority of the country. Increases are smaller than this in some parts of the country, generally on higher ground (Defra, 2009b).

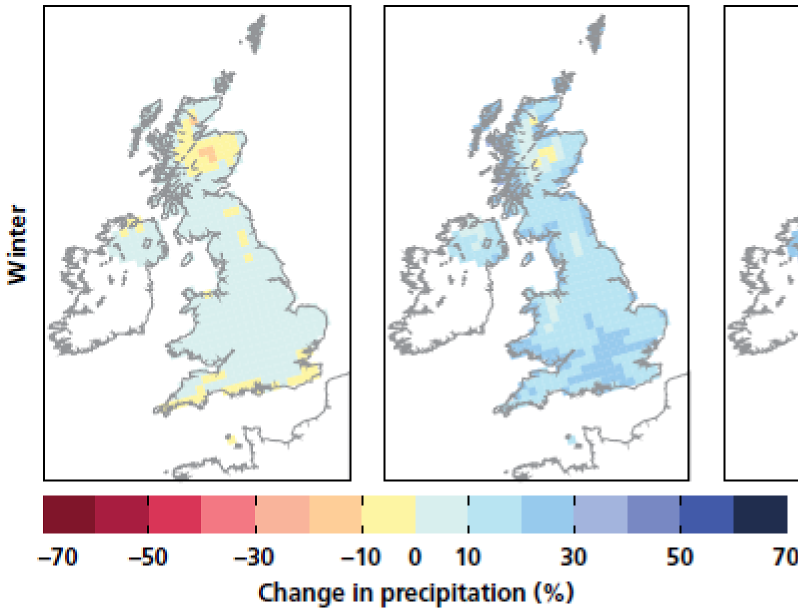


Figure 5 Changes (%) in winter mean precipitation (Defra, 2009b)

2.4 Extreme weather events used in this thesis

This thesis examines the resilience of buildings to extreme hot weather conditions and extreme rainfall. The Design Summer Year weather data from CIBSE were used in order to examine the performance of the buildings in extreme hot weather. Based on the literature review, this study adopts a definition of extreme rainfall event as an event with a 0.1% chance of happening (1 in 1000 event).

2.4.1 Design Summer Years (DSY)

The DSY was introduced in 2002 to represent a 'near extreme' warm summer, in recognition of the need to have a sequence of warm weather data for use with dynamic thermal simulation programs for the assessment of overheating risk in naturally ventilated and passively cooled ('free running') buildings (CIBSE, 2014c). In 2014, they were revised based on the TM49 methodology that uses 'weighted cooling degree hours' (WCDH) as a metric of summer warmth (CIBSE, 2014c). In addition to that, two more metrics are used to define overheating. These are the conceptual building and the comfort model.

The conceptual building is a building in which the internal operative temperature is equal to the outside dry-bulb temperature at all times. It corresponds physically to a building in which there is always a very high ventilation rate, so that heat gains are quickly removed, and the internal temperature is close to the outside temperature (CIBSE, 2014c).
In the adaptive model given in BS EN 15251, the comfort temperature is related to the running mean of the outside dry-bulb temperature, according to the following relationship (CIBSE, 2014c):

$$T_{conf} = 0.33T_{rm} + 18.8 \tag{1}$$

Where:
T_{conf} is the predicted comfort temperature on a given day (°C)
T_{rm} is the running mean daily average temperature given by:

$$T_{rm} = \alpha T_{rm-1} + (1 - \alpha)T_{mean-1} \tag{2}$$

Where:

α is a constant (0.8),

T_{rm-1} is the running mean temperature for the proceeding day (°C)

T_{mean-1} is the average temperature for the proceeding day

Using the definition of the comfort temperature, the WCDH is a quadratic expression given by (Virk and Eames, 2016):

$$WCDH = \sum_{all\ hours} \Delta T^2 \qquad (3)$$

and

$$\Delta T = T_{op} - T_c \text{ , } T_{op} - T_c > 0 \qquad (4)$$

where

T_{op} is the internal operative temperature.

The weighting puts a much greater importance on external temperatures which depart further from the comfort temperature. The WCDH approximation is related to the duration of the exceedance event as well as emphasizing more extreme temperatures in order to take into account the severity of the event.

The updated DSYs for London were selected using the WCDH metric for 3 locations within the city. These locations consist of some of the warmest in the UK with a high probability of this overheating metric being exceeded (Virk and Eames, 2016).

The Design Summer Years are available for three different representations of hot events (Eames, 2016). DSY-1 represents a moderately warm summer year, defined as a year with a static weighted cooling degree hour return period closest to 7 years. DSY-2 represents an intense extreme summer, which is chosen as the year with the event which is about the same length as the moderate summer year but has a higher intensity than the moderate summer. Finally, DSY-3 represents the long extreme year, which is determined by the year with a less intense extreme than the high-intensity year, more intense extreme than the moderate summer year but also with a longer duration than the moderate summer year (Virk and Eames, 2016). Unlike to the DSY-1 that has a return period close to 7 years, the return period of the DSY-2 and DSY-3 varies based on the examined location.

2.4.2 Definition of extreme rainfall

Evidence that extreme rainfall intensity is increasing on a global scale has strengthened considerably in recent years. Research now indicates that the most significant increases are likely to occur in short-duration storms lasting less than a day, potentially leading to an increase in the magnitude and frequency of flash floods. Furthermore, several observation-based analyses have indicated that sub-daily extreme rainfall is intensifying more rapidly than daily rainfall (Westra *et al.*, 2014).

In the National Flood Resilience Report published by the Government, it is stated that when we want to assess what extreme flooding looks like we typically model the effects of a scenario with a nominal 0.1% chance of occurring in a year at any given location, using local detailed models (HM Government, 2016).

This thesis adopts this definition of extreme rainfall events, and in the case studies where the resilience of buildings to extreme rainfall is examined, the modeled extreme rainfall events have a 0.1% chance of occurring in a year.

2.5 Responses to extreme weather events

The Royal Society (2014), in its report “Resilience to extreme weather,” defines three resilient responses: “surviving,” “adapting,” and “transforming.” Surviving is the initial response and includes withstanding the potential hazards even if this results in a reduced quality of the system. Adapting is a more active response which includes making in order to potentially improve the quality of the system. Transformation goes one step further and includes making fundamental changes to the system (The Royal Society, 2014). The graph below represents these resilient responses against the likelihood and extent of an extreme weather event.

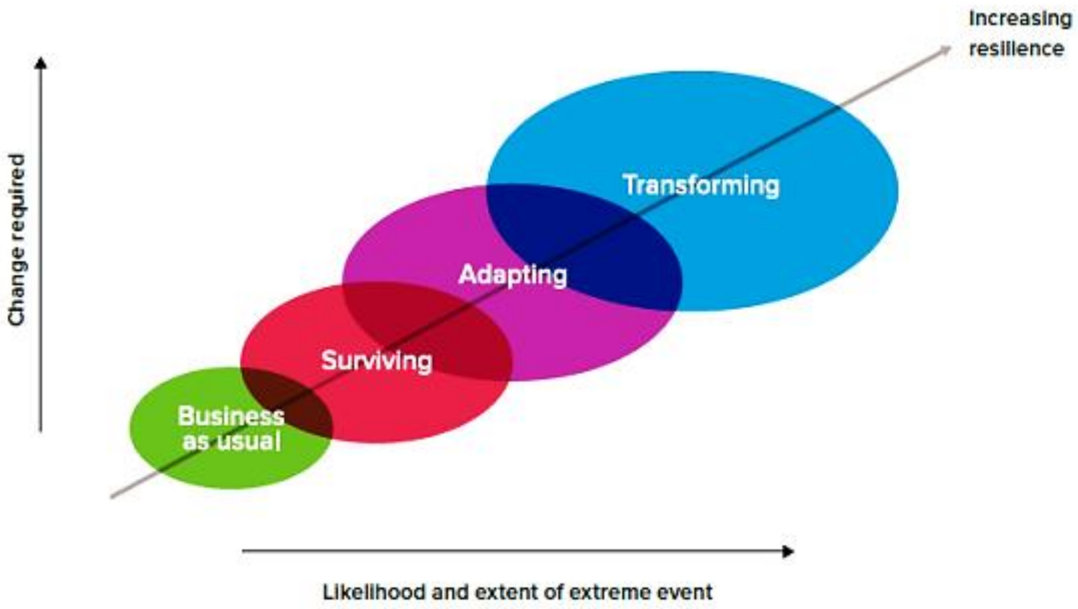


Figure 6 Surviving, adapting and transforming as components of resilience (Source: The Royal Society, 2014)

The IPCC report “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation” (2012) discusses short- and long-term responses to extreme weather events. As short-term responses, increased resilience, capacity building, broad social benefits from extensive participation in risk management and resilience planning, and the value of multi-hazard planning are mentioned. There is robust evidence in the literature to support disaster risk reduction as a strategy for long-term climate adaptation. Disaster risk reduction denotes both a policy goal or objective, and the strategic and instrumental measures employed for anticipating future disaster risk, reducing existing exposure, hazard, or vulnerability and improving resilience. However, it should be noted that cross-scale (spatial and temporal) interactions between responses focusing on the short term and those required for long-term adjustment can potentially create both synergies and contradictions among disaster risk reduction, climate change adaptation, and development (IPCC, 2012).

Adaptive measures should also be taken with regards to the design of our buildings. The impacts of the changing climate on the built environment can be categorised into those that affect the comfort and energy performance of the building, those that affect the construction and those that relate to managing the water (Gething, 2010). Implementation of passive design strategies, such as high levels of internal thermal mass, careful exclusion of solar gains, airtight construction, high levels of insulation and shading will be required in order to improve the energy performance of the buildings. Attention should be paid to the design of the foundations and the underground pipework. Three strategies are presented for dealing with flood risk areas: avoidance (not to build in flood risk areas), resistance (dry-proof building), and resilience (wet proofing) (Gething, 2010). In order to build confidence in our adaptation responses, it is essential that detailed on-site monitoring of how buildings behave in reality is cross-checked against the models that were used to design them (Gething and Puckett, 2013).

Climate change also affects human health and well-being. Responding to the health challenges posed by climate change requires a multilevel, interdisciplinary, and integrated response, so efforts should focus on developing partnerships among federal, state, and local government agencies, academia, nongovernmental organizations, and the private sector (Frumkin et al., 2008). In Europe, following the heatwave of 2003, there has been a strong commitment to building resilience at the city, regional, and national levels. Public health measures include media announcements, telephone help-lines cooling centers, special emergency service preparedness, home reach and evacuation, outreach to the homeless and utilities companies stopping disconnection for non-payment (The Royal Society, 2014).

2.6 Design solutions to improve the resilience of buildings to extreme hot weather

2.6.1 Passive cooling

Passive cooling is commonly understood as a set of natural processes and techniques to reduce indoor temperatures in opposition to the use of ‘active’ mechanical equipment (Prieto *et al.*, 2018). Maintaining a comfortable environment within a building in a hot climate relies on reducing the rate of heat gains into the building and encouraging the removal of excess heat from the building. To prevent heat from entering into the building or to remove it once it has entered is the underlying principle for achieving cooling in passive cooling concepts (Kamal, 2012). The most commonly adopted passive cooling measures include shading of the building, improvements in the glazing quality, ventilation, installation of green roofs, and an increase in the insulation and thermal mass of the building.

2.6.1.1 Shading

The main function of a shading system is the protection of the building's transparent envelope from solar radiation in summer conditions, so preventing overheating by blocking the access of unwanted energy flow into the building (Bellia, De Falco and Minichiello, 2013).

In addition to the architectural features, the shading effect (either by external objects or by the building itself) can also affect the thermal and energy performance of a building (Chan, 2012). For dwellings and conservatories, shading is the most direct and effective passive solar method of avoiding overheating. Shading effectiveness is obtained by preventing the transmission of unwanted solar radiation into the building envelope (Amoako-attah, 2015). This helps to reduce the amount of cooling loads required in order to achieve the desired thermal comfort conditions within the building.

Shading devices are classified into three categories based on their position on the glazing unit (external, internal, and mid-glass panes). External devices include horizontal projections, vertical fins, louvers, roof overhangs, and window reveals. Of the various types of shading system, external devices are the most effective in decreasing heat gains because they intercept and dissipate (mainly by convection) most of the heat in solar radiation before it reaches the building surface (European Commission, 1999). In the case of internal shading devices, such as interior blinds or drapes, the solar radiation goes through the glass and hits the shade, effectively heating it. Because of this, the effectiveness of most internal shades in preventing heat gain in the internal space is limited. Internal devices protect occupants against the immediate effects of direct sunlight and glare, but most of the heat absorbed is released into the room by convection (Uspenskiy, 2013). The mid glass pane shading systems are the construction of double or triple glazing with integrated shading systems between the panels. Examples of interpane sunshades are Venetian blinds, fabric screens, pleated curtains, and roller blinds (Hastings *et al.*, 2007).

2.6.1.2 Glazing

Although windows are the primary medium for the lighting of a building, they contribute considerably to the building’s energy consumption, either commercial or residential (Gorgolis and Karamanis, 2015).

There are two main factors characterising windows’ energy performance: the U-value and the g-value (or Solar Heat Gain Coefficient, SHGC) (Gorgolis and Karamanis, 2015). The U-value is the rate of heat loss or the energy transferred between the inner and outer of a building. It includes heat which is transferred through convection, thermal radiation (without solar radiation) and conduction. Both glazing and framing or only the center-of-glass heat loss can be expressed per time, area, and temperature difference (W/m2 K). The g-value is the part of solar radiation that passes through the window inside the building. Because the g-value includes solar radiation, which is absorbed and then is re-emitted, glazing surfaces have a significant impact on it. Except for these two values, transmittance in visible is another crucial factor for apparent reasons (Gorgolis and Karamanis, 2015). For passive solar heating applications, windows with a low U-value and high total solar energy transmittance are preferred (Sadineni, Madala, and Boehm, 2011).

Low emissivity glass is commonly used to reduce solar heat gains since they offer a virtually clear appearance, admit more daylight, and permit much brighter, more open views to the outside (Wolf, 2006). Low-emissivity (Low-e) glass is made by applying thin metal coatings (for example, clear silver or tin oxide) on the glass (Mohelníková and Altan, 2009). Higher solar control efficiency can be achieved with the application of two reflective layers in the coating stack. These coatings are referred to as ‘low-E^{2}’; they cause little change in daylight transmittance, but reduce solar heat gain by 50-70%, compared to conventional low-E coatings (Wolf, 2006).

2.6.1.3 Ventilation

Ventilation is one of the most essential needs of a building as it maintains the indoor air quality necessary for health and well-being (Hacker, JN, Belcher, SE & Connell, 2005). In a free-running building, natural ventilation is the principal means of removing heat.

During the summer night time, ventilation strategies can be adopted to cool down the building and improve the thermal comfort conditions for the occupants.
Ceiling fans can also be used to increase indoor air movement and raise the convective heat transfer coefficient, which facilitates the process of rejecting heat from massive walls at night (Balaras, 1996).

Mixed mode ventilation comprises the use of natural ventilation and mechanical cooling with the aim of reducing the amount of energy required to achieve thermal comfort conditions. It is essentially the provision of the least amount of mechanical air movement and cooling that can still achieve the conditions required (CIBSE, 2004). Mixed-mode or hybrid cooling systems are designed to make maximum use of passive cooling methods but incorporate supplementary mechanical cooling systems for use in the most extreme conditions (Ezzeldin and Rees, 2013). Although natural ventilation on its own is only applicable to a narrow range of climates, a hybrid ventilation system, using a natural ventilation strategy combined with a mechanical system, can extend the applicability of natural ventilation in more severe climatic conditions (Ji, Lomas, and Cook, 2009).
Naturally ventilated buildings should be designed with a relatively narrow plan form to facilitate the passage of air through the building (Aynsley, 2007). Cross ventilation can achieve a high air change rate and ventilate a deeper floor plate than single sided ventilation (BSRIA, 2009).

Cooling energy requirements can be reduced by using low-energy technologies (Kolokotroni and Aronis, 1999). Of the available technologies, night ventilation is particularly suited to office buildings because these are usually not occupied during the night. Night ventilation can affect internal conditions during the day in four ways:

- reducing peak air-temperatures
- reducing air temperatures throughout the day, and in particular during the morning hours
- reducing slab temperatures
- creating a time lag between the occurrence of external and internal maximum temperatures

2.6.1.4 Green roofs

A building roof that is either wholly or partially covered with a layer of vegetation is called a green roof (Sadineni, Madala and Boehm, 2011). Roofs are an important part of the building envelopes that are very susceptible to solar radiation and other environmental changes, thereby influencing the indoor comfort conditions for the occupants (Sadineni, Madala, and Boehm, 2011). Green roofs help to reduce the urban island effect and reduce heat gains by a combination of thermal mass, a degree of insulation and evapotranspiration (Gething and Puckett, 2013).

There are two categories of green roofs: intensive and extensive (Sadineni, Madala and Boehm, 2011). Intensive green roofs have a deeper substrate layer and allow the cultivation of deep rooting plants such as shrubs and trees. Extensive green roofs have a thinner substrate layer, which allows the growth of low-level planting such as lawn or sedum (Sadineni, Madala, and Boehm, 2011).

The effectiveness of cooling achieved by the application of green roofs is highly dependent on wind speed and on keeping the soil damp. High wind speeds reduce the cooling effect by removing the cooled air produced by transpiration on the surface of the grass roof. Keeping the soil damp is also crucial because the cooling effect of evapotranspiration will no longer be available if the soil dries out (Gething and Puckett, 2013).

In the case of green walls, putting on a foliage cover to the external wall of a building will influence the building’s energy consumption. Compared to a bare wall, the foliage cover reduces the heat transfer rate between the indoor and outdoor climate, as the surface temperatures of green walls show a more stable course (Oosterlee, 2013).

Green facades are climbing plants grown either directly against, or on support constructions affixed to exterior building walls. Similar to other forms of green infrastructure, they are increasingly being considered as a design feature to cool internal building temperatures, decrease building energy consumption and facilitate urban adaptation to a warming climate (Hunter *et al.*, 2014).

The peer-reviewed literature published in English indicates that green facades promise to deliver the most considerable cooling and energy-saving benefits in climates with hot, dry summers and for buildings with westerly aspects (Hunter *et al.*, 2014). In their review they argue that the integration of concepts and methods from plant biology, ecology, horticulture, and soil science is crucial to the development of this emerging field.

2.6.1.5 Insulation

The result of the use of insulation is to lessen heat gain and heat loss. Insulation also influences the interior mean radiant temperature (MRT) by isolating the interior surfaces from the effect of the exterior conditions and also decreases draughts produced by temperature differences between walls and air (Kamal, 2012).

In summer, this can have two effects: a beneficial one of preventing heat from entering the building during the day and a negative one of preventing heat escaping at night. In summer, insulation can also have the beneficial effect of preventing the heat that builds up in the building's external facade as the sun shines on it reaching indoors (Hacker, JN, Belcher, SE & Connell, 2005).

2.6.1.6 Thermal mass

The thermal mass of a building determines its ability to store heat energy, as either sensible or latent heat, and this, in turn, can have a significant influence on indoor temperatures, power requirements and occupant comfort (Reilly and Kinnane, 2017). Thermal mass has a positive effect on thermal comfort (Balaras, 1996). This is because thermal mass has the beneficial effect of reducing peak indoor temperatures. However, it can also have the adverse effect of keeping a building warmer at night. For this reason, to be effective at moderating temperature, thermal mass needs to be combined with night ventilation to remove the heat absorbed during the day (Hacker, JN, Belcher, SE & Connell, 2005).

The location of thermal mass is essential. One may distinguish two cases, based on whether the heat storage material receives energy by solar radiation (direct) or by IR radiation and room air convection (indirect). Direct heat gains are experienced by the outer building envelope, which is exposed to solar radiation and by the interior surfaces, which may absorb incident solar radiation as it enters through the building's openings. Indirect heat gains are experienced by opaque elements inside the building from the energy which is transferred indoors from direct gain surfaces. Direct locations are much more effective than indirect for placing heat storage mass (Balaras, 1996).

The thermal mass optimization is affected by the thermo-physical properties of the building material, building orientation, thermal insulation, ventilation, auxiliary cooling systems, and occupancy patterns (Sadineni, Madala, and Boehm, 2011).

2.7 Flooding

Climate change is expected to increase the severity, frequency, and extent of flooding. According to research, an estimated 1.8 million people are residing in regions of the UK at significant risk of river, surface water or coastal flooding. The population residing in such areas is expected to rise to 2.6 million by the 2050s under a 2°C scenario and 3.3 million below a 4°C scenario, assuming low population growth and a continuation of current levels of adaptation (Kovats, Osborn and Whitman, 2017).

Analysis conducted for the Climate Change Risk Assessment 2017 suggests that 0.5 to 1 meter of sea level rise could make some 200km of coastal flood defenses in England highly exposed to failure in storm conditions. Sea level rise and increased wave action will make it increasingly difficult and costly to maintain current sea defense lines in some areas.

Flooding is debatably the weather-related hazard that is most widespread around the globe. A flood is defined as water overflowing onto land that usually is dry (C A Doswell III, 2003).

Flooding is recognised as the most significant risk, currently and in the short term, across the UK (Defra, 2012). Around 5.2 million properties are at risk of flooding in England. Annual flood damage costs are in the region of £1.1 billion. These costs could rise to as much as £27 billion by 2080 (Bennett and Hartwell-Naguib, 2014). Floods can also have dangerous indirect impacts, including damage to critical energy, water, communications, and transport infrastructure. They can also affect with essential public services such as schools and hospitals (Environmental Agency, 2009).

2.7.1 Types of flooding and flood zones

In England, the most frequent forms of floods are (Environmental Agency, 2009):

- **River flooding** that happens when a watercourse is unable to cope with the water draining into it from the nearby land. This can happen, for example, when heavy rain falls on an already waterlogged catchment.
- **Coastal flooding** that results from a combination of high tides and stormy conditions. If low atmospheric pressure concurs with a high tide, a tidal surge may happen, which can result in severe flooding.
- **Surface water flooding** which occurs when significant rainfall overwhelms the drainage volume of the surrounding area. It is challenging to forecast and pinpoint, much more so than river or coastal flooding.
- **Sewer flooding** that occurs when sewers are overwhelmed by heavy rainfall or when they become blocked. The likelihood of flooding depends on the capacity of the local sewerage system. Land and property can be flooded with water contaminated with raw sewage as a result. Rivers can also become polluted by sewer overflows.
- **Groundwater flooding** that occurs when water levels in the ground rise above surface levels. It is most probable to happen in zones underlain by permeable rocks, called aquifers. These can be extensive, regional aquifers, such as chalk or sandstone, or may be more local sand or river gravels in valley bottoms underlain by less permeable rocks.

Flood zones have been established by the Environmental Agency to be used within the planning process as a starting point in determining how likely somewhere is to flood. Planning Policy Statement 25 states that planners should steer development to Flood Zone 1, the zone of lowest flood risk, wherever possible. Where there are no sensibly available sites in Flood Zone 1, planners should consider reasonably available sites in Flood Zone 2, applying the Exception Test if necessary. Only where there are no reasonably available sites in Flood Zones 1 or 2, should sites in Flood Zone 3 be considered (Communities and Local Government, 2010).

Table 1 Probability of flooding for each of the defined flood zones (Planning Practice Guidance 25)

Flood Zone	**Definition**
Zone 1 **Low Probability**	Land having a less than 1 in 1,000 annual probability of river or sea flooding. (Shown as 'clear' on the Flood Map – all land outside Zones 2 and 3)
Zone 2 **Medium Probability**	Land having between a 1 in 100 and 1 in 1,000 annual probability of river flooding; or Land having between a 1 in 200 and 1 in 1,000 annual probability of sea flooding.
Zone 3a **High Probability**	Land having a 1 in 100 or greater annual probability of river flooding; or Land having a 1 in 200 or greater annual probability of sea flooding.
Zone 3b **The Functional Floodplain**	This zone comprises land where water has to flow or be stored in times of flood. Local planning authorities should identify in their Strategic Flood Risk Assessments areas of functional floodplain and their boundaries accordingly, in agreement with the Environment Agency.

Planning practice guidance also classifies buildings according to their flood risk vulnerability. Among others, basement dwellings, caravans, mobile homes and park homes intended for permanent residential use are classified as 'highly vulnerable'. Under 'more vulnerable' are classified the hospitals, buildings used for dwelling houses or student halls and residential institutions such as residential care homes and children's services homes. 'Less vulnerable' are classified buildings used for shops, financial, professional and other services and buildings used for agriculture and forestry (Communities and Local Government, 2010).

2.7.2 Design for flood risk

Flood risk is a design challenge that is becoming increasingly relevant for several reasons (RIBA, 2009). As discussed in Section 2.3, the UK Climate Projections show that we can expect to have an increase in the annual mean precipitation. Especially in the winter, precipitation increases are in the range of +10% to +30% over the majority of the country (Defra, 2009b). Furthermore, climate change is predicted to cause more extreme weather patterns. As a result, there will be a higher risk of tidal flooding, inland flooding from rivers and surface water run-off.

In addition to that, the risk of flooding is intensified by the heightened need for new housing and the increasing urbanisation. Higher densities of development reduce the amount of natural soak-away available and strain the existing drainage infrastructure. Moreover, the pressure for new housing and the current policies that prioritise the regeneration of brownfield land, much of which is already at flood risk, could result in more development within the floodplain (RIBA, 2009).

Therefore, in order to mitigate the risk of flooding, it is essential to identify design considerations that will better the resilience of buildings to flooding and determine suitable structural and non-structural flood defenses for each area.

2.7.2.1 Building design considerations

Flood-resilient buildings are designed and built to decrease the effect of flood water coming into the building so that no long-lasting impairment is caused, structural integrity is maintained, and drying and cleaning are easier (GOV.UK, 2014).
It is generally accepted that total prevention of water ingress or “dry proofing” of a building is challenging to achieve. There are two main strategies that are recommended in order to improve the resilience of buildings to flooding, and their applicability depends on the water depth that the property is subjected to. These strategies are the water entry strategy and the water exclusion strategy. Flood depth is considered to be the main parameter in the design strategy since this will determine whether it is feasible to try to exclude and/or delay floodwater from entering the property. The definitions of the water entry strategy and the water exclusion strategy are presented below (Bowker, Escarameia and Tagg, 2007).

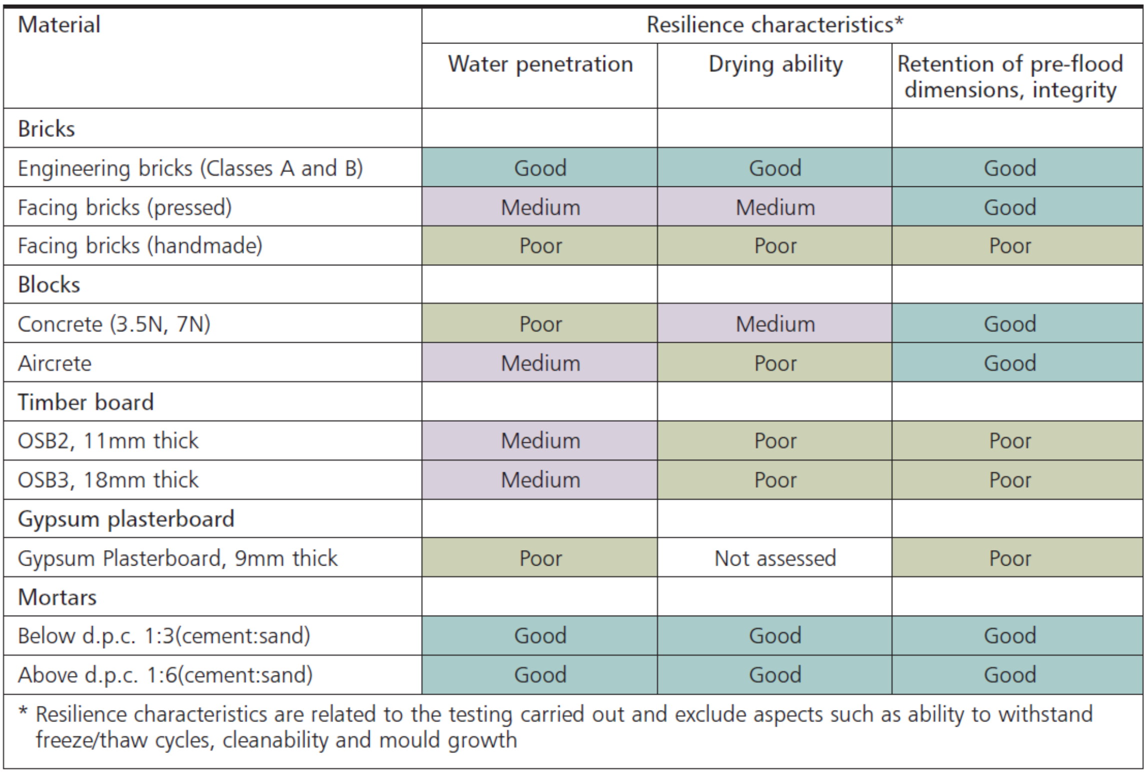
Water exclusion strategy: This strategy is favored when low flood water depths are involved (not more than 0.3m). Emphasis is placed on minimizing water entry while maintaining structural integrity, and on using materials and construction techniques to facilitate drying and cleaning.

Water entry strategy: This strategy is, therefore favored when high flood water depths are involved (greater than 0.6m). Emphasis is placed on permitting water into the building, facilitating draining and consequent drying.

Each building should be individually assessed in order to identify the required building materials in order to achieve the required levels of flood resistance. In areas that have a high flood risk, building materials that have increased resistance to water penetration, drying ability, integrity, and retention of pre-flood dimensions should be considered. Table 2 provides a list of building materials and their rating against flood resilient criteria.

Denser materials like concrete and bricks are found to have good resilience characteristics. (Bowker, Escarameia and Tagg, 2007). Building materials that are effective for "water exclusion strategy" include engineering bricks, cement-based materials including water retaining concrete and dense stone. Building materials that are suitable for "water entry strategy" include: facing bricks, concrete blocks, sacrificial, or easily removable external finishes or internal linings (Bowker, Escarameia and Tagg, 2007).

Table 2 Resilient characteristics of building materials (Communities and local government, 2007)



Material	Resilience characteristics*		
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity
Bricks			
Engineering bricks (Classes A and B)	Good	Good	Good
Facing bricks (pressed)	Medium	Medium	Good
Facing bricks (handmade)	Poor	Poor	Poor
Blocks			
Concrete (3.5N, 7N)	Poor	Medium	Good
Aircrete	Medium	Poor	Good
Timber board			
OSB2, 11mm thick	Medium	Poor	Poor
OSB3, 18mm thick	Medium	Poor	Poor
Gypsum plasterboard			
Gypsum Plasterboard, 9mm thick	Poor	Not assessed	Poor
Mortars			
Below d.p.c. 1:3(cement:sand)	Good	Good	Good
Above d.p.c. 1:6(cement:sand)	Good	Good	Good

* Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth

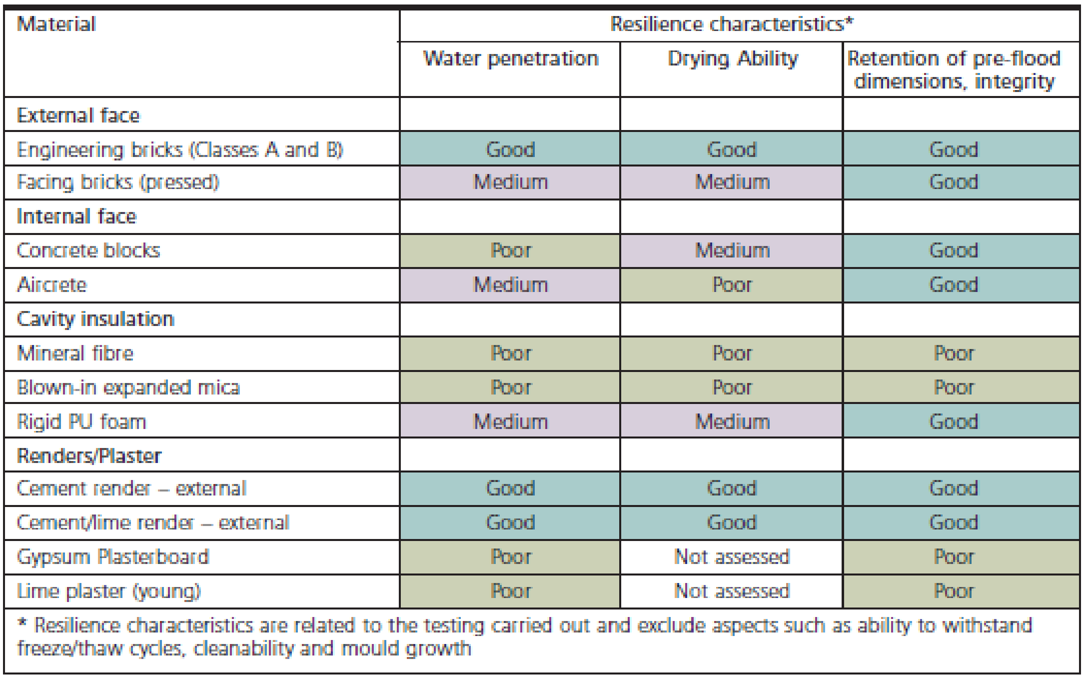
The type of foundation used in a building is usually determined by the ground conditions. However, improvements can be made to increase the flood resilience characteristics of a foundation. Laboratory work carried by CIRIA shows that groundwater can penetrate through the blockwork in cavity walls. Therefore, attention should be taken to minimise the passage of water. As a general principle, water exclusion strategy should be adopted in foundations when predicted flood depth is less than 0.3m above the floor level. Similarly, when the flood water depth is greater than 0.3m, water entry strategy should be adopted for foundations. When the water entry strategy is adopted, the foundation should be constructed using durable materials that will not be affected by water and should use construction methods and materials that promote easy draining and drying (Northumberland County Council, 2010)**.**

In a flood event, the performance of ground floors can be affected by the water ingress from the ground and exposure to standing water. From the above two situations, water ingress from the ground is potentially more sever as it is possible to affect the structural integrity of the floor. Hence calculations should be carried out to ensure that floor has the necessary strength to resist uplifting forces and deformations (Northumberland County Council, 2010).

One of the most efficient ways of decreasing the impact of flooding is to raise the floor level of the property above expected flood levels. However, for existing houses, this will not usually be possible (CIRIA, 2003). For existing buildings with a solid floor, it should be investigated if a good connection between the damp-proof membrane for the floor and the damp proof course in the wall is in place. It should also be inspected if there are cracks in existing floors, as they may allow water through the floor into the building. For buildings with suspended floors, a low point can be created in the surface of the soil or concrete sub-floor. This will assist in cleaning and drainage after a flood. Alternatively, the void can be filled to reduce the rate of future water ingress and prevent ‘puddles’ of water remaining inside the property for a long time after flooding (CIRIA, 2003).

Following the laboratory investigations carried out by CIRIA, wall components were categorised as good, medium, or poor with regards to their water penetration, surface drying, and structural integrity performance. Table 3 presented below, rates the performance of various wall components based on the resilience characteristics mentioned above.

Table 3 Flood resilience characteristics of walls (based on laboratory testing)(Bowker, Escarameia and Tagg, 2007)



Material	Resilience characteristics*		
	Water penetration	Drying Ability	Retention of pre-flood dimensions, integrity
External face			
Engineering bricks (Classes A and B)	Good	Good	Good
Facing bricks (pressed)	Medium	Medium	Good
Internal face			
Concrete blocks	Poor	Medium	Good
Aircrete	Medium	Poor	Good
Cavity insulation			
Mineral fibre	Poor	Poor	Poor
Blown-in expanded mica	Poor	Poor	Poor
Rigid PU foam	Medium	Medium	Good
Renders/Plaster			
Cement render – external	Good	Good	Good
Cement/lime render – external	Good	Good	Good
Gypsum Plasterboard	Poor	Not assessed	Poor
Lime plaster (young)	Poor	Not assessed	Poor
* Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth			

For masonry walls, the mortar joints should be thoroughly filled to reduce the risk of water penetration. Solid masonry walls are a good option but will need to be fitted with internal or external wall insulation in order to comply with Building Regulations (Bowker, Escarameia and Tagg, 2007).

Cavity walls with no insulation have better flood resilient characteristics as they promote rapid dry after a flood event. The requirements for insulation can be satisfied by external insulated render or internal thermal boards (Bowker, Escarameia and Tagg, 2007).

Where the frequency of flooding is high, reinforced concrete walls should be considered in the water exclusion strategy as these walls provide sufficient resisting forces to the pressures generated by flood water. External insulation is recommended rather than the internal insulation because it can be easily replaced if necessary (Bowker, Escarameia and Tagg, 2007).

2.7.2.2 Flood Defenses

In general, flood defenses can be divided into two broad categories; structural and non-structural defense measures. Structural measures include the construction of dams and reservoirs, while non-structural measures include planning, preparedness, legislation, and financing.

Structural measures are an important reactive mitigation measure to reinforce flood defense structures with the aim to protect human health and safety, and valuable goods and property. Structural measures may present in many different ways, such as flood defense structures (dams, reservoirs), channel and catchment modification (floodway and flood plain), and flood proofing (embankment) (Defra and Environment Agency, 2007).

Non-structural measures are an anticipatory response for flood hazard management. The review showed that many different methods had been adopted for non-structural measures. Defra and the Environment Agency in their report Risk assessment for flood incident management define four mitigation measures. These measures are flood warning and forecasting, emergency planning, evacuation measures, and public education (Defra and Environment Agency, 2007).

Chapter 3. Methodology

3.1 Identification and justification of the research paradigm

Thomas Kuhn (1996) defines a paradigm as accepted examples of actual scientific practice - examples which include law, theory, application, and instrumentation together - providing models from which spring particular coherent traditions of scientific research (Kuhn, 1996). The paradigm to be used in this study is based on the positivism research paradigm approach.

Much of the modern philosophy of science simply elaborates upon various empiricist positions, most notably the radical empiricist stance is known as positivism (Caldwell, 1980). The positivist paradigm asserts that real events can be observed empirically and explained with logical analysis (Kaboub, 2008). A positivist investigator has an idea or notion that the universe or world conforms to permanent and unchanging laws and rules of causation and happenings, that there exists an intricacy and complexity that could be overcome by reductionism; and with the intention of asserting an importance and emphasis on impartiality, measurement, objectivity and repeatability (Aliyu *et al.*, 2014).

A quantitative methodology was used for this research. The positivist research paradigm underpins a quantitative methodology (Antwi and Hamza, 2015). Creswell (1994) defines quantitative research as a type of research that explains phenomena by gathering numerical data that are analysed using mathematically based methods. In addition to that, quantitative research methods attempt to maximise objectivity, replicability, and generalisability of findings and are typically interested in prediction (Harwell, 2011). The data in this study are expressed in numeric terms, such as dimensions, temperature, time, and percentages. Furthermore, the aim of this research is to analyse the required data and make predictions about the performance of buildings under extreme weather conditions.

Quantitative approaches, when they are appropriately conducted, permit generalisations to be made about large populations based on much smaller (representative) samples. Further advantages are that, given a set of identifying conditions, they can assist in establishing the causality of the impact of given variables on project outcomes and (in principle) they allow other researchers to validate the original findings by independently replicating the analysis (Rao and Woolcock, 2003).

3.2 Research design, planning, and execution

Initially, the research focused on providing definitions of the examined extreme weather events. These definitions arose from the study of the literature and the current weather data of each location. Furthermore, it provided a definition of the term "Resilience of building" in order to justify the extent and the context of the research.

The current and most up-to-date TRY and DSY weather files were provided by CIBSE for the execution of the simulations. Simulations were performed using both the weather data of the current weather conditions and weather data of extreme weather conditions in order to evaluate the impact each extreme weather event has on the building's performance.
As mentioned above, this research examines three different types of buildings. Plans and elevations of the examined building were acquired in order to create the model of the building. For the buildings where actual energy consumption data exist, they have also been gathered and used for the validation of the results of the simulations. This research used two software packages:

- EDSL TAS – Thermal and energy simulation.
- XP SWMM – Water management simulation.

Upon the creation of the models in EDSL TAS, the simulation was initially done using the current weather data. The model of the building is created in the software and validated by comparing the actual energy consumption of the building with energy consumption of the building provided by the simulation. Subsequently, the simulation is performed again using the weather data that correspond to the examined extreme weather conditions. The comparison of the results with the results obtained from the initial simulation shows how the thermal performance of the building is affected when it is subjected to extreme heat waves.

The effects of heavy rainfall on the buildings were simulated using the XP SWMM software. In this case, not only the building but also the surrounding area was modelled. A comparison between the results of the simulation using the current weather conditions and the one using extreme weather conditions was made in order to identify potential risks for each of the examined buildings. The research looks into building design solutions to increase the resilience of building against extreme rainfall, flood defenses, drainage system design, and water supply solutions.

Upon completion of the simulations for all the examined extreme weather conditions and based on the definition of the term “Resilience of building,” the research was able to identify how and to what extent the resilience of the building is affected by each extreme weather event.

Applicable solutions were analysed and presented for each of the examined scenarios in order to enhance the resilience of the building. Proposed solutions were tested using the building models in order to validate their efficiency in increasing the resilience of the buildings to the extreme events under investigation. Finally based on the findings, the research is able to provide design guidelines to be used in new and existing built constructions.

3.3 Modelling and simulation

This study made use of two software packages. EDSL TAS was used for the thermal and energy simulations of the examined buildings, and XP SWMM was used for the simulation of the flooding events.

3.3.1 EDSL TAS

Thermal simulations of the examined buildings were performed using EDSL TAS version 9.3.2, a building simulation program developed by Engineering Development Solution Software. TAS is a building modeling and simulation tool, capable of performing dynamic thermal simulations of buildings and accurately predicting energy consumption, $C0_2$ emissions, operating costs, and occupant comfort (EDSL, 2015a).

The modeling process of a building in EDSL TAS is divided into three parts. The first part is the creation of the 3D model of the building, the second part is the assignment of the various building characteristics, and the third part is the simulation of the building. Creation of the building’s 3D model was performed in the TAS 3D Modeler (.t3d). The first step is to import the building’s floor plans to the model and identify the height of the walls. The next step is to create the required building elements and the windows of the building. Based on the imported drawings, the user creates a model of floors, assigns the building elements to the walls and positions the windows. Finally, the user identifies the different zones of the building and assigns a name to them. Upon completion of the modelling of each floor, a validation of the model is required in order to check if there are any errors or warnings. The same process is repeated for all the floors of the building. When the 3D modeling of the building is completed the model is exported to the TAS Building Simulator (.tbd). At this point, the user needs to identify the building's construction materials, its internal conditions, and assign a suitable calendar and weather file. Construction should be applied to all the building elements that were created in the 3D Modeler. If the exact construction of a building element is not available in the TAS Construction Library, the user can create a new construction in order to correctly represent the actual construction of the examined building. Following that, appropriate internal conditions should be applied to the zones of the building based on the building type and the use of the zone. In addition to that, a calendar is assigned to the building. This is used to identify different types of days where the building has a different operation schedule. Finally, the user assigns to the model a weather file that represents the weather conditions of the location of the building.

Following the input of the model's parameters, the building can be simulated using the TAS Building Simulator. Simulations can be performed for a complete calendar year or only for selected periods of interest. The results of the simulation are shown in the TAS Results Viewer (.tsd). Results are shown for each individual zone.

Finally, for the simulation of the HVAC systems, the results of the TAS Building Simulator are imported into the TAS Systems application (.tpd). TAS Systems is used for obtaining yearly, monthly, daily, and hourly results for consumption, demand, costs, and $C0_2$ emissions. In TAS Systems, the user should define the type of HVAC systems and their parameters. If it is required, different HVAC systems can be applied to different zones or group of zones. Also, if the building uses renewable energy sources (photovoltaic panels, wind turbine), the generated electricity from these sources can also be calculated.

3.3.2 XP SWMM

Simulations of the flood events presented in this thesis were performed using XP SWMM version 15.0, a software package developed by XP Solutions. XP SWMM is a comprehensive software package for planning, modeling, and managing sustainable drainage systems. It is used to simulate natural rainfall-runoff processes and the performance of engineered systems (XP Solutions, 2016).

The first step of the modeling process in XP SWMM is the importing of the image of the examined area and the Digital Terrain Model (DTM). The image of the area is used to model the various land uses and apply the relevant parameters. The DTM is a topographic model of the area and contains spatial elevation data.

In the following, the user should identify the catchments of the examined area and their draining points. Additional parameters that include the rainfall, infiltration, land uses, drainage, and soil type should also be modelled.

Modeling of buildings in XP SWMM can be done with two methods. The area of a building is modeled either as inactive or as a fill area. When modeling a building as an inactive area, a boundary is created in the perimeter of the building and water is not allowed to enter the building. However, as this assumption is not valid when the water levels exceed the level of the sill or the level of the windows, this method can result in overestimation of the water depth around the building. Modeling of buildings as fill areas allows the user to set a constant elevation that represents the level of the sill or the windows. When the water depth exceeds the set elevation, it will enter the building. This is a more realistic approach, and it allows for the identification of the risk of individual buildings for flooding.

XP SWMM can operate in three different modes. The three modes are runoff, sanitary, and hydraulics mode. Each mode has a different function and produces different types of results. In the Runoff mode, the program simulates the rainfall, infiltration, evaporation and other hydrologic processes for the defined catchments and calculates the runoff to a collection point. In the Hydraulics mode, the program simulates the storage and transport of water through drainage or foul sewer network. Sanitary mode is used to calculate storage and treatment processes.

3.4 Examined buildings

3.4.1 Office building

The Paragon building is located in West London, at the Brentford site of the University of West London. The School of Psychology, Social Care and Human Sciences and College of Nursing, Midwifery, and Healthcare are based at the Brentford site. The areas of the building are being used as classrooms, lecture theatres, offices, laboratories and IT rooms. The building also houses the university's library and a canteen. It remains operational during the whole year and the summer period is also used for the university's summer school classes. The total area of the building is 11167 m^2, it has 11 floors, and a mezzanine level and the total height is 45.57 m. The most substantial proportion of the building's facade is covered by a curtain wall facade. The rest of the facade is a solid wall.

Figure 7 View of the Paragon building (Source uwl.ac.uk)

Heating is provided in the building by a packaged boiler system that comprises three gas-fired boilers. Two gas valves are fitted to provide control of the fuel to the boilers. Cooling is provided by a chilled water system that comprises three air-cooled chillers. Chilled water is circulated by three pumps which are designed to allow a flexible operation in response to demand. Also, differential pressure switches are located across the pump section that provides a feedback signal indicating the water flow status in the flow pipework.

There are three air handling units (AHU) located on the third floor and one located on the roof that supplies fresh air to the building via fan coil units. The AHU that is located on the roof serves all floors while from the three AHU that are located on the third floor, one serves the two lecture theatres, one serves the floors from the ground to the third, and one serves the floors from the fifth to the ninth.

The U-Values of the building elements that were used are shown in Table 4.

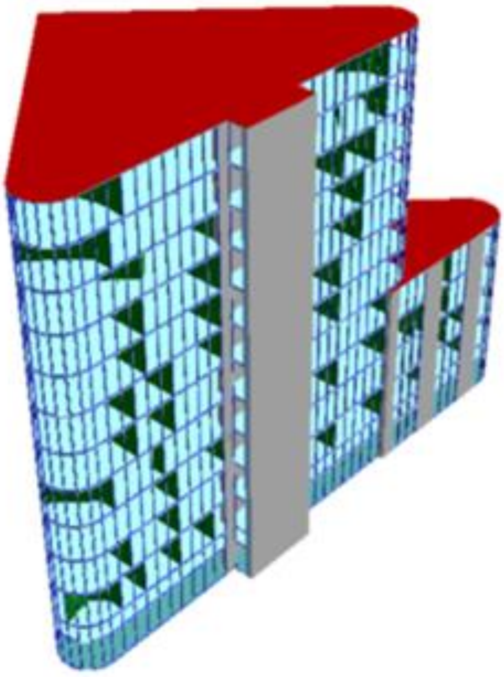


Figure 8 View of the model of the building

Table 4 U-values of the building elements

Construction	**U-Value (W/m^2 °C)**
External wall	0.35
Internal wall	0.241
Roof	2.768
Windows	1.424

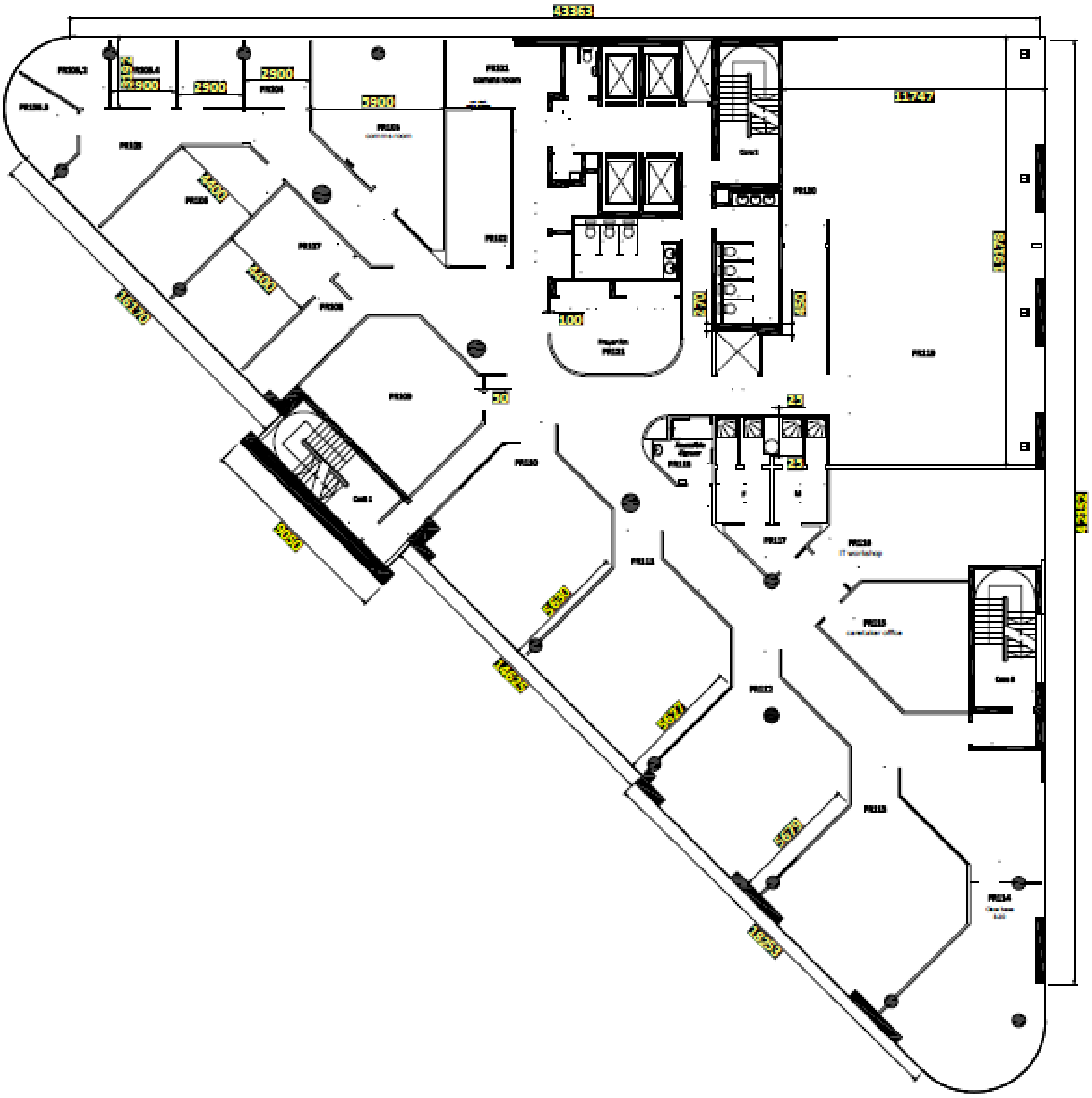


Figure 9 Plan of the first floor of the Paragon building

3.4.2 School building

The examined building is a one story new build school building with a total area of 1343 m^2. The architectural plan of the building is shown in Figure 10. The internal space of the building consists of classrooms, interview rooms, offices, WC, kitchen, plant room, and circulation areas. It has seven similarly sized classrooms with an average area of 65.25 m^2. Three classrooms are south facing, and four are north facing. External shading is provided for the south-facing classrooms by polycarbonate roof panels. On the top of the roof, a photovoltaic solar system is installed. All classrooms have the same window formation, as shown in Figure 13. The upper windows have an area of 0.55 m^{2,} and the middle windows have an area of 1.43 m^2. The bottom part of the formation consists of aluminum panes.

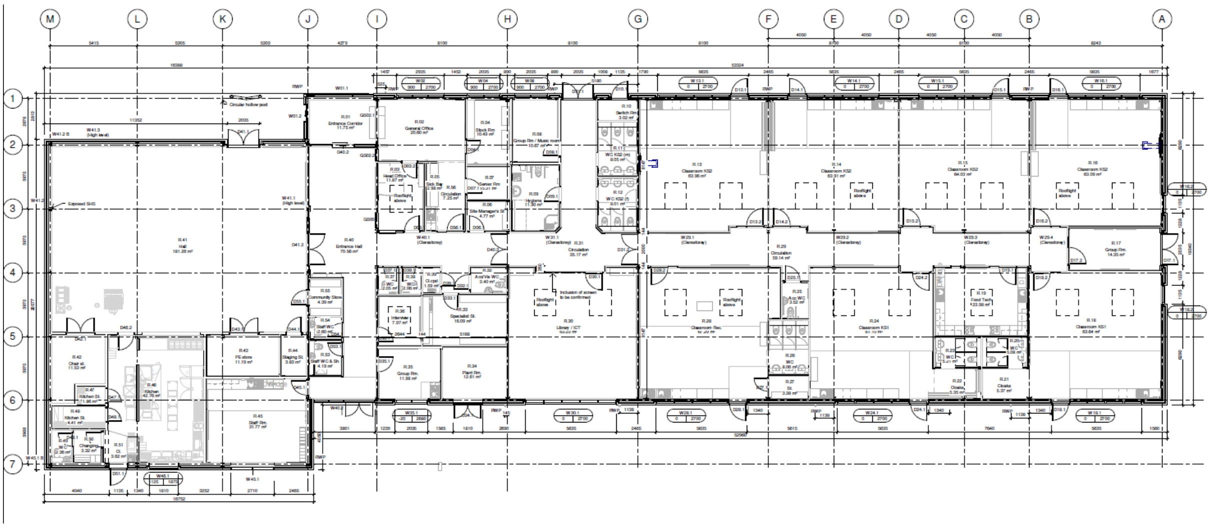


Figure 10 Architectural plan of the school building

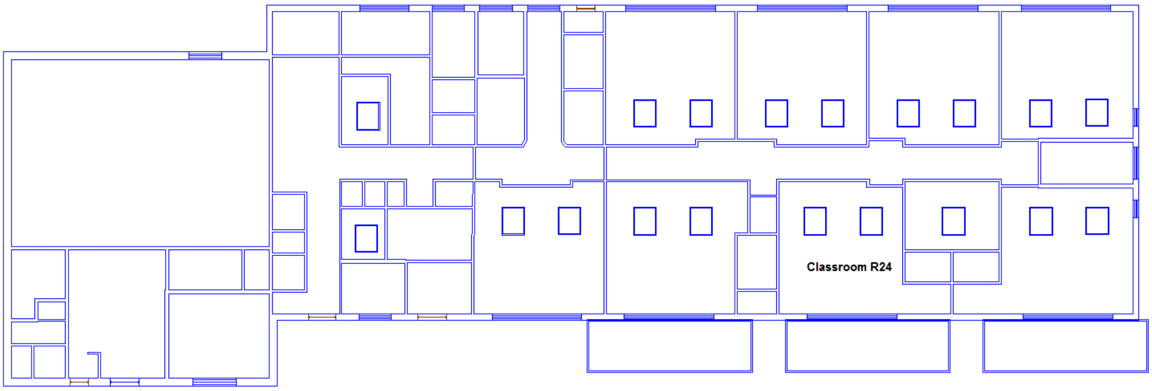


Figure 11 View of the 2D model of the school building

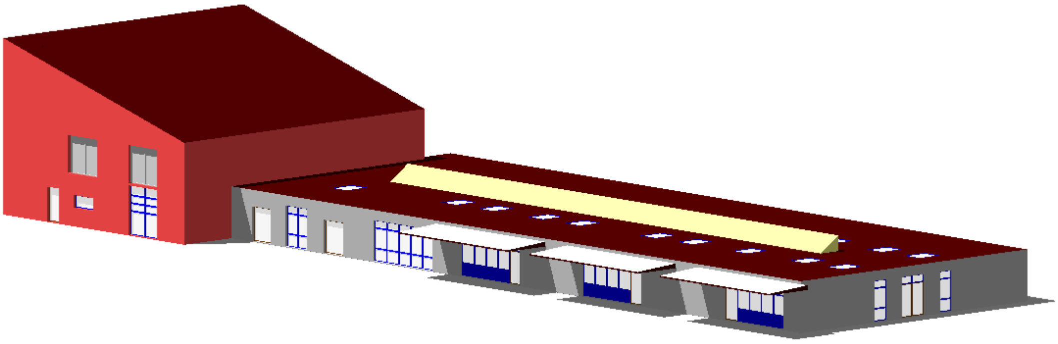


Figure 12 3D Model of the building

Table 5 shows the modeling and simulation parameters of the building fabric used in this study. Figures 11 and 12 show the plan and the 3D model of the building as they were created in EDSL TAS.

Table 5 Building fabric U-values (School building)

Construction	**U-Value (W/ m^2 °C)**
External wall	0.25
Partition wall	0.728
Roof	0.164
Windows	1.538
Ground floor	0.21

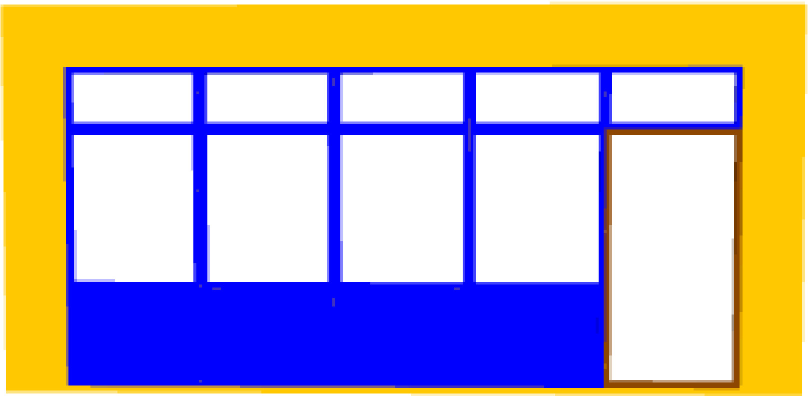


Figure 13 Window formation of classrooms

3.4.3 Residential building

The examined residential building is a two-floor house with a total area of 333 m^2. On the ground floor, the building's zones consist of a living room, a dining room, hall area, a kitchen with a utility room, two storage areas, a WC and the garage. On the first floor, the building has four bedrooms and a bathroom. The building is naturally ventilated. The U-values of the building materials can be seen in Table 6 below.

Figure 14 3D view of the building model (Front)

Figure 15 3D view of the building model (Rear)

Table 6 Building fabric U-values (Residential building)

Construction	**U-Value**
External wall	0.24 W/m^{2}K
Partition wall	0.728 W/m^{2}K
Roof	0.13 W/m^{2}K
Windows	2.30 W/m^{2}K

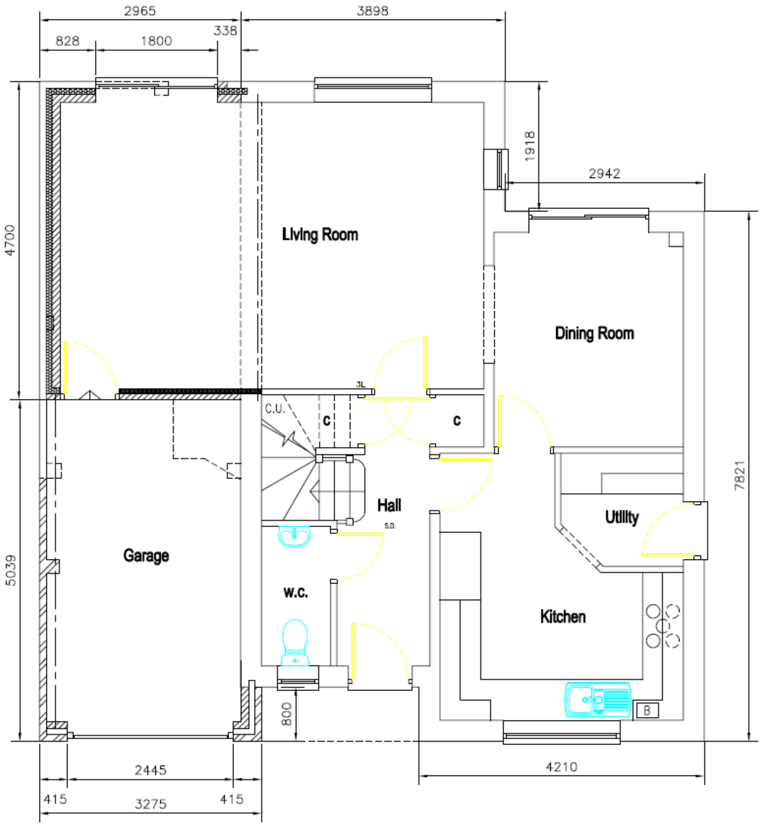


Figure 16 Residential building - ground floor

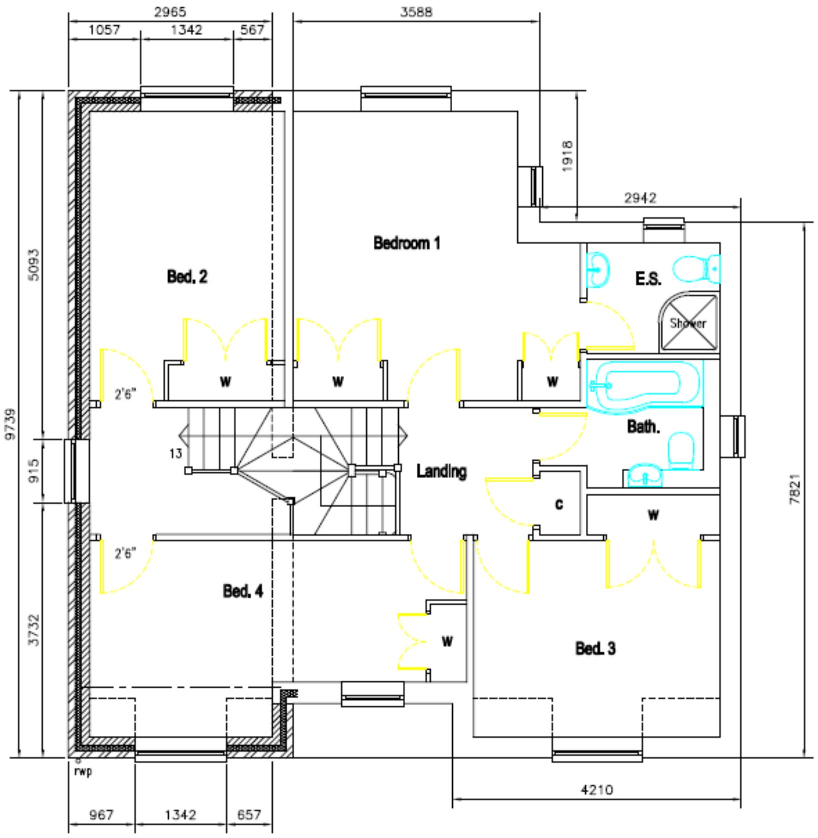


Figure 17Residential building - first floor

Chapter 4: Effect of Window-to-Wall Ratio on Thermal Comfort and Energy Consumption

The effect of the window-to-wall ratio on thermal comfort conditions and energy consumption was examined for the office building described in section 3.4.2.

4.1 Introduction

The Climate Change Act, which was passed in 2008, commits the UK to reduce emissions by 80% in 2050 from 1990 levels (Climate Change Act, 2008). Considering that buildings account for 37% of all UK greenhouse emissions (European Commission, 2015), it is important to find solutions to reduce the emissions of the buildings in order to achieve this target. Emissions from buildings comprise 45% direct emissions due to burning fossil fuels for heat and 55% indirect emissions related to electricity use (Committee on Climate Change, 2013). Therefore, the applied solutions should aim to reduce both the heating demand, which is usually served by a gas or oil-fired boiler and the cooling demand, which is usually served by appliances using electricity.

Commercial buildings with fully glazed facades are popular in the UK. They allow the light to penetrate into the interiors of the building and provide an unrestricted view of the outside to the occupants. Moreover, they contribute to the aesthetics of the building. However, the amount of solar gains resulting from a glazed facade can overheat the building, increase the cooling demand, and gas emissions. In addition to consuming considerable amounts of energy, the large amount of solar radiation passing through the glass facade often causes occupants to experience thermal discomfort (Hwang and Shu, 2011)

The window-to-wall area ratio (WWR) has an important effect on building energy consumption for heating and air conditioning (Su and Zhang, 2010). This study aims to quantify the effect of the window-to-wall ratio on the cooling and lighting loads of an institutional building during the non-heating period (May to September) and investigate its effect on thermal comfort.

4.2 Predicted Mean Vote (PMV)

Buildings that are cooled or heated mechanically can also overheat if the ventilation system is, for example, undersized or poorly controlled. Here BS EN 15251 (BSI, 2007) defines the acceptable indoor conditions according to the PMV index, and overheating is, therefore, a function not only of temperature but also of the humidity, air speed and the clothing and activity of the occupants. The extent of overheating will also be judged according to the PPD.

The predicted mean vote is arguably the most influential and widely used thermal comfort model (Kim, et al., 2015). It is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (Table 7).

Table 7: Seven Point thermal sensation scale (ISO, 2005)

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

PMV may be calculated for different combinations of metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and air humidity (ISO, 2005).

From the PMV value, the predicted percentage dissatisfied (PPD) can be determined. PPD is an index that establishes the number of people that feel a dissatisfaction from the thermal conditions. It can be calculated by the following equation:

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)$$

(ISO, 2005)

4.3 Modelling of the building

This study examined eight different window-to-wall ratios, from 20% to 90%. For each of the examined cases, the width of the windows of the building was alternated by 10%. The resulting effect on the facade of the building can be observed in Figures 16-23.

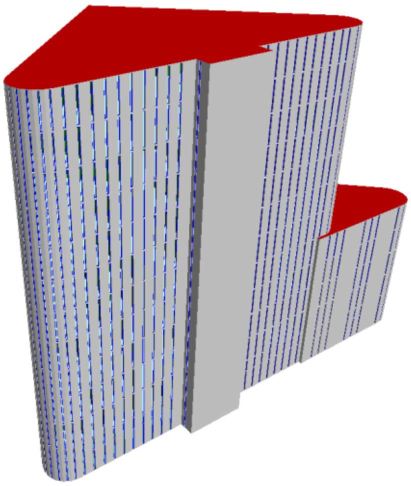


Figure 18 20% Window-to-wall ratio

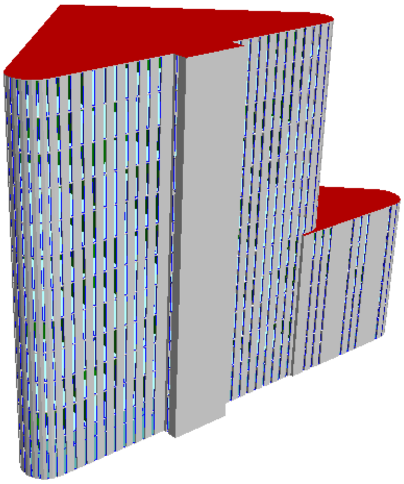


Figure 19 30% Window-to-wall ratio

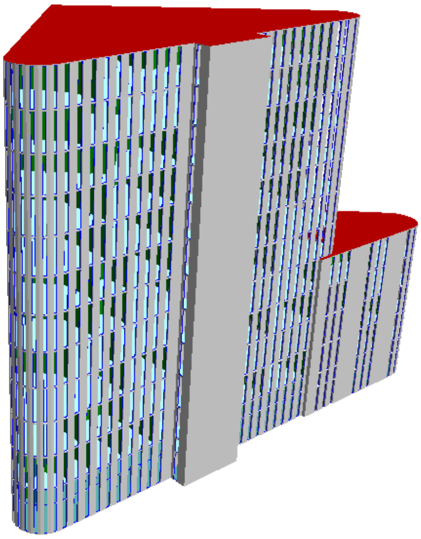


Figure 20 40% Window-to-wall ratio

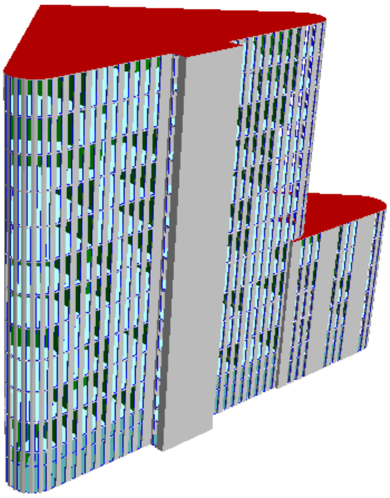


Figure 21 50% Window-to-wall ratio

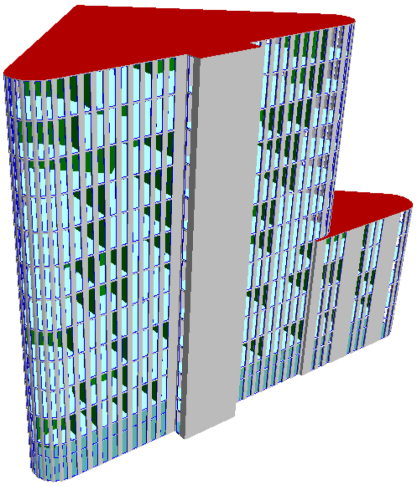


Figure 22 60% Window-to-wall ratio

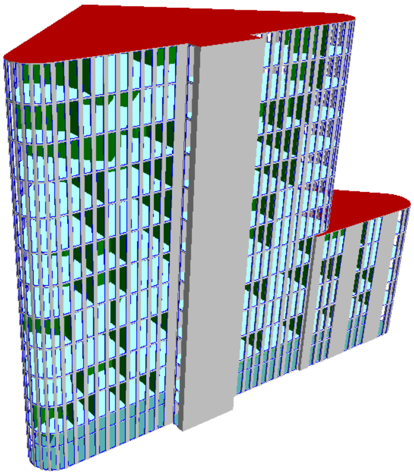


Figure 23 70% Window-to-wall ratio

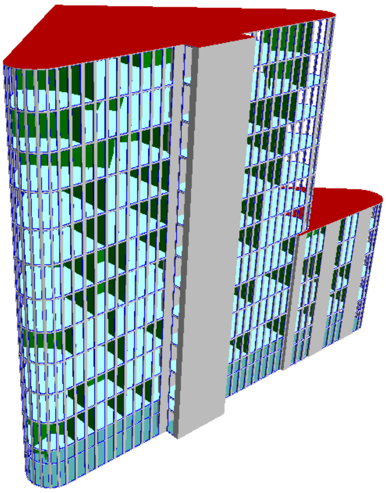


Figure 24 80% Window-to-wall ratio

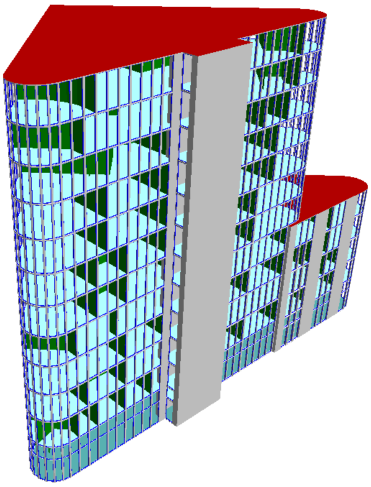


Figure 25 90% Window-to-wall ratio

In order to examine the effect of the window-to-wall ratio on the lighting loads, a function that controls the lighting of the zones of the building was modelled. This function models a photocell approach of the lighting based on the occupancy of the building. Furthermore, target illuminance levels were defined for each zone. The target illuminance levels were adopted by the recommended comfort criteria presented in CIBSE Guide A (CIBSE, 2015a). The target illuminance levels that were modelled for this study can be seen in Table 8. With the application of the target illuminance levels, artificial lighting will be provided in the room only when the natural lighting entering the building is not enough to cover the modeled levels of target illuminance.

Simulations of the building were performed using the DSY-2 weather data for the simulation of the current weather conditions and the DSY-2 High 90% weather data for the simulation of the projected weather conditions of the 2050s.

Table 8 Modelled illuminance levels

Room type	**Illuminance (lux)**
Office	400
Classroom	300
Lecture hall	500
Corridor	100
Laboratory	100
Kitchen	500

4.4 Effect of window-to-wall ratio on cooling and lighting loads

The graphs presented below show the total resulting in cooling loads and lighting loads for the examined cases during the non-heating period. Also, in Tables 9-12, a monthly breakdown of the loads is presented.

For both examined weather scenarios, the least amount of cooling loads is obtained with a 30% window-to-wall ratio. This is explained by the fact that when the building is modelled with a 20% window-to-wall ratio, it requires significantly more lighting in order to achieve the target illuminance. The additional heat generated by the lighting fixtures resulted in additional cooling in order to achieve the temperature set point.

The total of the cooling and lighting loads receives its lowest value when the building is modeled with a 50% window-to-wall ratio under the current weather conditions and with a 40% window-to-wall ratio under the projected weather conditions. However, in both cases, the difference between these two cases is 0.5 kWh/m^2.

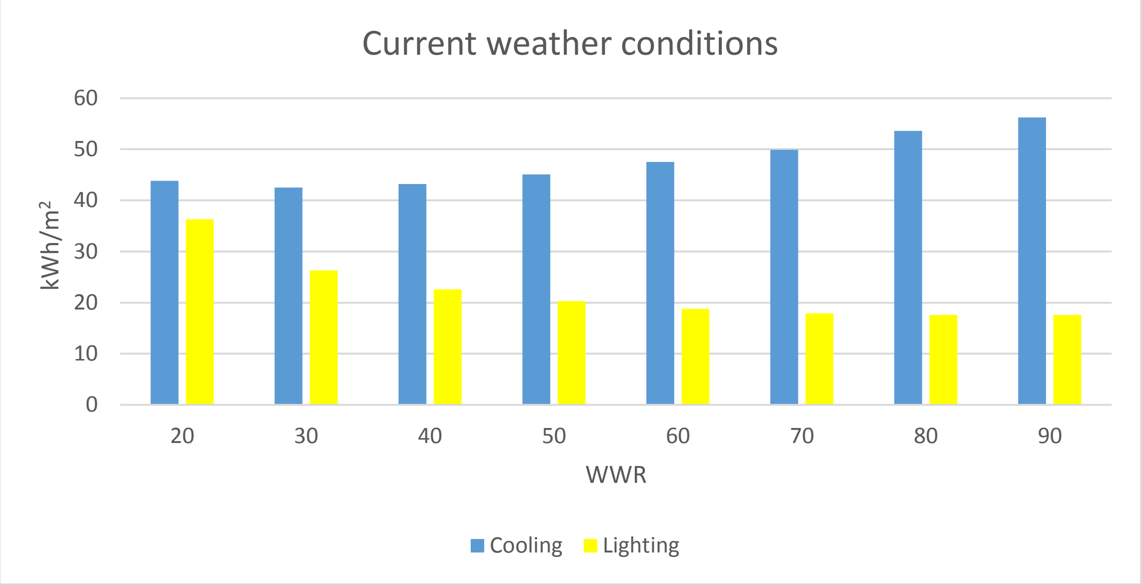


Figure 26 Cooling and lighting loads for the examined WWR in kWh/m^2

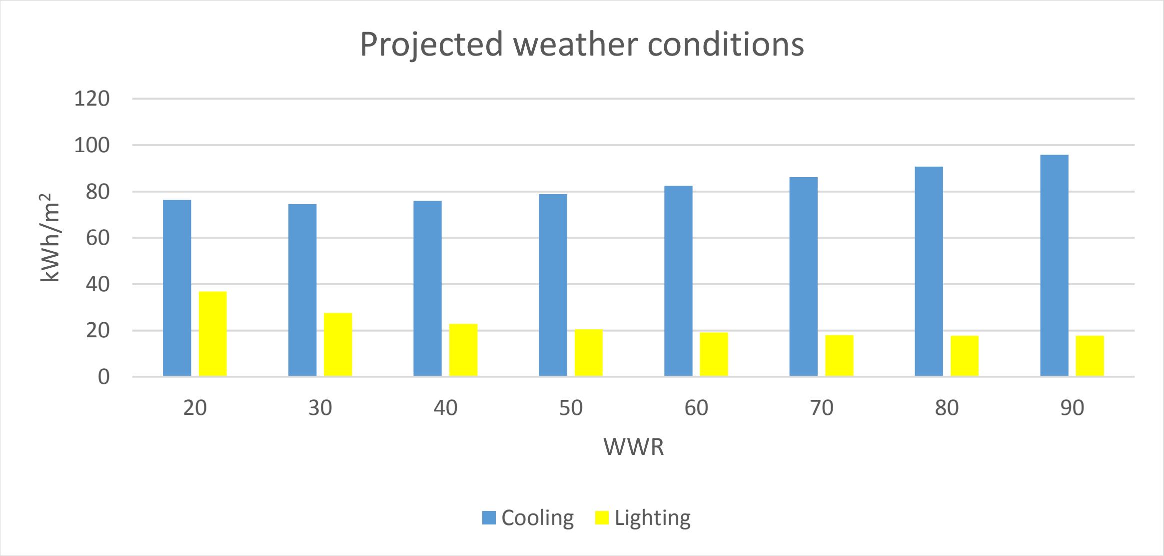


Figure 27 Cooling and lighting loads for the examined WWR in kWh/m^2

Table 9 Monthly cooling loads for the examined WWR - Current weather conditions

Cooling loads (kWh/m^2)						
%	May	June	July	August	September	Total
20	3.4	10	10.5	13.1	6.8	43.8
30	3.2	9.5	10.3	13	6.5	42.5
40	3.2	9.7	10.5	13.3	6.5	43.2
50	3.3	10.2	11.1	13.9	6.6	45.1
60	3.5	10.8	11.7	14.6	6.9	47.5
70	3.7	11.4	12.3	15.3	7.2	49.9
80	4.1	12.5	12.8	16.4	7.8	53.6
90	4.3	13	13.8	17	8.1	56.2

Table 10 Monthly lighting loads for the examined WWR - current weather conditions

Lighting (kWh/m^2)						
%	May	June	July	August	September	Total
20	8.1	6.7	6.4	7	8.1	36.3
30	5.9	4	4.8	5.3	6.3	26.3
40	5	3.9	4	4.5	5.2	22.6
50	4.4	3.5	3.7	4	4.7	20.3
60	4.1	3.2	3.4	3.7	4.4	18.8
70	3.9	3	3.2	3.6	4.2	17.9
80	3.8	3	3.2	3.5	4.1	17.6
90	3.8	3	3.2	3.5	4.1	17.6

Table 11 Monthly cooling loads of the examined WWR - Projected weather conditions (the 2050s)

Cooling (kWh/m^2)						
%	May	June	July	August	September	Total
20	9	16.2	18.3	19.8	13.1	76.4
30	8.3	15.7	18.2	19.8	12.6	74.6
40	8.4	16.1	18.6	20.2	12.6	75.9
50	8.6	16.9	19.4	21	12.9	78.8
60	9.1	17.7	20.4	21.8	13.5	82.5
70	9.5	18.6	21.4	22.7	14	86.2
80	10.1	19.4	22.5	23.9	14.9	90.8
90	10.7	20.8	23.7	25	15.7	95.9

Table 12 Monthly lighting loads for the examined WWR - Projected weather conditions (the 2050s)

Lighting (kWh/m2)						
%	May	June	July	August	September	Total
20	8.1	6.7	6.6	7.1	8.3	36.8
30	5.9	4.8	5	5.4	6.4	27.5
40	5	4	4.1	4.5	5.3	22.9
50	4.4	3.6	3.7	4.1	4.7	20.5
60	4.1	3.3	3.5	3.8	4.4	19.1
70	3.9	3	3.3	3.6	4.2	18
80	3.8	3	3.2	3.6	4.1	17.7
90	3.8	3	3.2	3.6	4.1	17.7

4.5 Effect of window-to-wall ratio on thermal comfort

For the calculation of the PMV/PPD values, the simulated values of the air temperature, mean radiant temperature and relative humidity have been used. The air speed was set to 0.1 m/s. When considering the calculations for the thermal comfort of the office room, the occupants' metabolic rate was set to 1.2 met and the clothing to 0.7. The building is considered to be in Class II, so the acceptable limit for the PMV is ± 0.5 (PPD≤10%) (BS EN 15251, 2007).

The graphs presented below show the PPD calculations for room 1004, for the examined window-to-wall ratios during the day of the year with the highest temperature for the current and the projected weather conditions. The horizontal axis shows the working hours and the vertical axis of the PPD.

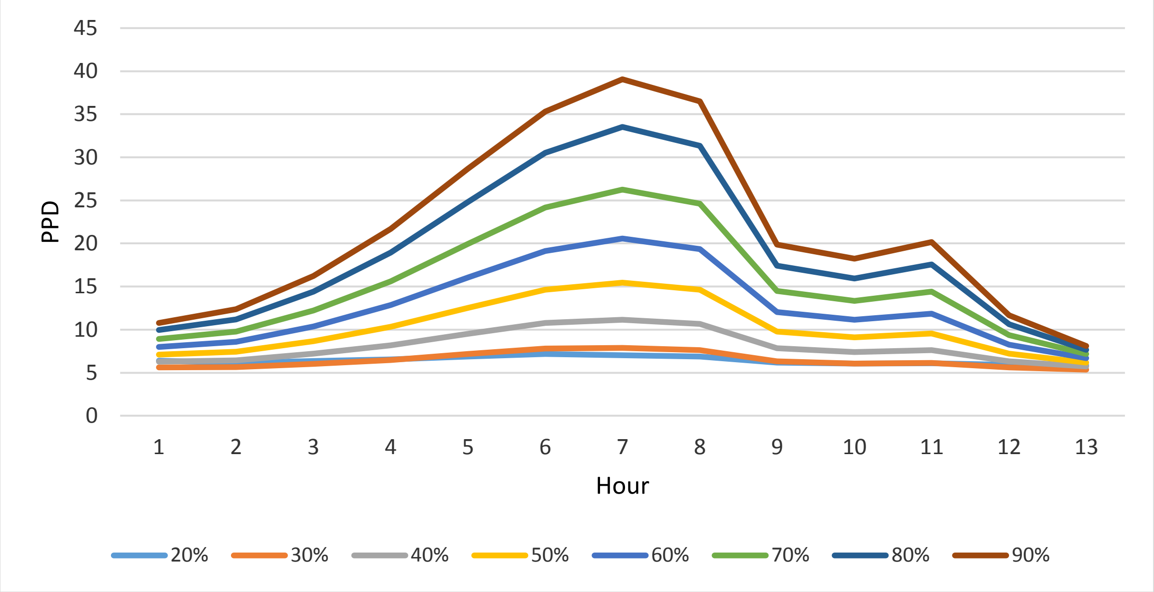


Figure 28 PPD under current weather conditions

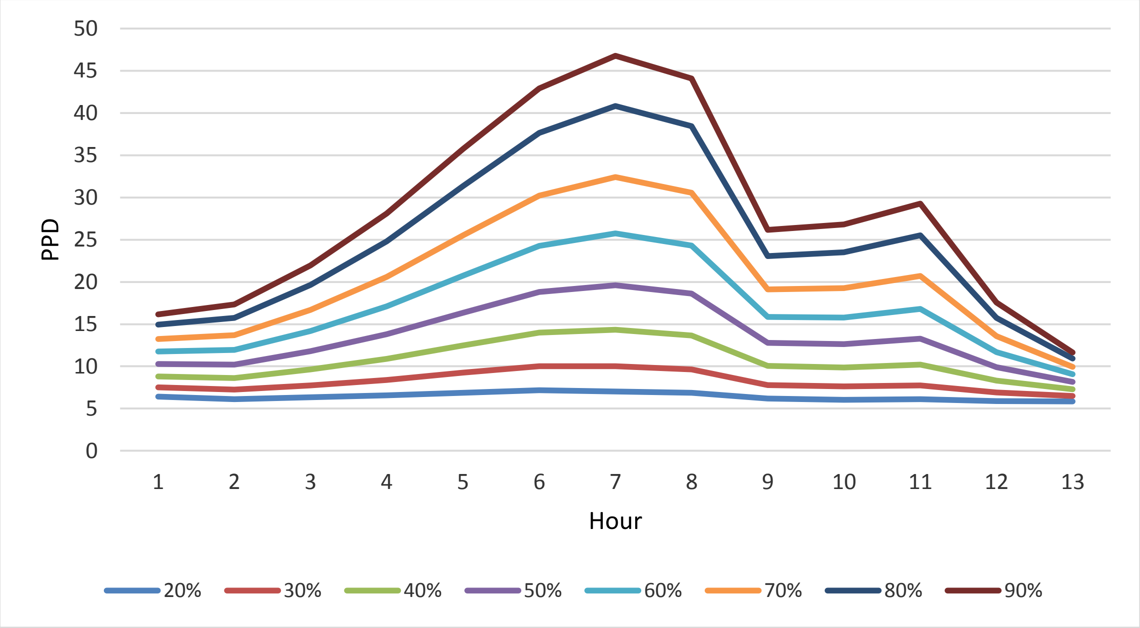


Figure 29PPD under the projected weather conditions

As can be observed from Figure 26, under the current weather condition, the smallest percentage of dissatisfied people results when the window-to-wall ratio is at 20% or 30%. From the other examined cases, only when the building is modelled with a 40% window-to-wall ratio, the PPD of the room stays close to 10%, which represents the acceptable thermal comfort conditions. For the cases from 50% to 90% it can be seen that they achieve good thermal comfort conditions at the beginning and the end of the day, but they result in high PPD in the middle of the day.

Figure 27 shows the PPD calculations under the projected weather conditions of the 2050s. It can be seen that the most comfortable conditions resulted in a 20% window-to-wall ratio. Only when the building is modelled with a 30% window-to-wall ratio does room remain within thermal comfort conditions for the whole duration of the day. Furthermore, it can be seen that the thermal comfort conditions of the room have worsened in all of the examined scenarios.

4.6 Conclusions

This study examined the effect of the window-to-wall ratio of an educational building, on the cooling and lighting loads and the thermal comfort under the current and the projected weather conditions of the 2050s.

Results of the simulations of the examined cases show that the least amount of cooling loads is achieved when the building is modelled with a 30% window-to-wall ratio and the least amount of lighting loads is achieved when the building is modelled with 90% window-to-wall ratio. It is worth noting that the case with 80% window-to-wall ratio has identical lighting loads with the 90% and lighting loads of the 70% case were only marginally higher. The versions of the building with 40% and 50% window-to-wall ratio have the lowest combined value of cooling and lighting loads.

Furthermore, the study examined the thermal comfort conditions of a room during the day with the highest temperature. Under the current weather conditions, the room achieves the best comfort conditions when the building is modelled with a 20% or 30% window-to-wall ratio. Under the projected weather conditions, the room achieves the best thermal comfort conditions when the building is modelled with a 20% window-to-wall ratio. However, even with a 30% window-to-wall ratio, the room remains within acceptable comfort conditions for the whole of the working day. All the other examined cases result in unacceptable comfort conditions.

Chapter 5: Effect of Relative Humidity on Thermal Comfort

The effect of relative humidity on thermal comfort conditions was investigated for the office building described in section 3.4.2.

The schedule of the building was set to weekdays and weekends. Based on the usage of the building, the occupancy profile was set from 08:00 to 20:00, and the cooling setpoint during the occupied hours was set to 21°C. The windows of the building were modelled with a blind that covered 50% of their glazing area.

5.1 Introduction

The climate is changing, and buildings are already performing poorly in several ways, the most obvious of these is the summer overheating of buildings with large areas of glazing, lightweight construction, or which are well insulated without enough ventilation. Those buildings that are performing well now and those who are currently being designed and built for the current climate may become intolerable for occupants by 2080 without the use of active cooling and associated high energy usage (CIBSE, 2014d).

UK Climate Projections examine three different greenhouse gas emissions scenarios and show how future climate could change if we fail to reduce our emissions. The high emissions scenario could result in an average summer temperature rise of 5°C in the south west of England by the 2080s (Defra, 2009). This will significantly affect the thermal and energy performance of our buildings.

Achieving thermal comfort conditions is vital in order to ensure the well-being and productivity levels of the occupants. Furthermore, when considering educational buildings, thermal comfort has also been related to student performance (Zomorodian, Tahsildoost, & Hafezi, 2016).

Educational buildings are responsible for a significant amount of the UK's non-industrial energy consumption, and a considerable amount of this energy is used to provide thermal comfort (Barbhuiya and Barbhuiya, 2013). This study focuses on the non-heating period (May to September) and examines the differences in cooling loads and thermal comfort in a higher education building under current weather conditions and future projected weather conditions of the 2050s.

5.2 Effect of relative humidity on thermal comfort

For the most common thermal comfort, human application, relative humidity levels can vary between 30%-70%.

The effect of relative humidity on thermal comfort is not considered to be significant when the indoor temperature is within the recommended range. It is generally accepted that within the ‘comfort’ range (20-26°C) humidity has a second order of importance, as the operative temperature rises towards the body temperature evaporation and respiration becomes an essential mechanism for heat loss from the body (CIBSE, 2015a).

Relative humidity affects thermal comfort more significantly at higher temperatures. It is recognised that at higher temperatures - particularly in high relative humidity, which limits the body’s ability to keep cool through perspiration - heat stress can occur while the body cannot maintain its core temperature of 37 °C (CIBSE, 2014). High levels of relative humidity can work against the evaporative cooling effects of sweating and leave the body prone to overheating (Boduch and Fincher, 2009). The combination of high temperature and high humidity introduces a feeling of sultriness or oppression, which occurs above 70% relative humidity at 21°C and above 60% relative humidity at 23°C (DIN, 1994). A maximum room relative humidity of 60% within the recommended range of summer design operative temperatures would provide acceptable comfort conditions for human occupancy and minimize the risk of mould growth (CIBSE, 2015a).

5.3 Estimation of thermal comfort conditions

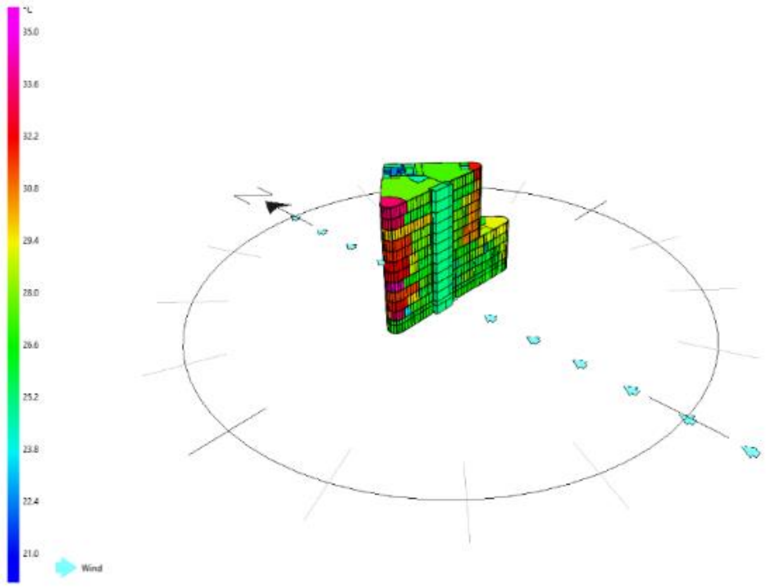


Figure 30 Mean radiant temperature range at the time of the highest external temperature

In order to examine the thermal comfort, a room located on the east side of the building was selected. Room 1004 is used as an office. According to the simulated results that room was found to have the highest mean radiant temperatures in the day and at the time of the highest external temperature. The calculation of the PMV/PPD values was performed similarly to the method described in section 4.2.

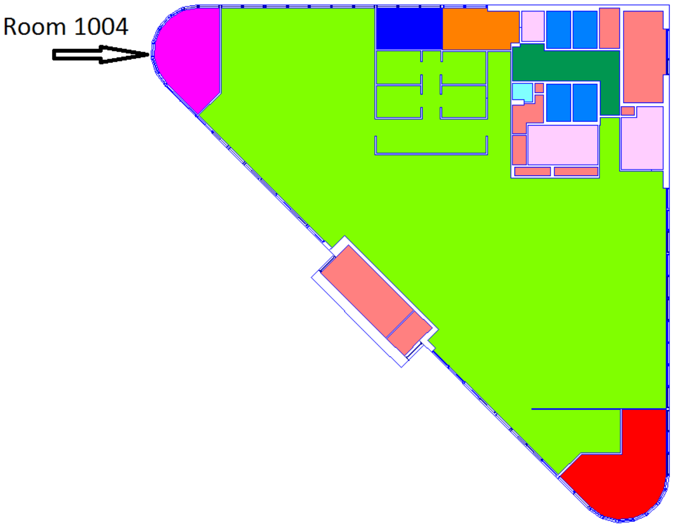


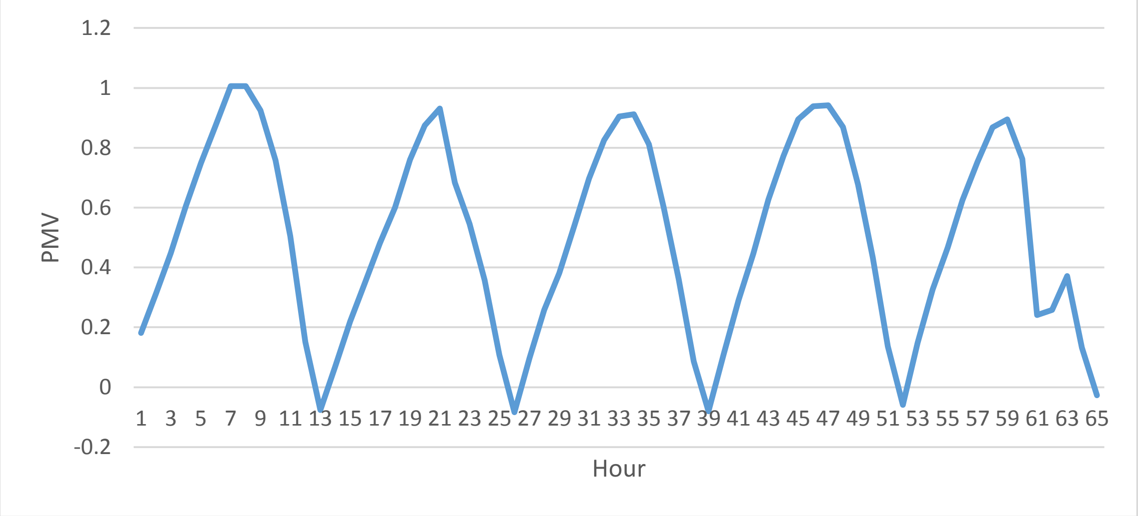
Figure 31 Zoning of the 10th floor and location of room 1004

All PMV/PPD calculations presented below are only for the occupied hours of the building for the period from May to September. In total, the occupied hours of the examined period were 1378.

5.3.1 Room 1004 (Office)

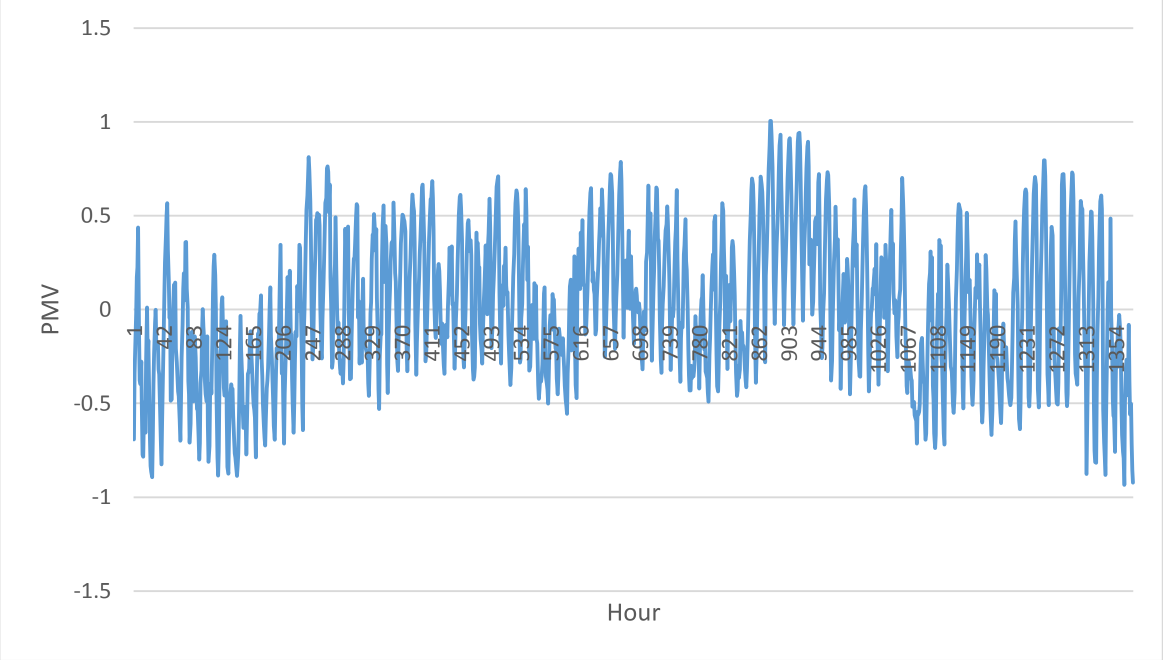
5.3.1.1 Baseline calculations

Graph 1 shows the PMV values of the examined room during the week with the highest external temperature. The examined week is formed of 5 working days, with each of those days having 13 working hours. Consequently, the points (13, 0), (26, 0), (39, 0), (52, 0) and (65, 0) of the graph represent the end of the working day. It can be observed that PMV receives values close to zero at the beginning and the end of the working day. As the temperature rises, thermal comfort decreases and in the middle of the working day when the temperature is at its highest PMV point receives the highest value, which results in the highest percentage of dissatisfied people. The peak point for the examined week occurs either at 14:00 or at 15:00. As the day progresses and external temperature decreases, PMV values decrease until they reach their lowest point at the end of the working day at 20:00.

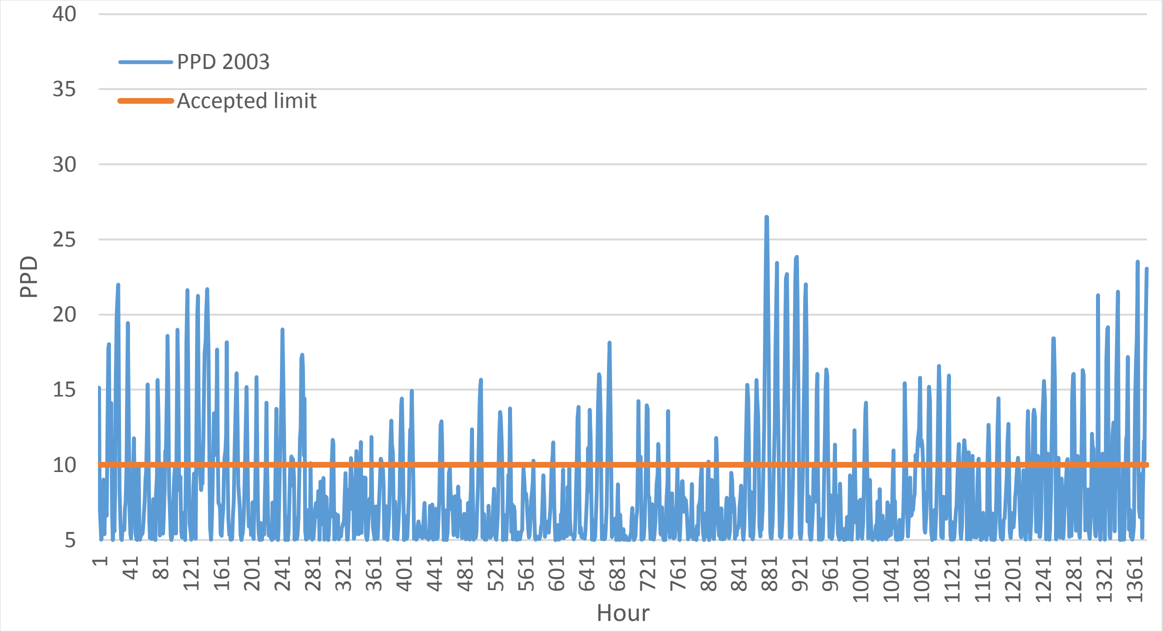


Graph 1 PMV values during the hottest week of the year

Graphs 2 and 3 below show the hourly results for the predicted mean vote and the percentage of dissatisfied people for the baseline calculations. There are 318 hours with a PPD of over 10%. This equals to 23% of the occupied time. It can be observed that the highest concentration of hours above the 10% limit are at the two ends of the graph, which represent May and September. Furthermore, it can be seen from Graph 3 that during the beginning and the end of the non-heating period the PMV receives negative values up to -0.9, which means that people feel slightly cool while during the summer months the PMV values are positive with a maximum value of +1.005, which means that people feel slightly warm in the room. The negative values that appear during the summer months represent the beginning and the end of the working day, where under the examined internal conditions, people feel slightly cold.



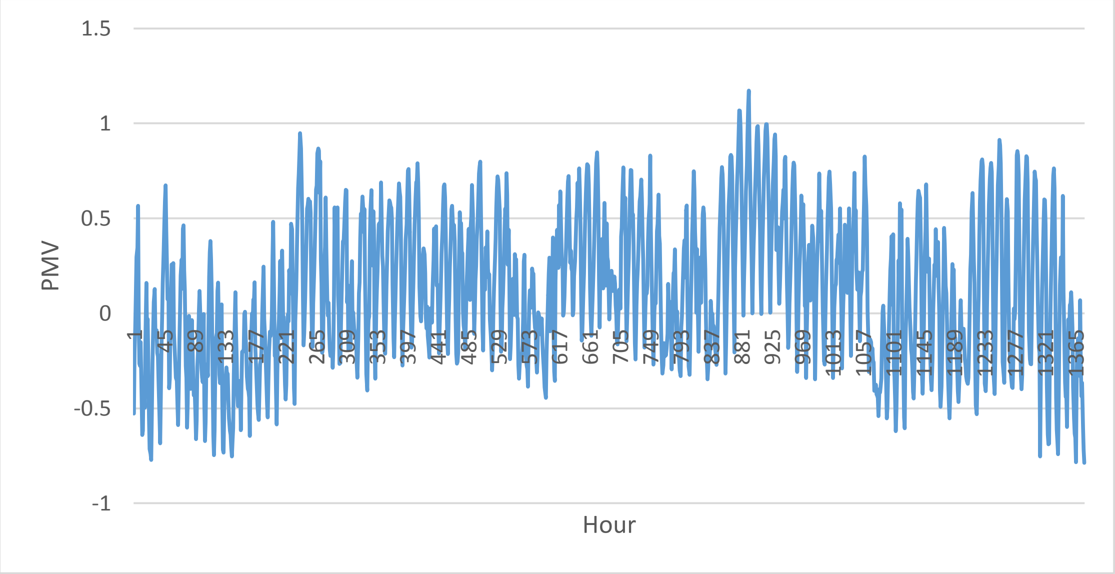
Graph 2 Hourly PMV during occupied hours – Baseline



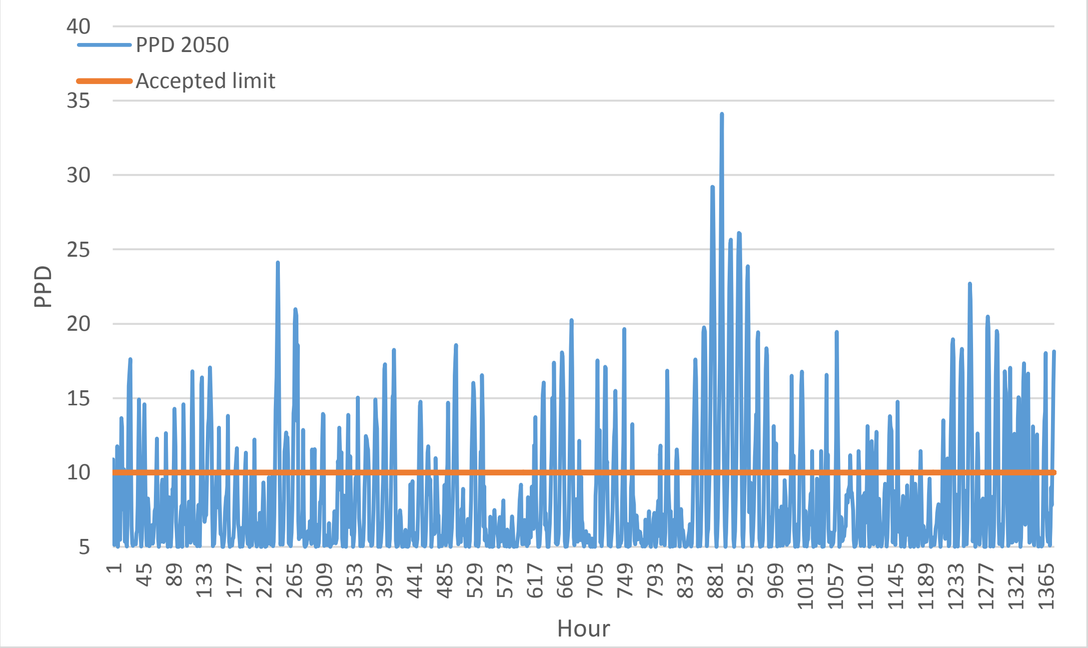
Graph 3 Hourly PPD values - Baseline

5.3.1.2 Future weather calculations

Graphs 4 and 5 below show the PMV and PPD values under the examined future weather conditions. Graph 7 shows the PMV value for the examined room during the hottest week of the year and presents a comparison with the 2003 DSY. As can be observed, the results show a similar pattern with the baseline calculations; however, the negative PMV values at the beginning and the end of the non-heating period have dropped (lowest value at -0.78) and the positive PMV values during the summer months have increased (highest value at 1.17).



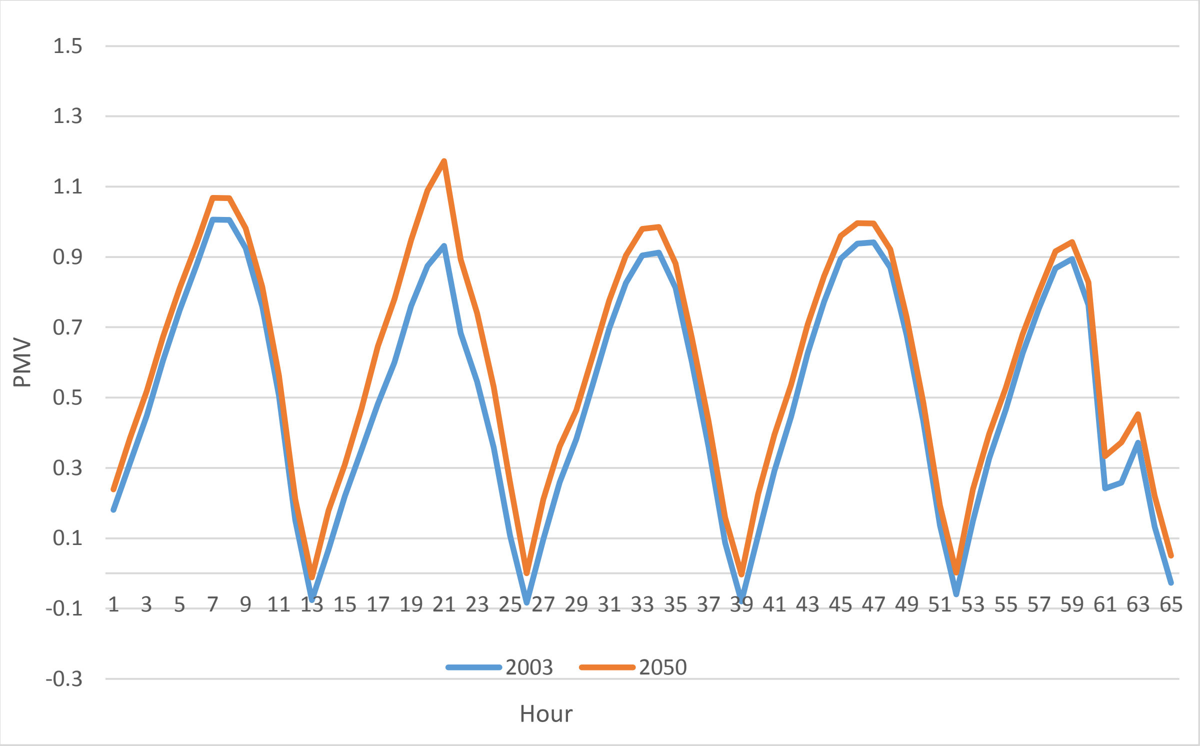
Graph 4 Hourly PMV values - Future weather



Graph 5 Hourly PPD values - Future weather

Comparing the PPD results of the two examined weather datasets, it can be seen that although the room has the same internal conditions as in the baseline calculations, the thermal comfort of the occupants under the future weather conditions will worsen during the summer months but will be slightly improved during May and September. In the baseline scenario, it was estimated that the occupants feel slightly cold during May and September and slightly warm during the summer months. The increased external temperature of the future weather conditions leads to an increase of the mean radiant temperature and as a result of the operative temperature of the room. In terms of thermal comfort, this increase in the temperature is beneficial forMay and September but has a negative effect during the summer months. Out of the 1378 occupied hours, 333 are above the 10% PPD threshold.

Graph 6 below shows the PMV values of the two examined weather scenarios during the hottest week of the year. It can be seen that the thermal comfort of the occupants will be worst during all hours of the working day except for the last one of the working day (20:00).

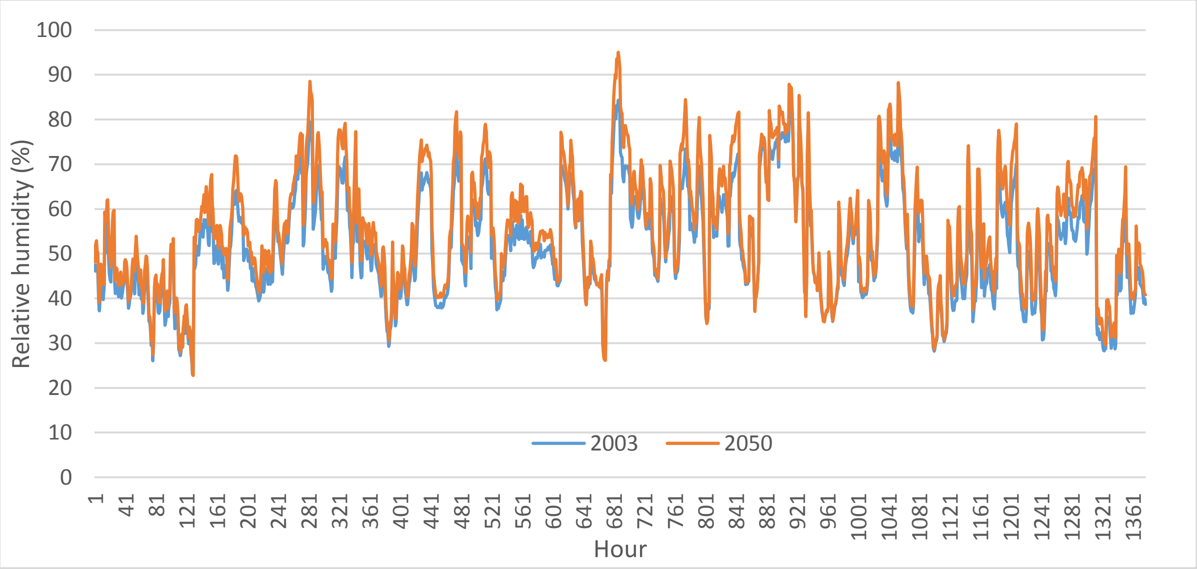


Graph 6 Comparison of PMV values during the hottest week of the year

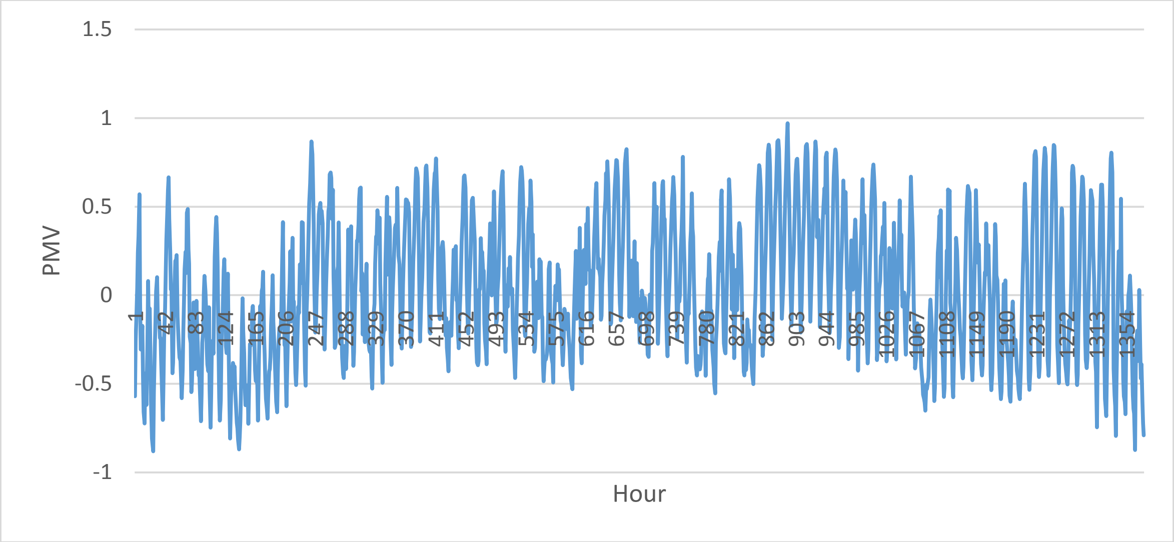
5.4 Effect of relative humidity

As discussed above, the factors that affect the PMV are the internal temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate, and clothing. Air velocity, metabolic rate, and clothing were considered to be unchanged during the examined period and were the same for both of the examined scenarios. The internal temperature was set to 21°C, and the mean radiant temperature used for the calculations of the PMV was calculated by the software package.

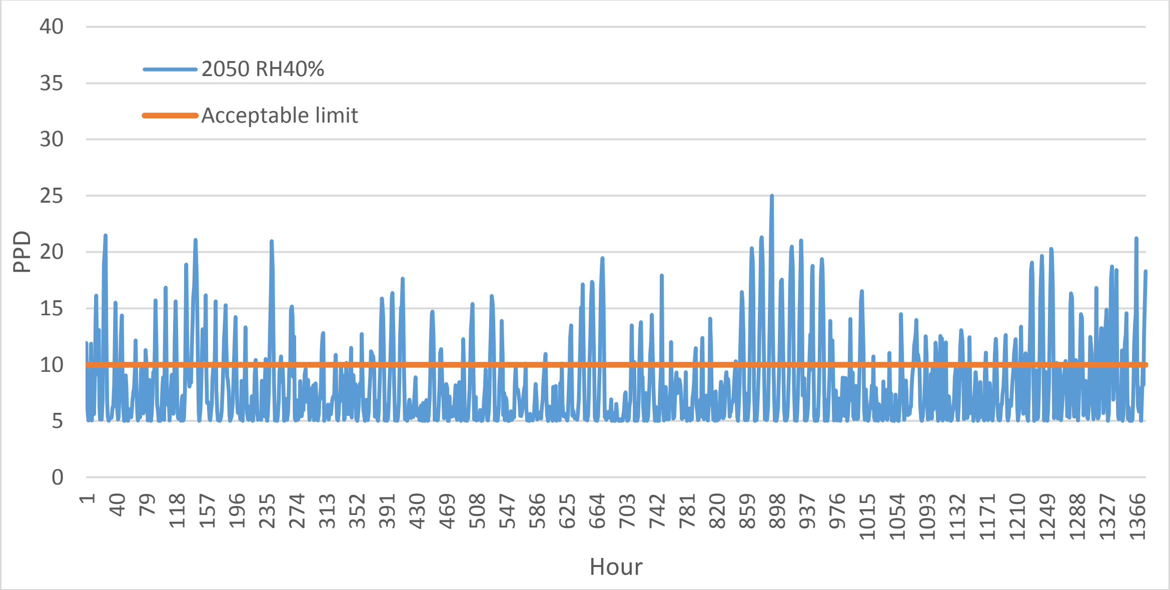
In the simulations, in the results which have been presented so far, there was no control set to the values of relative humidity. Graph 7 shows the simulated relative humidity of the room for the two examined scenarios. It can be observed that in both cases, the relative humidity receives values outside of the 30%-70% accepted range. In order to examine the effect of relative humidity to thermal comfort, a set point of 40% was defined, and a simulation of the thermal performance of the building using the future weather conditions was performed. Graphs 8 and 9 show the PMV and PPD values under the examined future weather conditions when the relative humidity control is applied.



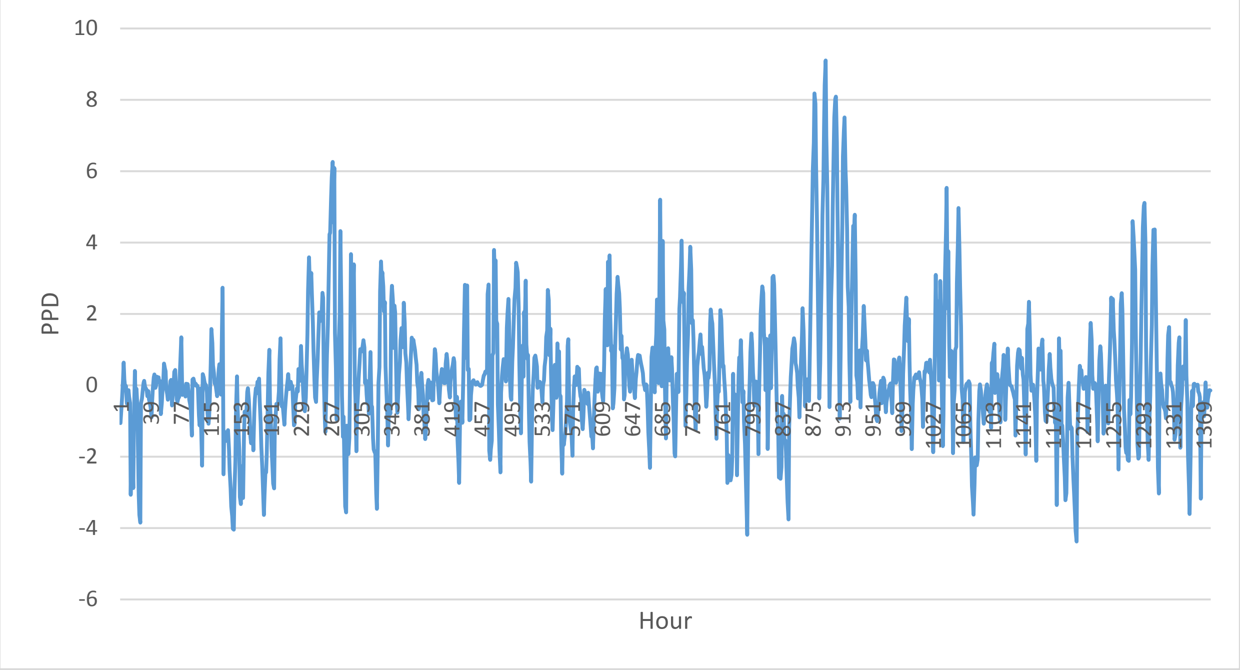
Graph 7 Comparison of the simulates relative humidity between Baseline and future weather



Graph 8 PMV values - Future weather - Relative humidity 40%



Graph 9 PPD values - Future weather - Relative humidity 40%

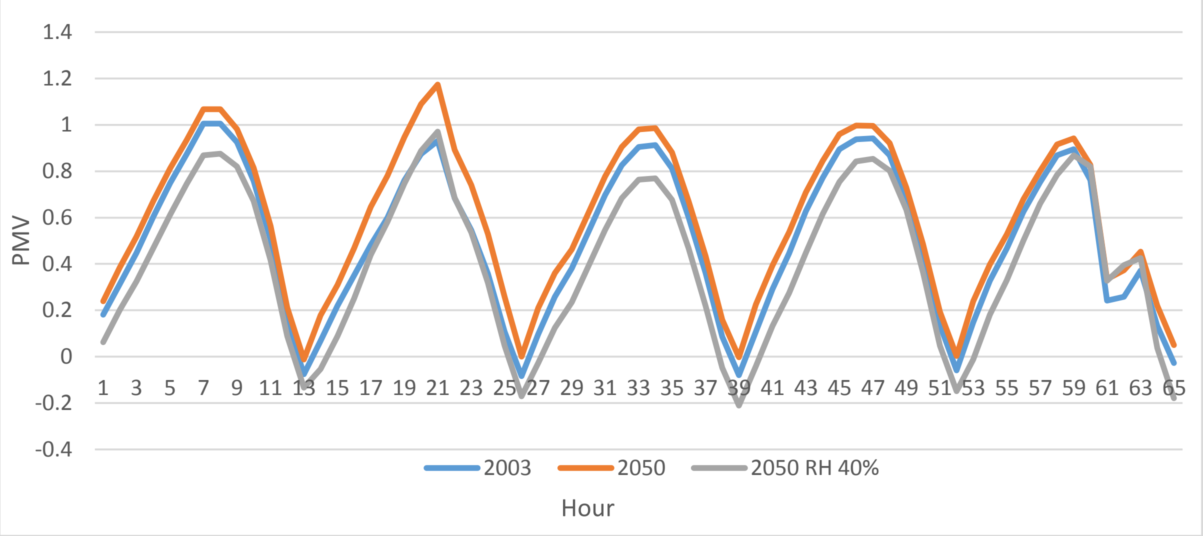


Graph 10 Difference of PPD with and without relative humidity control (Future weather)

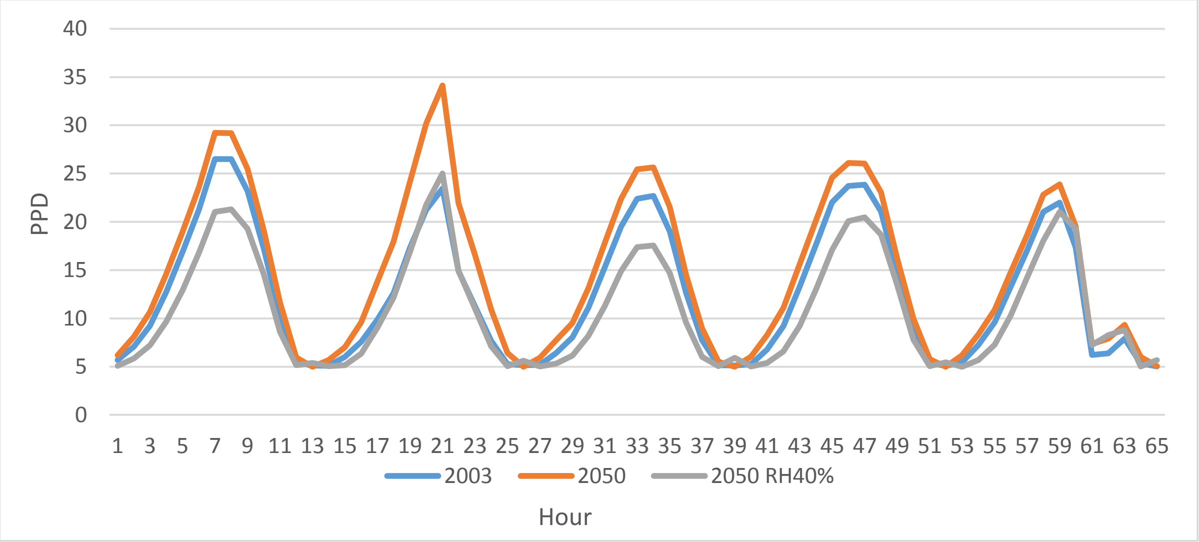
Graph 10 above shows the difference of the percentage of dissatisfied people between the scenarios with no humidity control and with humidity control at 40%. Simulations in both scenarios were performed using the future weather data. Positive values mean that the PPD value for this specific hour is higher in the scenario with no humidity control. Out of the examined 1378 hours, 739 have a better thermal comfort conditions when the relative humidity control is applied, and 639 hours have better thermal comfort conditions when no relative humidity control is applied. Looking further into the results, when the relative humidity control has a positive effect on the thermal comfort, it reduces the PPD by 1.35 on average and presents a maximum hourly decrease of 9.1.

On the other hand, when relative humidity has a negative effect, it increases the PPD by 0.97 on average and presents a maximum hourly increase of at the hour where it has the most negative effect it increases the PPD by 4.37. Also, it is worth noting that during the period of the warm spell, the relative humidity control has its most positive contribution to the thermal comfort. In total, under the examined scenario, 312 hours are above the 10% PPD threshold.

Graph 11 below shows the comparison of the PMV values for the hottest week of the year. As can be observed, when relative humidity is set to 40%, thermal comfort conditions improve to 2003 levels or better during most of the working hours. However, during the hours in the end and the beginning of the day, the 2050s scenario with no relative humidity control will have the best thermal comfort conditions between the three examined scenarios.



Graph 11 Comparison of PMV values during the hottest week of the year - 3 scenarios



Graph 12 Comparison of PPD values during the hottest week of the year - 3 scenarios

5.5 Conclusions

This study aimed to investigate the effect of relative humidity on the thermal comfort of a fully glazed office building in West London under the 2003 weather conditions and the projected weather conditions of the 2050s. The examined period is from May to September.

Study of the thermal comfort shows different results for May and September, where the occupants feel slightly cool in the examined space, and for the summer months, where the occupants feel slightly warm. Results of the thermal comfort under the projected weather conditions show the same pattern as in the baseline; however, thermal comfort is slightly improved during May and September and marginally worsens during the summer months.

Investigation of the effect of relative humidity on thermal comfort has shown that when the relative humidity is set to 40%, 53% of the total occupied hours had a smaller percentage of dissatisfied people. However, if we examine only the summer months, thermal comfort is improved in 68% of the total occupied hours. Effect of the relative humidity control on the PPD can also be seen in Graph 12, where the comparison between the three scenarios is presented.

Chapter 6: Ventilation Techniques to Reduce the Risk of Overheating of a School Building

In the UK, schools house about 10 million pupils who spend about 70% of their time inside a classroom during school days (Bakó-Biró et al., 2012). Thermal comfort conditions significantly affect the health and performance of teachers and students in classrooms. Uncomfortable conditions will not enable teachers to work at their best and children to learn as well as they could (CIBSE, 2015b). Overheating of schools is already a problem in many parts of the country (Ben Smith, 2015).

Schools represent a challenge to building designers, especially in terms of thermal comfort during the summer months due to overheating. Classrooms are densely occupied spaces with high levels of occupancy and increasingly contain large amounts of IT equipment (Firth and Cook, 2010). Apart from the high heat gains due to operating at full or nearly full capacity most of the time with high internal heat gains from equipment, an additional challenge is presented by the intermittent occupancy as pupils move between spaces (CIBSE, 2015b). In addition to that, schools are particularly vulnerable to increased temperatures due to the young age of occupants, and limited opportunities for behavioral adjustments to improve thermal comfort in classrooms (Teli et al., 2017). A further challenge is presented by recent research, which has shown that comfort temperature levels are lower for children than adults (Teli et al., 2017). Thermal comfort field surveys during spring and summer in naturally ventilated classrooms in the UK found this comfort temperature difference to be around 2°C (Teli, Jentsch and James, 2012).

The recorded increase in the global average temperature over the past century has raised concerns about the likelihood of overheating in buildings without mechanical ventilation. In addition to that, heat waves have become more frequent and intense (Teli et al., 2017). Considering the rise of temperature and the increase in the frequency and intensity of extreme weather events shown in the UK Climate Projections (UKCP09) (Defra, 2009b), overheating problems are likely to become more severe in the future.

This chapter discusses the risk of overheating under extreme hot weather conditions of new build naturally ventilated school buildings under the BB101 criteria in 14 different locations in the United Kingdom.

6.1 UK Climate Projections

The UK Climate Projections are the key source of climate change information on which research organizations, regulation, and policy-making bodies, and the insurance industry are basing their responses to changes in our climate.

The Projections provide data for three different (high, medium, low) future scenarios of greenhouse gases. These emission scenarios are based on different pathways showing how a range of factors, such as population, economic growth and energy usage, might change over time. For the next two to three decades, there is little difference between the scenarios in terms of how they will impact global temperatures. After this point the impact of different emissions levels becomes significant, leading to a very wide difference between low and high greenhouse gas emission scenarios by the 2080s (Defra, 2009a).

The UKCP09 show that all locations in the UK will get warmer in the future, more so in the summer than in the winter. In addition to that, extreme weather events will appear with a higher frequency and intensity (Defra, 2009a). Gething, in his report “Design for Future Climate”, presents a series of maps that have been assembled from UKCP09 data to give overviews of the likely range of change across the country and across all three emissions scenarios for a number of the most relevant climate variables (Gething, 2010). Figure 30 below shows the projected summer mean temperature change (◦C) relative to 1the 961-1990 baseline for the three emissions scenarios.

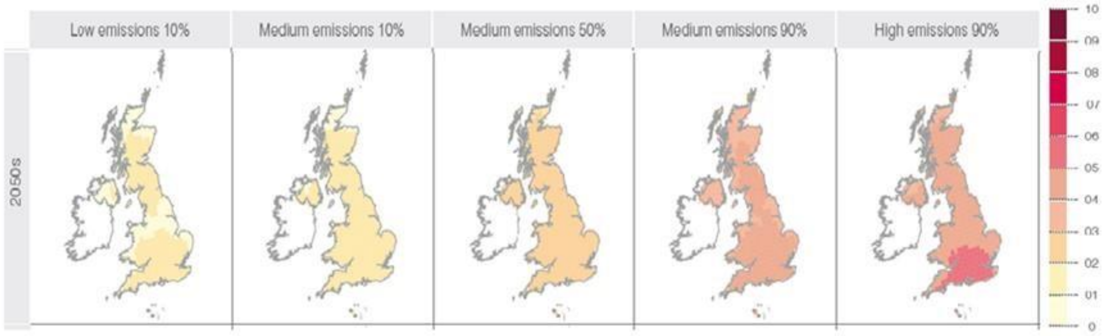


Figure 32 Projected summer mean temperature change (◦C) relative to the 1961-1990 baseline (Gething, 2010)

6.2 Overheating

The thermal conditions inside a building are determined by the interactions between the external climate and the building, the building shell and the internal space and the internal space and the occupants (Teli, Jentsch and Bahaj, 2011). Overheating implies that building occupants feel uncomfortably hot and that this discomfort is caused by the indoor environment (CIBSE, 2013). Thermal discomfort is a sign that the mechanisms that we have in place to remain comfortable are inadequate. So, if a student finds it hard to concentrate during an exam at school because the room is too hot for that particular task, the school building, its services or the building management, have individually or collectively failed in an important task (CIBSE, 2013).

BB101 defines the regulation standards and provides design guidance for ventilation in school buildings. In BB101, the performance standards for summertime overheating in compliance with the Approved document L2 for teaching and learning areas are:
The average internal to external temperature difference should not exceed 5°C (i.e., the internal air temperature should be no more than 5°C above the external air temperature on average).

The internal air temperature when space is occupied should not exceed 32°C.
There should be no more than 120 hours when the air temperature in the classroom rises above 28°C.

In order to show that the proposed school will not suffer overheating, two of these three criteria must be met (BB101, 2006). An overheating analysis was performed for the occupied hours of the building for the period from May to September.

6.3. Methodology

For the purpose of this study, thermal and energy simulations of a school building were performed to identify locations in the UK where naturally ventilated school buildings, with similar construction, were likely to comply with the BB101 overheating criteria. The examined locations were Belfast, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton, and Swindon. Modeling and simulation of the building were performed with the aid of the EDSL TAS software package. Amoako-Attah and Jahromi have provided a detailed description of the modeling process (Amoako-Attah and B-Jahromi, 2015). The DSY weather files by CIBSE were used.

As this study aims to study the risk of overheating under extreme hot weather conditions, the DSY-2 weather files, which represent the most intensive warm spell, were selected. The performance of the building under the projected weather conditions of the 2050s was examined using the high emission scenario (90% percentile change). When examining the performance of the building for London, the London Weather Centre weather file was used.

Initially, the building was modeled as naturally ventilated, and the risk of overheating was investigated for all the examined locations. In the following for the locations where the building failed to comply with the overheating criteria, the building was simulated in mixed mode and as mechanically ventilated, and the amount of cooling loads required to achieve thermal comfort conditions was quantified. Finally, the performance of the building was examined under the projected weather conditions of the 2050s.

6.4 Examined building

The examined building is a one-floor new build school building with a total area of 1343 m^2. The internal space of the building consists of classrooms, interview rooms, offices, WC, kitchen, plant room, and circulation areas. It has seven similarly sized classrooms with an average area of 65.25 m^2. Three classrooms are south facing, and four are north facing. External shading is provided to the south-facing classrooms by polycarbonate roof panels. On the top of the roof, a photovoltaic solar system is installed. All classrooms have the same window formation, as shown in Figure 33. The upper windows have an area of 0.55 m^2, and the middle windows have an area of 1.43 m^2. The bottom part of the formation consists of aluminum panels. Table 13 shows the modeling and simulation parameters of the building fabric used in this study. Figures 31 and 32 show the plan and the 3D model of the building as they were created in EDSL TAS.

Table 13 Building fabric U-values

Construction	U-Value (W/m2K)
External wall	0.25
Partition wall	0.728

Roof	0.164
Windows	1.538
Ground floor	0.21

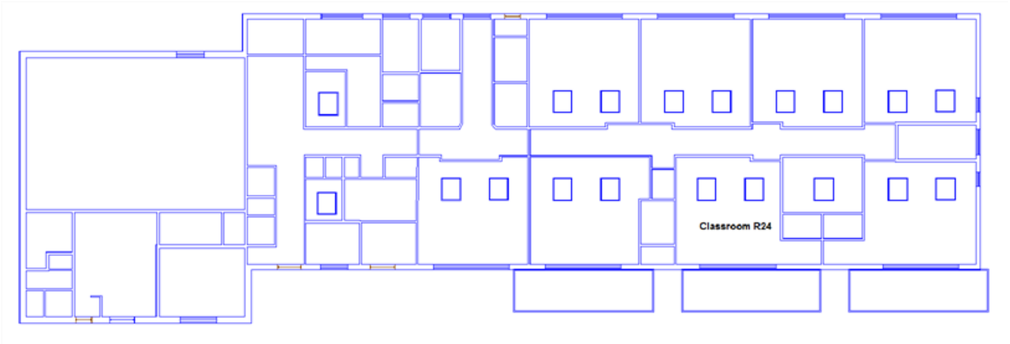


Figure 33 2D model of the building created in EDSL TAS

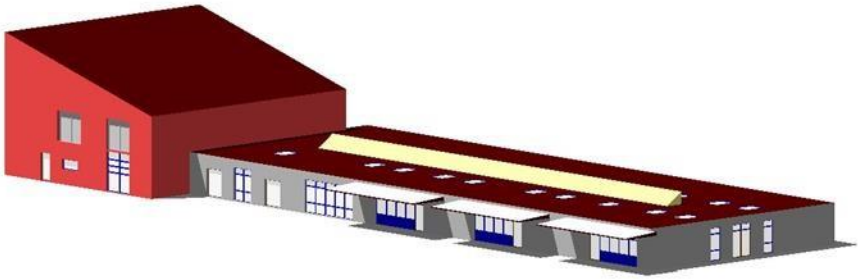


Figure 34 3D model of the building created in EDSL TAS

Figure 35 Window formation of classrooms

6.5 Ventilation modes

Different functions were set to control the ventilation of the building in the examined scenarios. In the mixed mode and mechanical ventilation scenario, mechanical cooling is provided to ensure that the zone's temperature will not go above 28 °C.

For the modeling of natural ventilation, a function was defined to control the opening of the window based on the temperature of the adjacent zone. The aperture was set to begin to open if the dry-bulb temperature in the adjacent zone exceeded 21 °C and it would be fully opened if the dry-bulb temperature reached 23 °C. The openable proportion of the window was set at 30%. This function was applied both to the upper and middle window of the window formation of the classrooms, as shown in Figure 33.

Similarly, to the natural ventilation mode, the function that controls the mixed mode ventilation is controlled by the adjacent zone dry bulb temperature. Opening of the aperture functions as in the natural ventilation mode; however, in this scenario the aperture would begin to close if the temperature in the adjacent zone reached 25 °C to allow mechanical ventilation to be used. Furthermore, if the external temperature exceeded the internal temperature, the aperture would begin to close.

In the mechanical ventilation mode, a minimum ventilation rate was set at 2.0 $l/s/m^2$. This ventilation rate was selected to cover the minimum daily average rate of 5 l/s per person (BB101 2006). Furthermore, additional ventilation could be provided if it was required. The additional ventilation is controlled by the zone's dry bulb temperature. It starts when the temperature in the zone reaches 21 °C and increases proportionally until the temperature reaches 25 °C. At this point, the additional ventilation rate plus the minimum value is applied to the zone. The additional ventilation starts to reduce when the inside and outside temperatures are equal and is completely off when the outside temperature is one full degree above the inside. The additional ventilation rate was set at 1.2 $l/s/m^2$ to ensure the capability of the mechanical ventilation system to provide 8 l/s per person at any occupied time (BB101 2006).

6.6 Results

Results for both the current weather conditions and the projected weather conditions of the 2050s are shown for classroom R24, which is south facing and has a total area of 66.3 m^2. The exact location of classroom R24 in the building plan can be seen in Figure 31. For the scenario where the building is considered to be naturally ventilated each location was examined against the three criteria defined in BB101. Whenever the results of the simulation fail to fulfill one of the criteria, this is presented with the letter (F) next to the value.

When the building is considered to be in mixed mode or mechanically ventilated, mechanical cooling is also provided to keep the temperature at a maximum 28 °C during occupied hours. As a result, in these two scenarios, the building does not overheat for any of the examined locations and weather conditions. For these two scenarios, the required amount of cooling loads to achieve comfort conditions is presented.

6.6.1 Natural ventilation

Table 14 Compliance with BB101 overheating criteria for current weather conditions

Location	Criterion 1 (◦C)	Criterion 2 (◦C)	Criterion 3 (hours)
Belfast	7.21 (F)	36.14 (F)	41.5
Birmingham	6.3 (F)	39.7 (F)	139 (F)
Cardiff	6.5 (F)	36.48 (F)	82
Edinburgh	7.21(F)	30.68	23.5
Glasgow	7.41(F)	31.46	17.5
Leeds	6.61 (F)	35.41 (F)	64
London	6.05 (F)	36.9 (F)	195 (F)
Manchester	7.08 (F)	34.21 (F)	68.5
Newcastle	7.27 (F)	33.13 (F)	32
Norwich	6.11 (F)	35.53 (F)	75
Nottingham	6.67 (F)	35.60 (F)	69
Plymouth	6.50 (F)	33.38 (F)	59.5
Southampton	6.11 (F)	33.20 (F)	104

Swindon	6.11(F)	35.38 (F)	103

As can be observed from Table 14, only Edinburgh and Glasgow fulfill the BB101 criteria under the current weather conditions. In the other twelve examined locations, the classroom overheats. Furthermore, it is worth noting that London and Birmingham are the only two areas in which the air temperature in the classroom rises for more than 120 hours above 28 °C and they also have two of the highest maximum internal air temperatures. Southampton, Plymouth, and Newcastle are all less than 1.5°C above the maximum allowed internal air temperature.

Table 15 Compliance with BB101 overheating criteria future weather conditions

Location	Criterion 1 (◦C)	Criterion 2 (◦C)	Criterion 3 (hours)
Belfast	6.53 (F)	37.60 (F)	74
Birmingham	5.77 (F)	41.54 (F)	208.0 (F)
Cardiff	5.98 (F)	38.43 (F)	159.0 (F)
Edinburgh	6.38 (F)	32.61 (F)	48.5
Glasgow	6.62 (F)	32.91 (F)	48.5
Leeds	6.03 (F)	37.06 (F)	104.5
London	5.64 (F)	41.89 (F)	488 (F)
Manchester	6.41 (F)	35.99 (F)	105
Newcastle	6.57 (F)	34.60 (F)	66
Norwich	5.62 (F)	37.33 (F)	131 (F)
Nottingham	6.03 (F)	37.41 (F)	110.5
Plymouth	5.86 (F)	35.40 (F)	97
Southampton	5.67 (F)	35.38 (F)	196.5 (F)
Swindon	5.68 (F)	37.30 (F)	206.5 (F)

Results of the simulations for the projected weather conditions of the 2050s show that all the examined locations fail the BB101 criteria for overheating. In London, the examined classroom is above 28 °C for 488 hours and in Birmingham for 208. Except for London and Birmingham, Cardiff, Norwich, Southampton, and Swindon also show more than 120 hours above 28 °C. Glasgow and Edinburgh are both less than 1 °C above the maximum allowed internal air temperature.

6.6.2 Mixed mode and mechanical ventilation

Table 16 below shows for both the mixed mode and mechanical ventilation scenario and for all the locations, the required cooling loads to keep the internal temperature of the examined zone below 28 °C under the current weather conditions. These cooling loads are the total loads required for the examined period. It can be observed that for all locations, mixed mode requires less energy compared to mechanical ventilation. The highest amount of cooling loads is required in London and equals to 526.1 kWh for the mixed mode scenario and 598.8 kWh for the mechanical ventilation scenario. The least amount of cooling loads is required in Edinburgh, Glasgow, and Newcastle. The difference between the cooling loads between the two examined scenarios is small. The highest difference is 99.5 kWh and is shown in Belfast.

Table 16 Required amount of cooling loads (kWh) for current weather conditions

Location	Mixed Mode (kWh)	Mechanical Ventilation (kWh)
Belfast	131	230.5
Birmingham	389.1	438.5
Cardiff	202.5	268.3
Edinburgh	49.4	72.1
Glasgow	42.6	69.3
Leeds	153.5	178.6
London	526.1	598.8
Manchester	144.8	168.7
Newcastle	63.3	76.1
Norwich	176.4	214.4
Nottingham	155	180.2
Plymouth	131.1	161.3
Southampton	212.8	278.2
Swindon	261.2	331.7

Table 17 shows the required cooling loads for the mixed mode and mechanical ventilation scenario under the projected weather conditions of the 2050s. Similarly, to the current weather condition scenario, the cooling loads required in the mixed mode scenario are less than the ones required in the mechanical ventilation scenario for all the examined locations. The highest amount of cooling loads is required in London and is 3.31 times higher compared to the current weather conditions. For Edinburgh, a comparison of the cooling loads between the two examined ventilation scenarios shows that the cooling loads are 30% more when the building is modelled with mechanical ventilation.

Table 17 Required amount of cooling loads (kWh) for future weather conditions

Location	Mixed mode (kWh)	Mechanical ventilation (kWh)
Belfast	195.7	230.5
Birmingham	578.1	719.6
Cardiff	438.1	506.4
Edinburgh	125.6	178.0
Glasgow	124.5	165.4
Leeds	273.0	319.4
London	1745.2	1799.8
Manchester	250.7	284.7
Newcastle	127.3	161.3
Norwich	354.3	418.4
Nottingham	283.8	333.3
Plymouth	259.2	315.7
Southampton	530.0	586.9
Swindon	583.4	656.1

6.7 Conclusions

This study examined the risk of overheating for a school building in 14 different locations in the UK using the CIBSE DSY weather data sets. It identified locations in the UK where naturally ventilated school buildings with similar construction are likely to achieve thermal comfort conditions even under extreme hot weather conditions. Furthermore, it examined the performance of the building in mixed mode and as mechanically ventilated, and it quantified the number of cooling loads required in order to comply with the BB101 criteria. Finally, it performed simulations of the building under projected weather conditions of the 2050s and presented a comparison between the current and the future weather conditions.

The results of the simulations show that in most parts of the UK examined in this study, schools with similar characteristics with the one investigated in this case study are likely to have problems passing the overheating standards under both the current and the projected weather conditions of the 2050s. More specifically, under the current weather conditions and when the building is modelled as naturally ventilated, only Edinburgh and Glasgow comply with the overheating criteria. For all the other areas that failed to pass the overheating criteria set in BB101, additional measures should be adopted in order to avoid the risk of overheating. Simulations of the building with the projected weather conditions show that none of the examined areas complies with the overheating criteria in the future.

In both the mixed mode and mechanical ventilation scenario, cooling at 28 °, C was provided in the classroom, and thus the overheating criteria are met in both the current and the projected weather conditions, but with an energy penalty. Schools in the UK have been traditionally designed as naturally ventilated and as such currently spend no or little energy for cooling. Depending on the location of the building, the additional energy needed to cover the cooling loads required to achieve thermal comfort conditions will have a different impact on the total energy consumption of the building. School buildings in the southern regions of the UK are likely to experience more severe overheating problems than the ones in the north, and therefore the amount of energy required to comply with the overheating criteria will be higher. More specifically, in London, where the highest amount of cooling loads is needed, in order to comply with the overheating criteria under the current weather conditions and when the building is considered to have mixed mode ventilation, a total of 7.94 kWh/m^2 for cooling is required and when the building is modeled as mechanically ventilated the required amount of cooling loads is 9.03 kWh/m^2. When examining the future weather conditions, these figures rise to 26.32 kWh/m^2 and 27.15 kWh/m^2 respectively. According to the Good Practice Guide from Carbon Trust, the typical annual consumption of electricity for a primary school in England is 32 kWh/m^2. Cooling loads will need to represent over 25% under the current weather conditions and over 82% under the future weather conditions of the annual electricity consumption to comply with the overheating criteria. Comparison of the required cooling loads both for the current and the projected weather conditions in all the examined locations shows that mixed mode requires less energy to comply with the overheating criteria.

In conclusion, this study has shown that the examined classroom, when simulated as naturally ventilated and under the current weather conditions, complies with the overheating criteria set in BB101 only in Edinburgh and in Glasgow. Classrooms of naturally ventilated school buildings in Edinburgh and Glasgow with a similar design and construction parameters with the one investigated in this case study are more likely not to have overheating problems compared to the rest of the examined locations. In addition to that, this study presented results that show a significant increase in the amount of cooling loads required to achieve thermal comfort conditions. Mixed mode ventilation should be preferred over mechanical ventilation strategy as it results in less energy consumption.

Chapter 7: Effect of Automated Natural Ventilation and Lighting Strategy on the Thermal Comfort for a Residential Building

7.1 Introduction

Recent evidence has shown that the overheating risk needs to be taken seriously in the residential sector (CIBSE, 2017). Domestic overheating has not always been a problem in the UK, but climate change, increased urbanization, construction of high rise apartment blocks and winter energy efficiency measures have all contributed to the amplification of high internal temperatures (CIBSE, 2017). Overheating in homes is recognised as a serious health problem, but it is on a smaller scale to that due to cold dwellings in winter. Although clearly dependent on the summer weather, research has shown that there may be close to 2,000 deaths every year due to heat. However climate change projections suggest the heat related deaths could rise to around 5,000 per year in the 2080s if action is not taken (Department for Communities and Local Government, 2012)

Achieving thermal comfort conditions is essential in order to ensure the well-being and productivity levels of the occupants as homes that overheat cause significant discomfort and stress to the occupants. This study aims to identify how the application of automated control systems in residential buildings affects the thermal comfort conditions and the energy consumption of the examined building. To achieve its aims, it examines a typical detached residential building in the UK, using the weather data sets from the Chartered Institution of Building Services Engineers (CIBSE).

7.2 Literature review

7.2.1 ICT on smart homes

Smart Homes are becoming a reality with information and communication technologies (ICT) being increasingly present in our homes (EPSRC, no date). A Smart Home is a home that is equipped with highly advanced automatic systems such that all lighting, heating, security system, appliances, and electronic devices can be controlled remotely via smartphone, computer or other devices through the internet or local network (Firth *et al.*, 2013). The effective integration of the artificial lighting system and daylight occurs only when the artificial lighting system can be switched on or off as a function of daylighting levels reaching the working surface (Ghisi and Tinker, 2005).

It is clear that the behaviour of the occupants in a building can impact significantly on the temperatures in the home (Department for Communities and Local Government, 2012). However building occupants may lack the time, knowledge, or inclination to create optimally efficient environmental conditions. This is where smart building technology can step in, learning and anticipating user preferences, and altering conditions to meet user needs more precisely and flexibly than we can (Royal Academy of Engineering, 2013).

7.2.3 Occupant behavior

Often, there is a substantial discrepancy between the calculated and the real total energy use in buildings. The reasons for this disparity are generally poorly understood and largely have more to do with the role of human behavior than the building design (Fabi *et al.*, 2011).

It is well documented in the literature that the behavior of the occupants has a significant impact on the performance of the building. Andersen et al. (Andersen *et al.*, 2009) present several studies, where it is shown that similar buildings with different usage by the occupants have resulted in significant differences in energy consumption.

As occupant behaviors are part of the building system, with implications for building energy use (Lee and Malkawi, 2013), it is essential to consider the behavior of the building's occupants during its design phase. Better assumptions regarding the behavior of the occupants will result in better estimates of the building's energy consumption. Implementation of automated control systems in residential buildings could help to reduce the number of assumptions made about the behavior of the occupants during the design phase of building.

7.2.4 Window opening/closing behavior

Several studies have investigated which parameters affect the decision of the occupants of residential buildings to open or close a window. Reasons for opening and closing the windows can be biological, psychological, social, time and physical environment (Polinder *et al.*, 2013) Andersen et al. (Andersen *et al.*, 2009) report that the window opening mechanism is strongly related to the outdoor temperature.

The Department for Communities and Local Government in their report “Investigation into Overheating in Homes” report findings in the literature which show that windows were closed to control temperature and that the act of closing the windows is primarily driven by the need of keeping warm rather than keeping cool (Department for Communities and Local Government, 2012). Andersen. (Andersen *et al.*, 2009) notes that if a window is opened because the occupants feel too warm, it will probably stay open until they start to feel cold. This is also supported by the findings of another study performed by Raja et al. (Raja *et al.*, 2001) where reasons for closed windows are presented. These reasons mentioned by the people who were interviewed are ``others want them shut,'' ``to prevent draught,'' ``to keep the noise level low,'' or ``interference with blind'' (Raja *et al.*, 2001). Lisa Gobio-Lamin presented a literature review on domestic ventilation practices (Gobio-Lamin, 2012). The study discusses window opening behavior for different dwelling types and different rooms. It is stated that the preferred temperature in bedrooms is lower than in the living rooms and that bedroom windows are opened for much longer periods than the windows of other rooms. In addition to that, the findings of the literature review show that some occupants prefer to keep the windows of the main bedroom open during the night, even in cold weather conditions.

7.2.5 Acceptable thermal comfort conditions

The adaptive model described in ASHRAE 55-2010 (55-2010, 2010) was used to investigate the thermal comfort conditions of the occupants during the examined period. This model introduces the prevailing mean outdoor temperature (Tmo). The (Tmo) is calculated as an arithmetic average of the mean outdoor temperatures over no fewer than seven and no more than thirty sequential days before the day in question (Mousli and Semprini, 2001). Two sets of operative temperature limits – one for 80% acceptability and one for 90% acceptability - were defined. For typical applications, the 80% acceptability limits should be used. The 90% of acceptability limits are acceptable when a higher standard of thermal comfort is required.

The acceptable operative temperatures for naturally conditioned spaces are determined using the equations (6) to (9) (55-2010, 2010).

Upper 80% acceptability limit (°C)

$0.31*Tmo + 21.3$ (6)

Upper 90% acceptability limit (°C)

$0.31*Tmo + 20.3$ (7)

Lower 80% acceptability limit (°C)

$0.31*Tmo + 14.3$ (8)

Lower 90% acceptability limit (°C)

$0.31*Tmo + 15.3$ (9)

7.3 Methodology

Thermal simulations of the examined building were performed using EDSL TAS version 9.3.2, a building simulation program developed by Engineering Development Solution Software. TAS is a building modeling and simulation tool capable of performing dynamic thermal simulations of buildings and accurately predicting energy consumption, C02 emissions, operating costs, and occupant comfort (EDSL, 2015b).

The modeling process of a building in EDSL TAS is divided into three parts. The first part is the creation of the 3D model of the building, the second part is the assignment of the various building characteristics, and the third part is the simulation of the building.

Following the input of the model's parameters, the building can be simulated using the TAS Building Simulator. The results of the simulation are shown in the TAS Results Viewer (.tsd).

7.3.1 Description of the building

The examined residential building is a two-floor house with a total area of 333 m^2. On the ground floor, the building's zones consist of a living room, a dining room, a hall area, a kitchen with a utility room, two storage areas, a WC, and the garage. On the first floor, the building has four bedrooms and a bathroom. The building is naturally ventilated.

Table 18 Building fabric U-values

	Construction	U-Value
Building fabric U-Values	External Wall	0.24 W/m^{2}K
	Partition Wall	0.73 W/m^{2}K
	Roof	0.13 W/m^{2}K
	Windows	2.30 W/m^{2}K

The front elevation of the building model as it was created in EDSL TAS is shown in Figure 34.

Figure 36 Front elevation of the building

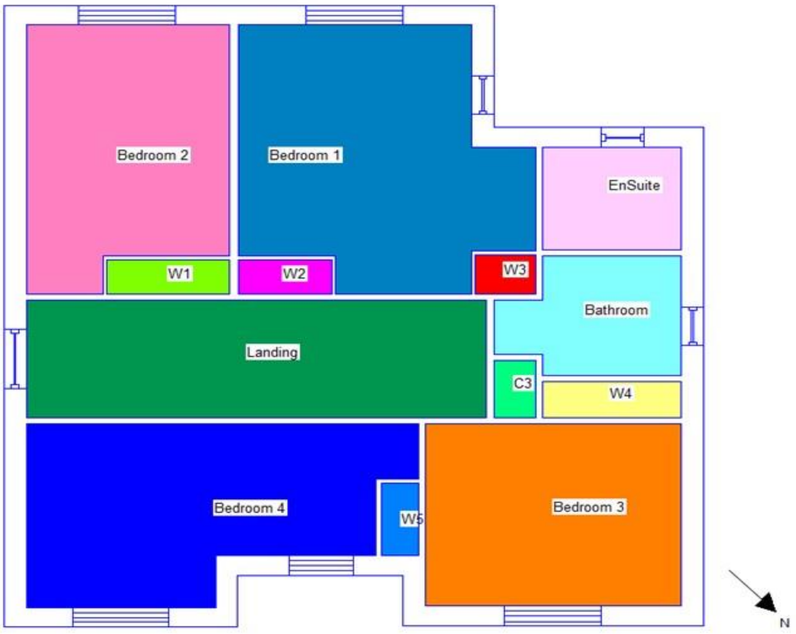


Figure 37 Zoning of the first floor

7.3.2 Examined scenarios

In order to investigate the effect of automated controls on the thermal comfort conditions and energy consumption, two scenarios were investigated. The first scenario represents a manual operation of the windows and the light, and the second scenario represents an automated operation.

The examined period is the week of the year, which includes the day with the highest external temperature. The day with the highest external temperature is the 222nd day of the year, so this study examined the week commencing on the 218th day of the year and ending on the 224th day of the year.

This chapter presents the results for Bedroom 2, which is south facing and Bedroom 3, which is north facing. The bedrooms are considered to be occupied 24 hours a day. Based on the findings of the literature review, the windows of the bedroom were considered fully opened at all times for the manual control scenario.

The findings of the literature review suggest that switching on the light in the early morning often means that it stays on throughout the day. The manual control of the lights is based on a similar norm. The occupants will turn the lights of each zone on when the illuminance levels are lower than the target illuminance, and they will leave them on until the end of the day. The start of the day is modeled to be at 06:00 and the end of the day at 22:00.

The automated opening and closing of the windows are controlled by a function. This function simulates natural ventilation with an external temperature cut-off. The aperture is modeled to begin to open when the resultant temperature in the adjacent zone exceeds 21°C and to be fully open when the resultant temperature reaches 23°C. If the external temperature exceeds the internal temperature, the aperture will begin to close. In order to examine the effect of automated control on the lighting loads, a function that controls the lighting of the zones of the building was modelled. This function models a photocell control of the lighting. Acceptable illuminance levels are maintained at all hours during the occupancy schedule. Target illuminance was set at 100lux. As illuminance increases, lighting gain will decrease. When examining the automated lighting control, a parasitic power of 0.57 W/m^2 is added to the total lighting gain. This is the amount of energy used by the photocell sensor.

7.4 Results and discussion

7.4.1 Thermal comfort

Figures 36 and 37 presented below show the operative temperature of bedrooms 2 and 3, respectively. The operative temperature of the manual control scenario is shown by the blue line, and operative temperature of the automated control scenario is shown by the green line. The vertical axis shows the temperature in (°C), and the horizontal axis represents the time. The purple horizontal lines show the 80% acceptability limit, and the yellow lines represent the 90% acceptability limit. The acceptability limits for each day were calculated by the mean outdoor temperature of the previous seven days.

As can be observed from the graphs, the more significant differences in operative temperature between the two scenarios occur during the daytime. This is due to the fact that in the automated control scenario, the windows close when the external temperature is higher than the internal temperature. As a result, lower operative temperatures are achieved, and thermal comfort conditions are improved.

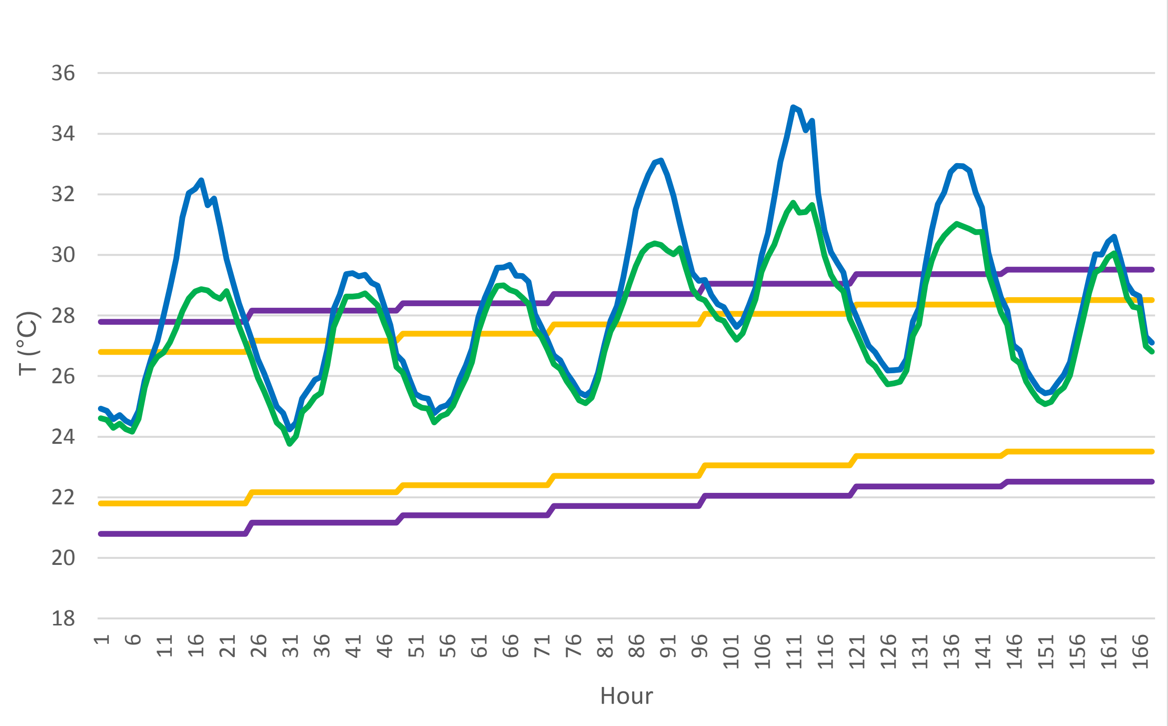


Figure 38 Comparison of operative temperatures (bedroom 2)

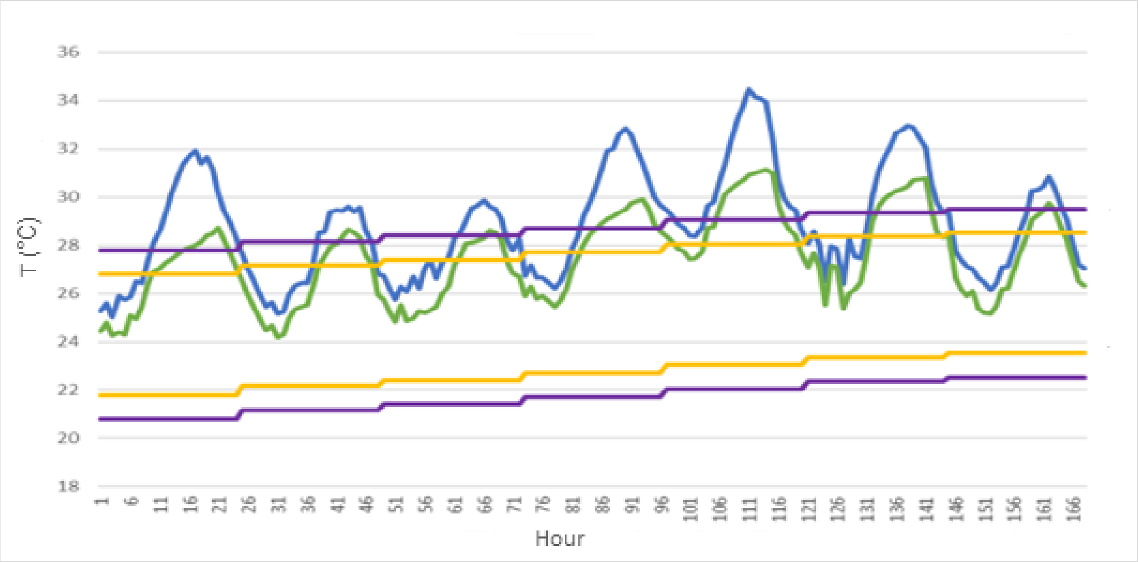


Figure 39 Comparison of operative temperatures (bedroom 3)

7.4.2 Lights

The results presented in Figure 38 below show the lighting gains for the two scenarios during the examined period. The blue bars represent the lighting gains for the manual control scenario and the yellow bars for automated control. A reduction of the lighting gains by 49% is recorded for both bedrooms.

Illuminance levels were investigated hourly, and the target illuminance was 100lux. At the start of the day, at 06:00, the illuminance levels were below 100lux, and lighting was provided in order to reach the target illuminance. When examining the manual control scenario, the lights remained on until the end of the day at 22:00 On the other hand when examining the automated control scenario; the lights were off all the hours that the target illuminance was achieved through daylight. In the automated control scenario, artificial lighting was required again at 19:00 in order to reach the target illuminance.

Application of automated systems can result in more energy efficient buildings and more comfortable conditions for the occupants. Furthermore, automated control systems could help to make more accurate estimations about the behavior of the occupants and thus to reduce the gap between the simulated and the actual performance of the building.

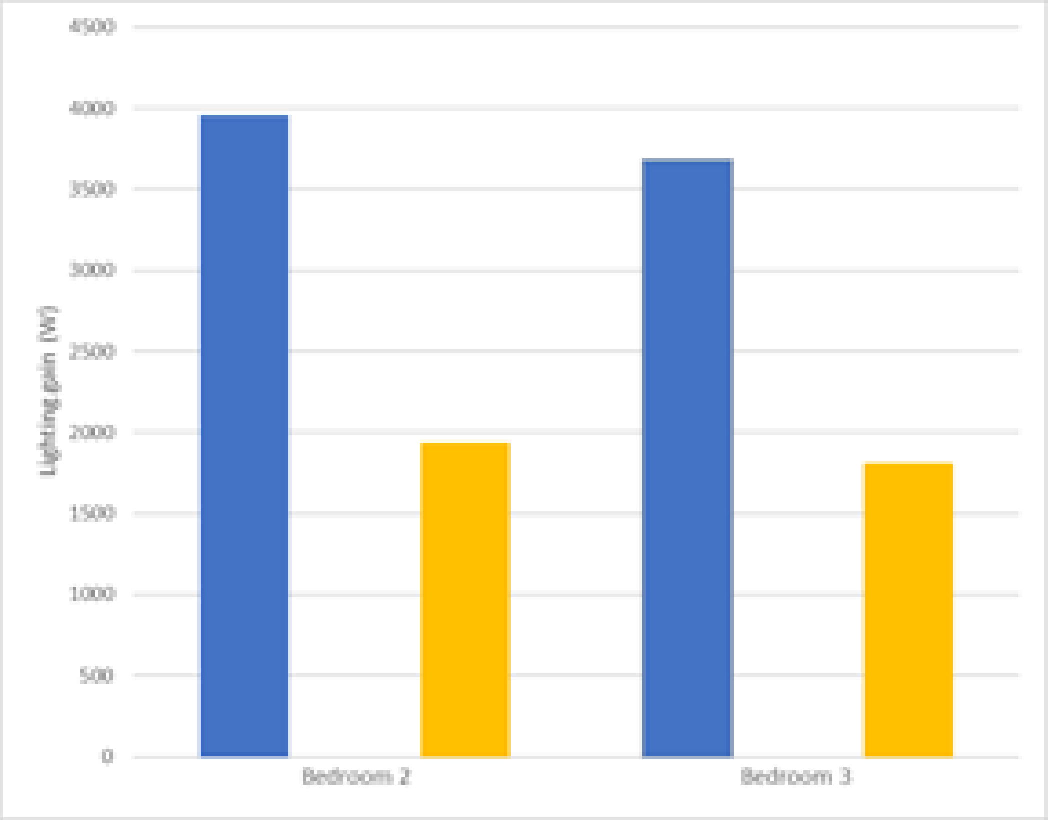


Figure 40 Lighting gains (W)

Chapter 8: Effect of Building Development on the Risk of Flooding

8.1 Introduction

There is an increasing body of evidence that extreme daily rainfall rates are becoming more intense. The two-month period of December 2013 and January 2014 was for England and Wales one of, if not the most, exceptional periods of winter rainfall in at least 248 years. The Met Office. In their report "The Recent Storms and Floods in the UK," provides detailed information about the severe winter storms throughout December, January and February 2013/14, which resulted in serious flooding across southern England (Met Office and Center for Ecology and Hydrology, 2014). In addition to that, we also need to account for the effect of climate change.

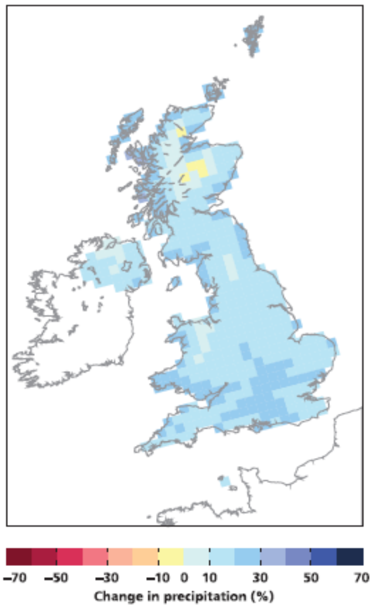


Figure 41 Central estimate of % change in winter precipitation from the 1961-90 baseline across 25hm quares (2080s for the medium emissions scenario) (UKCP09)

This is the key source of climate change information on which research organizations, regulation, and policy-making bodies, and the insurance industry are basing their responses to changes in the climate (CIBSE, 2014b). According to the UKCP09, we can expect warmer and wetter winters, hotter and drier summers, rising sea level, and more extreme weather events. These extreme weather events in the UK are likely to increase with rising temperatures, causing among other things, heavier rainfall events. As can be observed from Figure 39, which shows the central estimate of the percentage change in winter precipitation from the 1961-1990 baseline compared to the projected winter precipitation of the 2080s under the medium emission scenario, the amount of rainfall is very likely to increase in almost all areas of the UK. The highest increase (20-29%) is shown in the south of England. Increased winter precipitation is also likely to increase the risk of flooding.

There are several factors that contribute to the flood risk of a specific area. Flooding problems resulting from runoff of surface water generally increase as areas become more urbanized (James M. Wright, 2007), (Jha, Bloch and Lamond, 2013). Increased intensity of development in urban areas has given rise to land with a larger proportion of non-permeable surfaces (RIBA, 2009). In the UK, there is a continuous need for new housing.

The UK government has set a goal of 1,000,000 new homes by 2020 in order to cover the country’s housing needs. However, there are other studies that suggest that this will not be enough and that the aim should be to build 300,000 new home each year (Select Committee on Economic Affairs, 2016).

Therefore, it is important to investigate the effect of building development on the risk of flooding. Taking into account the projected increase in winter precipitation, this study examines an area that is currently completely undeveloped under extreme rainfall conditions and looks into the effect that building development has on the risk of flooding.

8.2 Surface water flooding

Surface water flooding occurs when the amount of rainwater exceeds the capacity of the drainage system and cannot be soaked up by the ground. Unlike flooding from rivers, surface water flooding can happen many miles from a river, often in places that people would not expect because it is a long way from a river or stream. Surface water flooding is influenced by features in the landscape, particularly buildings and roads and is caused by rainwater run-off from urban and rural land with low absorbency (RIBA, 2009). Furthermore, surface water flooding is difficult to predict and pinpoint, much more so than river or coastal flooding (Environmental Agency, 2009).

8.3 Effect of building development

The effect of urbanization on flood risk has been explored before by various studies (Nirupama and Simonovic, 2007), (Suriya and Mudgal, 2012).

The effect of development is generally to reduce the permeability of at least part of the site. This markedly changes the site’s response to rainfall. Without specific measures, the volume of water that runs off the site and the peak run-off flow rate is likely to increase. Inadequate surface water drainage arrangements in new developments can threaten the development itself and increase the risk of flooding to others (Communities and Local Government, 2010). Urbanization in flood plain areas increases the risk of flooding due to increased peak discharge and volume and decreased time to peak (Suriya and Mudgal, 2012).

8.4 Examined area

The examined area, as shown in Figure 40 (marked in red), is located in the suburbs of Askett town in the United Kingdom. The examined area was selected because it is very likely that significant building development will occur in the near future. At the moment, there are only 23 dwellings located on its south side. It is a greenfield with a total area of 114.2 hectares and four asphalt roads on its sides define its borders. The lowest elevation of the area is at 101 m and the highest at 120 m. The average slope is 1%. The soil in the examined area is loamy and some clayey with slightly impeded drainage. Clayey soils have few sand grains but a lot of extremely small particles, while loamy soils have a mix of sand, silt, and clay-sized particles and are intermediate in character. Slightly impeded drainage is a result of the compact deep subsoil that impedes downward water movement; after heavy rainfall, especially during the winter, the subsoil becomes waterlogged. In soils with impeded drainage, the effect is more severe and winter waterlogging results in very wet ground conditions (National Soil Resources Institute, 2016). The risk of flooding in the examined area is very low. Each year this area has a chance of flooding from surface water of less than 0.1% (Gov.uk, 2016).

Figure 42 Examined area

8.5 Modelling process

The modeling and simulation of the extreme rainfall event for the examined area were performed using the XP SWMM software package.

8.5.1 DTM

The digital terrain model (DTM) is a statistical representation of the continuous surface of the ground by a large number of selected points with known X, Y, and Z coordinates in an arbitrary coordinate field (Gold, 2005). Digital Terrain Models are a significant constituent of geographical information processing, and they help to model, analyze, and display phenomena related to topography or similar surfaces (Longley *et al.*, 1991). Topographical information of the examined area was imported into the software with the creation of a Digital Terrain Model. In order for the software to create the DTM, the coordinates and elevations of the area were loaded in the form of an XYZ file. A photo of the examined area was also loaded in the software and was applied to the same extent as the DTM.

8.5.2 Rainfall

As discussed above, each year, the examined area has a chance of flooding from surface water of less than 0.1%. For the purpose of this study, a rainfall event that has a duration of 240 minutes and a return period of 1000 years was applied to the model, in order to examine the effect of building development on the risk of flooding under extreme rainfall.

In order to create a rainfall event the storm generator of the XP SWMM software was used. The storm was created using the UK Storm Flood Studies Report (FSR) method. The required input for the generation of the storm are the M5-60 in mm, the dimensionless ratio R, the storm duration, the profile, the region of the storm and the return period. The M5-60 is defined as the amount of rainfall of an event with a return period of 5 years and duration of 60 minutes. The ratio R is calculated by dividing the M5-60 minutes value by the M5-2days value (The office of public works, 2012). The values of the M5-60 and R were identified using the Greenfield Runoff Estimation for Sites tool. The M5-60 value was set at 20 mm and the ratio R at 0.4. The duration of the storm was selected to be 240 minutes

(4 hours). Profile of the storm was set to winter and the region of England was selected. Finally the return period was set to 1000 years. Figure 41 below shows the intensity over time of the generated rainfall event.

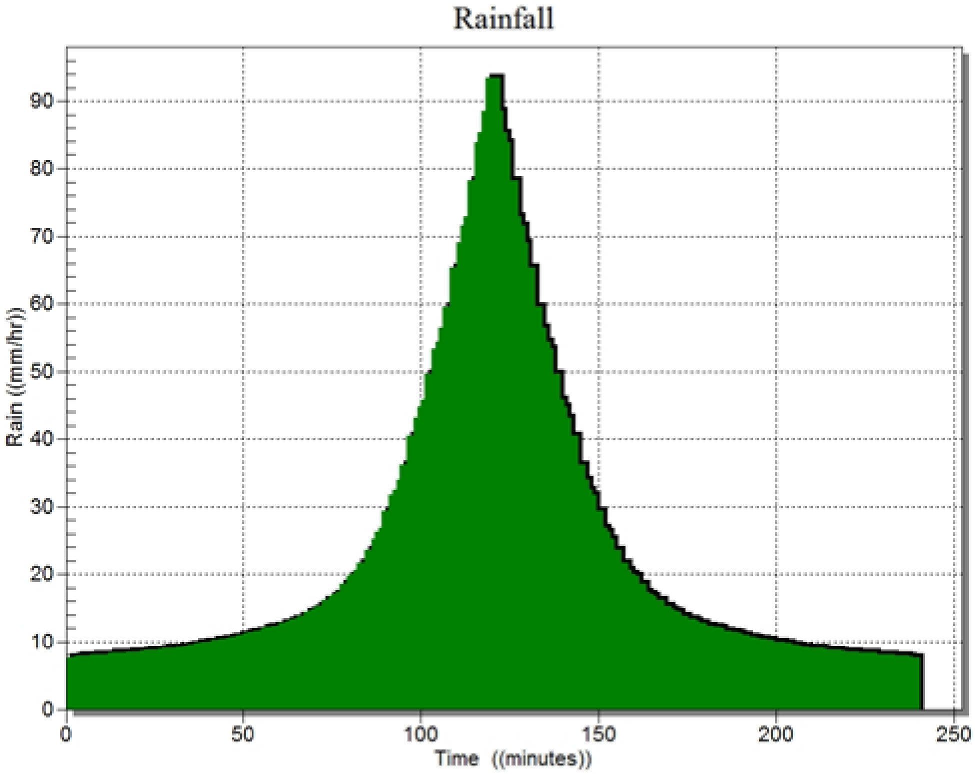


Figure 43Modeled rainfall event

8.5.3 Land uses

For the examined area, two different land uses have been modelled; one represents the greenfield area and the second one the asphalt roads on the boundaries of the area. The advantage of creating and applying different land uses to the model is that different Manning value and infiltration rates can be assigned to each land use. The Manning value applied to the greenfield area was 0.03, and to the road area, it was 0.016 (ODOT, 2014).

8.5.4 Infiltration

Infiltration is defined as the movement of the water from the soil surface into the soil. The uniform loss method was used to model the infiltration. This method allows for simulation infiltration as an initial amount, followed by a constant rate. The initial loss specifies the depth of rainfall that infiltrates before runoff occurs. The continuing loss occurs after the initial loss has been satisfied (*XP Solutions,* 2016). In this model, the initial loss was defined at 10 mm and the continuing loss at 2 mm.

The depression storage and the Manning's ''n'' value also needed to be specified both for the pervious and the impervious area of the model. Furthermore, for the impervious area, the zero-detention percentage needed to be identified.

Depression storage is the ability of a particular area of land to retain water in its pits and depressions and prevent it from flowing. Water stored as depression storage in impervious areas is depleted by evaporation. Depression storage for the impervious area is calculated by the following equation:

$$D_p = 0.0303 \times S \wedge -0.49 (\text{Correlation coefficient} 0.85) \qquad (10)$$

Where:
D_p = depression storage (inches)
S = catchment slope (%)

Water stored as depression storage in pervious areas is subject to both infiltration and evaporation. This parameter is best represented as an interception loss, based on the type of surface vegetation. For grassed urban surfaces, a value of 0.10 in. Is typical (*XP Solutions,* 2016).

The zero-detention percentage refers to the percentage of the sub-catchment impervious area with zero-depression storage (immediate runoff). The zero-detention percentage for the examined area was set at 20%.

Manning's ''n'' values were specified as discussed in the Land uses the section above.

8.5.5 Modelling of the buildings

Buildings were specified in the model as Fill Areas. This means that water can penetrate the building when it reaches above a defined Fill Level. The Fill Level for the buildings in this model was set at 0.30 m above the building's ground elevation.

8.6 Examined scenarios

The area was initially simulated as it is, with only the existing building development. This includes 23 dwellings, as shown in the bottom part of Figure 42 and the asphalt roads that are the boundaries of the examined area. In the following, a second scenario that represents the area as it is likely to be after the completion of the development works was modeled and simulated. In the second scenario, 123 new properties were modeled and also eight new asphalt road was added to connect them with the existing road network. Figures 42 and 43 below show the site as it was simulated in the two scenarios.

Figure 44 Scenario 1 - Current condition

Figure 45 Scenario 2 - Completed building development

8.7 Results and discussion

Comparison of the max water depth and hazard maps of the two scenarios.

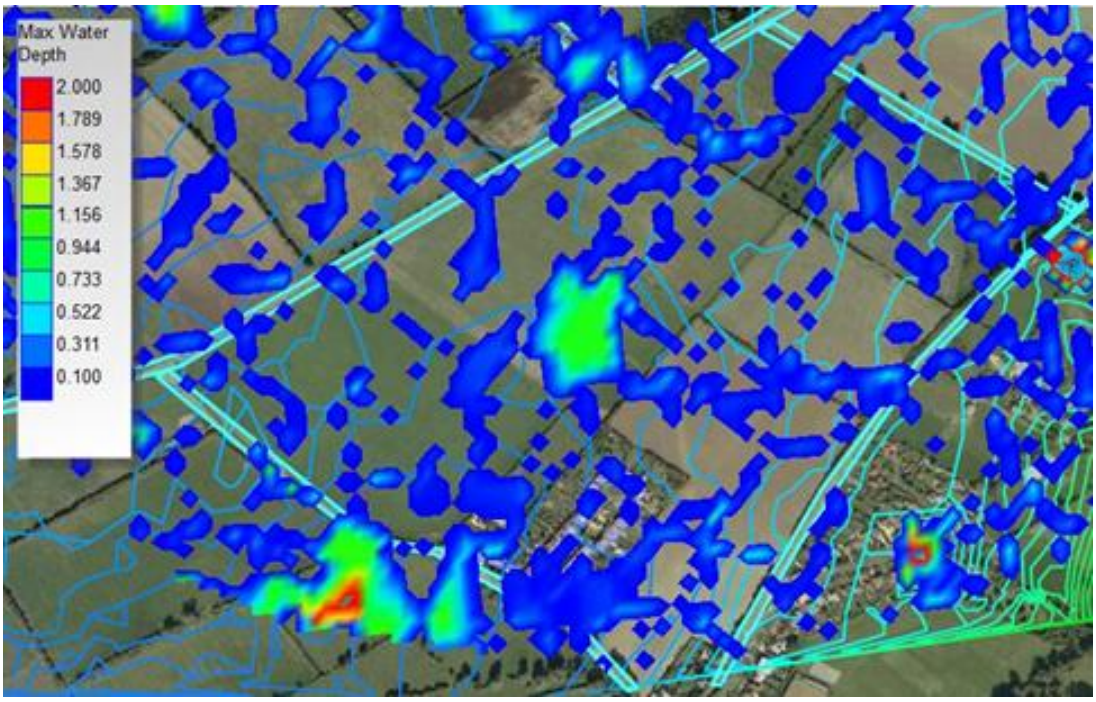


Figure 46 Max water depth under current building development

Figure 44 shows the maximum water depth of the examined area under the current building development. The maximum water depth is shown almost in the middle of the area and is at 1.05 meters. This due to the topography of the area that creates a pond in that spot, which fills with rainwater. Apart from that, it can be seen that there is a significant part of the area where the water depth is at 0 meters. For almost all the other areas the maximum water depth is below 0.30 m, with the exception being a few spots, mainly in the bottom right and top left part of the area, with a maximum depth of around 0.60 m. Also, the topography of the area forms another two ponds just outside of the limits of the examined field.

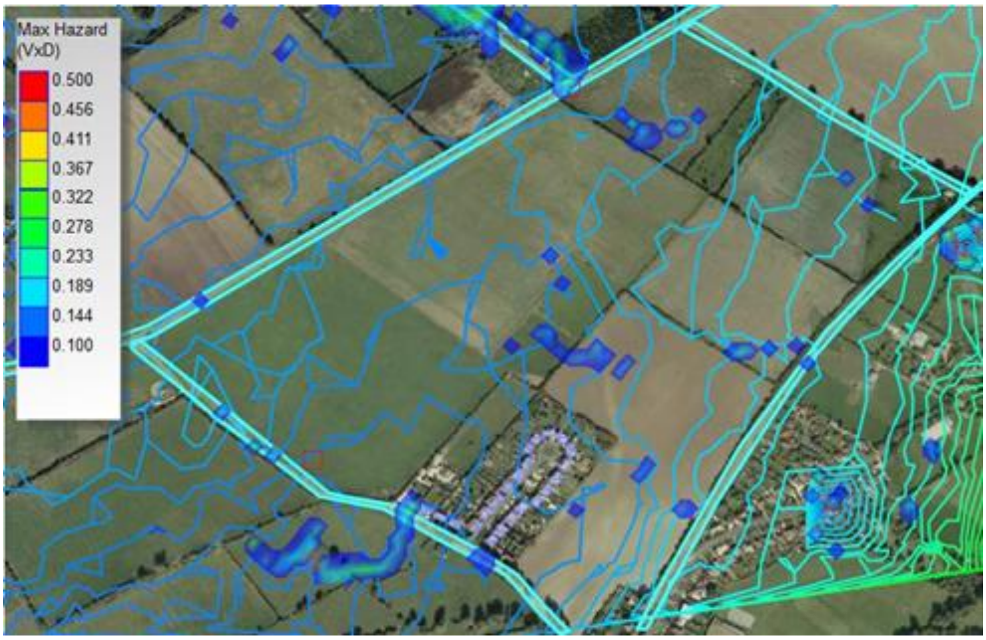


Figure 47 Max Hazard (VxD) under current building development

Figure 45 shows the maximum hazard (VxD) under the current building's development. As can be seen, almost the entire area has zero hazards. The areas where the hazard appears are the areas with the maximum depth described above. As discussed in section 8.4, where the examined area is analyzed, this area has only a 0.1% chance of flooding from surface water. The results of the simulation validate this, as the area shows almost zero hazards even under an extreme rainfall event with a return period of 1000 years.

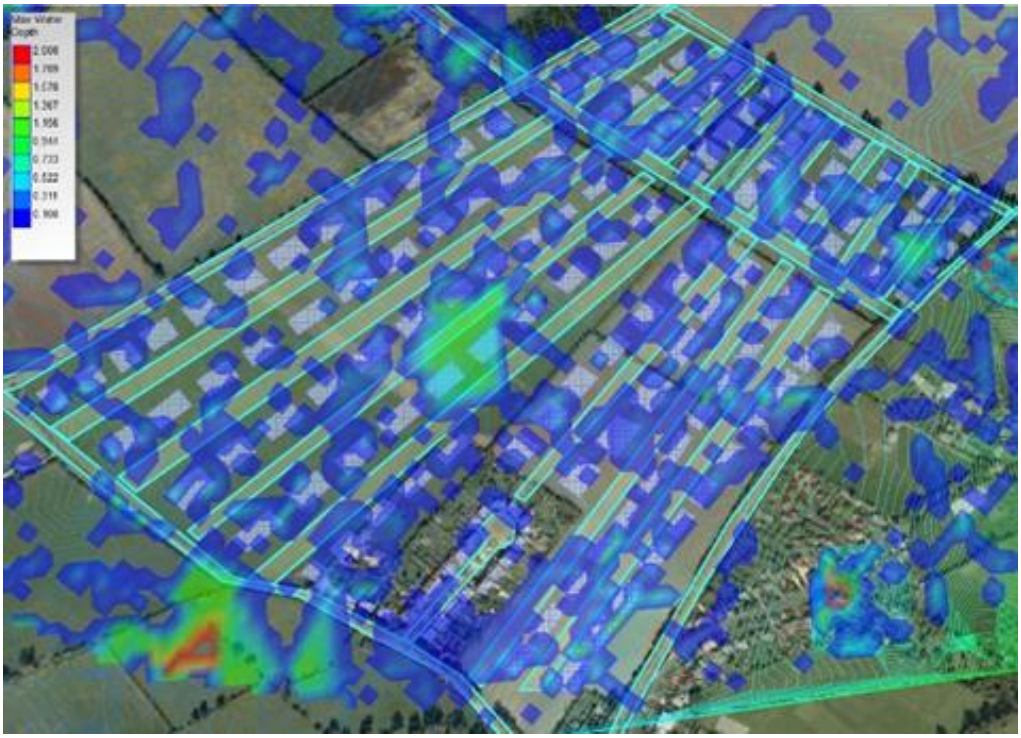


Figure 48 Max water depth after completion of building development

Figure 46 shows the maximum water depth in the examined area after the completion of the building development. The maximum water depth is in the middle of the field, where the pond is located, at 1.05 meters, which as expected is the same as in the first scenario. In addition to that, there is another spot with a maximum depth of 0.80 meters on the top right of the field. As it can be observed, the water covers the area of the modeled buildings. This is due to the fact that the buildings have been modelled as fill areas, with a fill height of 0.30 meters. For the buildings that are covered with water, water depth has exceeded the fill height and has penetrated inside the building. It is worth mentioning that all of the 123 buildings modeled in the second scenario are covered with water. Furthermore, there are various spots on the asphalt roads that show water depths from 0.10 to 0.80 meters.

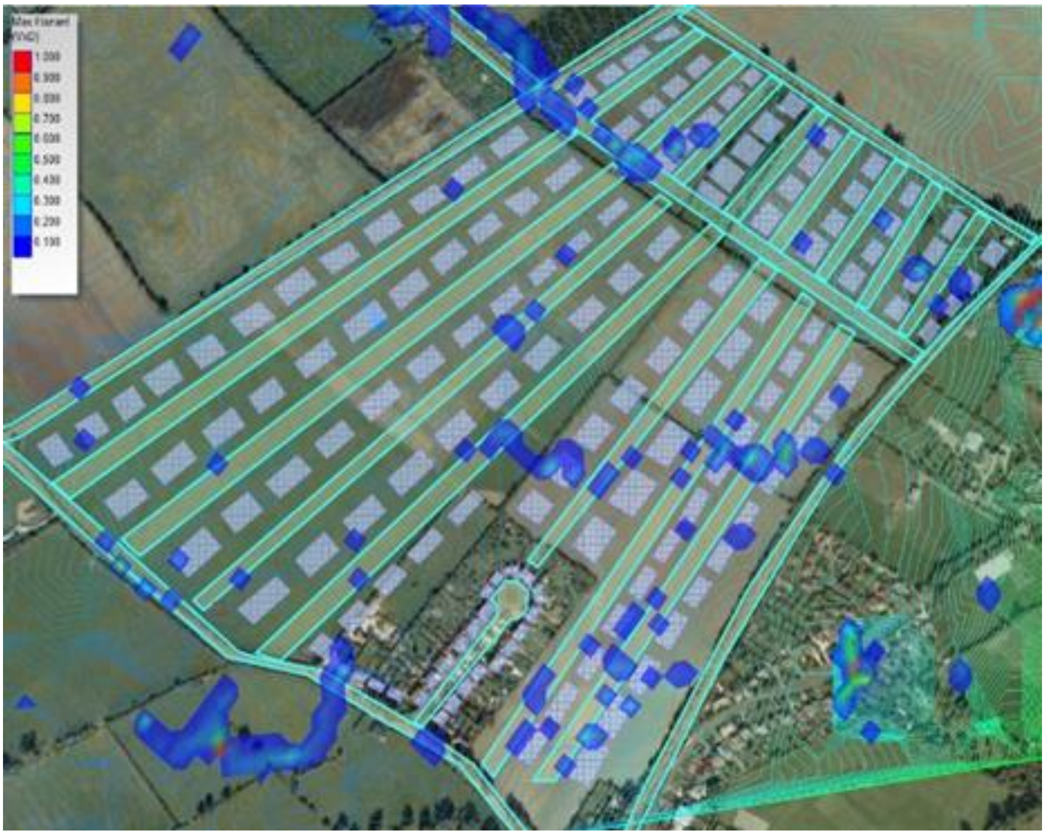


Figure 49 Max Hazard (VxD) after completion of building development

Figure 47 shows the max hazard of the examined building for the second scenario. Similar to the first investigated scenario, there is an extended area of the field with zero hazards. However, the areas with a max hazard above zero have increased compared to the case with no building development. The maximum hazard for this scenario is 0.63 and is located on the bottom left of the field, on the asphalt road, exactly on the borders of the examined field.

The modeling of the buildings as fill areas has significantly affected the result of the hazard map. Allowing the water to enter the building when it exceeded the height 0.3 meters has normalized the water depth across the field.

Chapter 9. The Effects of Sustainable Drainage Systems on Residential Developments During Extreme Rainfall

9.1 Introduction

Flooding is identified as the most significant risk, currently and in the short term, across the UK (Defra, 2012). There is an increasing body of evidence that extreme daily rainfall rates are becoming more intense (Met Office and Center for Ecology and Hydrology, 2014). In June–July 2007, severe rainfall during an extremely wet summer led to the flooding of 48,000 households and 7,300 businesses across England (The UK Cabinet Office, 2015). Throughout December, January and February 2013/14, the UK was affected by an exceptional run of severe winter storms, culminating in coastal damage and widespread flooding from January onwards (Met Office and Center for Ecology and Hydrology, 2014). Consequences of flooding may include the loss of human lives, damage to property and infrastructure, loss or interruption to the supply of essential goods and services, disruption to transport and energy networks and depending on the nature of the incident, contamination and environmental damage (The UK Cabinet Office, 2015).

Evidence that extreme rainfall intensity is increasing on a global scale has strengthened considerably in recent years. Research now indicates that the most significant increases are likely to occur in short-duration storms lasting less than a day, potentially leading to an increase in the magnitude and frequency of flash floods. Furthermore, several observation-based analyses have indicated that sub-daily extreme rainfall is intensifying more rapidly than daily rainfall (Westra et al., 2014). In the UK, the National Flood Resilience Report published by the Government in 2015, states that when we want to assess what extreme flooding looks like, we typically model the effects of a scenario with a nominal 0.1% chance of occurring in a year at any given location, using local detailed models (HM Government, 2016). Therefore, for the purpose of this study, the extreme rainfall events were modeled with a return period of 1000 years.

The UK Climate Projections are the key source of climate change information on which research organizations, regulation, and policy-making bodies, and the insurance industry are basing their responses to changes in the UK's climate. According to the UK Climate

Projections (UKCP09) published in June 2009, we can expect to have warmer and wetter winters, hotter and drier summers, rising sea levels and more extreme weather events (Gething, 2010). Increased precipitation is also likely to increase the risk of flooding.

In addition to that, the risk of flooding is intensified by the heightened need for new housing and the increasing urbanization. Higher densities of development reduce the amount of natural soak-away available and strain the existing drainage infrastructure (RIBA, 2009). The housing supply has increased in the UK by over 1.1 million since 2010 (Mun and Han, 2011). In the Autumn Budget 2017, the government announced a new policy which will raise the housing supply to its highest levels since 1970 with the aim of providing 300,000 houses per year (Mun and Han, 2011). Research shows that if we do not change the way we design our urban areas and manage surface water runoff more effectively, flood-related problems are going to get worse (CIRIA, 2015).

Sustainable drainage systems are an alternative approach to the design of drainage with the design objectives of controlling the quantity of runoff to support the management of flood risk and protect the natural water cycle, to manage the quality of runoff to prevent pollution, to create and sustain better places for people and to create and sustain better places for nature (CIRIA, 2015). They are designed to maximize the opportunities and benefits we can secure from surface water management and deliver high-quality drainage while supporting urban areas to cope with severe rainfall both now and in the future (CIRIA, 2015). Examples of SuDS are rainwater harvesting systems, green roofs, pervious pavements, bioretention systems, trees, swales, detention basins, soakaways, and infiltration basins (CIRIA, 2015). This chapter looks into the effect of rainwater harvesting, pervious pavements, and infiltration basins on the risk of flooding for a new build residential development in the south west of England.

Rainwater harvesting is the gathering of rainwater runoff for use. Runoff can be collected from roofs and other impermeable areas, stored, treated (when required) and then used as a supply of water for domestic, commercial, industrial and/or institutional properties (CIRIA, 2015). Rainwater harvesting systems involve three principal components: the catchment area, the collection device and the conveyance system and because of their simplicity, they can be expanded, reconfigured or relocated to meet each household’s needs (Liuzzo, Notaro and Freni, 2016). On average, every person in England and Wales uses around 150 litres of water per day (Environment Agency, 2003). The application of rainwater harvesting systems could help to capture runoff at the source as well as reduce the demand on mains water.

Pervious pavements provide a pavement suitable for pedestrian and/or vehicular traffic while allowing rainwater to infiltrate though the surface and into the underlying structural layers. The water is temporarily stored beneath the overlying surface before use, infiltration through the ground or as controlled discharge downstream (CIRIA, 2015). Permeable paving, as discussed by Hubert, Edwards, and Jahromi (Hubert, Edwards and Jahromi, 2013), uses conventional materials such as concrete or asphalt that are modified to allow the passing of flow in footpaths and larger structures such as car parks. Using this kind of sustainable drainage would significantly reduce the requirements of the local drainage systems to deal with runoff flows, while also providing “safe” locations for potential flooding that would not harm properties. Furthermore, permeable pavement systems have not only been established as a SuDS solution but also as a technology for pollutant control concerning surface runoff from areas used as roads or parking spaces, where contaminated water may infiltrate into the underlying soil (Scholz and Grabowiecki, 2007).

Infiltration basins are flat-bottomed, shallow landscape depressions that store runoff before infiltration into the subsurface soils. They are typically grassed structures, but some additional vegetation can enhance the appearance of the basin, stabilize side slopes, and prevent erosion and serve as wildlife habitat (CIRIA, 2015). Also, they are typically designed to half empty within 24 hours and can be served by either underground pipe networks that discharge into the basin, or a series of trenches and drains that lead to the basin. The use of trenches provides the added benefit of treating runoff to remove pollutants before reaching the basin.

This study examined a new build residential development located in the south west of England using the MicroDrainage software package and aims to identify the effect of three different types of SuDS (rainwater harvesting, permeable paving, and attenuations basins) on the risk of flooding under extreme rainfall events. The development is subjected to a rainfall event with a return period of 1000 year, and various storm durations were examined.

9.2 Materials and methods

9.2.1 Modelling of the examined area using MicroDrainage

The modeling of the case study was performed using the MicroDrainage software package. MicroDrainage, an Innovyze software package, is considered as the UK drainage and flood systems’ industry standard product (Hubert, Edwards and Jahromi, 2013).
Initially, the examined area was divided into individual subcatchments, each draining to a node within that area, and the areas of different impermeable and permeable surfaces were calculated. A baseline scenario, in which no SuDS were implemented in the model, was simulated using an extreme rainfall event with a return period of 1000 years. Simulations were performed for seven different storm durations. In the following, separate simulations were performed for each of the examined SuDS, and the results were compared with the baseline scenario against the assessment criteria specified in section 9.2.6.

9.2.2 Permeable Paving

From the subcatchment generation process, total impermeable area values are available for each subcatchment. These areas were further broken down into different types of impermeable areas, such as paths, roads, roofs, and parking. As 100% adoption of all paved areas is highly unlikely, either due to slope restrictions or maximum loading or the existence of proposed services which cannot be laid in permeable paving, the uptake of permeable paving within the development site was limited to designated car parking areas. The designated car parking areas of the examined location can be seen in Figure 49.
A partial infiltration system was selected for this research, which allows some infiltration into the ground while stored, but also allows for flow to enter the system. The partial infiltration system was chosen because ground conditions from different sites may vary and could mean that full infiltration with no connection to the surface water network s possible, or it could mean that permeability is poor, and no infiltration is possible, therefore a partial infiltration system was chosen as a compromise between the two scenarios.

Standard dimensions for permeable paving were used to replicate the attenuation on a subcatchment level, with a 0.6m depth and a voids ratio of 0.3 (CIRIA, 2015). To replicate the attenuation volume present within each subcatchment, an infiltration trench was modelled of 1m length and a width equal to the total parking surface area present within each subcatchment. The use of an infiltration trench allows for the partial infiltration to ground of 2500mm/hr (CIRIA, 2015) (this has been attributed a safety factor of 2, which leads to infiltration of 1250 mm/hr, which is used to factor the reduction of infiltration over time caused by sediment build up) and is connected into the surface water network by a 75 mm entry pipe.

9.2.3 Rainwater harvesting

Using a CIRIA SUDS Manual (CIRIA, 2015) the implementation of rainwater harvesting in the proposed development site was calculated based on the total roof area within each subcatchment identified from the subcatchment generation process. From the SUDS manual, the simple surface water management method was used.

This was used on the basis that the ratio between Yr (Yield Volume) and Dn (Average annual demand) is less than 0.33. Therefore annual average demand can be discounted towards the total storage volume.

$$D_N = P_d\, n\ \times 365\ \times 0.05 \tag{11}$$

Where:
D_N = total annual property demand for non-potable water (l)
P_d = daily demand per person (l)
n = number of occupants in the property

The daily demand per person was set at 40 liter/capita/day (CIRIA, 2015). According to the Office of National Statistics (Office for National Statistics, 2013), the average occupancy rate for properties in the United Kingdom is currently 2.3. Using the above-mentioned values, the total annual demand for non-potable water is calculated at DN = 1,679.

The design storm event runoff coefficient is identified in The SUDS Manual (CIRIA, 2015) as 0.9 (a standard pitched roof with tiles). This also specifies that the hydraulic filter efficiency ratio should be set as 90% (0.9) unless manufacturer specifications state otherwise.

The total storage area for each subcatchment was calculated using:

$$V_{SC} = \frac{A\ R_d\ \beta\ \eta}{1000} \tag{12}$$

Where:

V_{SC} = storage volume (m^3)

A = contributing runoff area (m^2)

R_d = design storm event rainfall depth (mm)

β = design storm runoff coefficient

η = hydraulic filter efficiency (ratio)

9.2.4 Attenuation basins

The third SuDS option considered in this case study consists of a series of attenuation basins and storage ponds that are located outside the development boundary along the route of the surface water network. The existing pipes at these locations have been replaced with 1 in 3 side sloped swales to the west of the site, while two large storage ponds have been sized to the south. These attenuation basins are designed with a limited discharge of 5 l/s. One of the attenuation basins is located at utility hole S51 with a total storage volume of 1,454.1m^3, and the second one is located at utility hole S47 with a total storage volume of 2,654.2m^3. The exact location of utility holes S47 and S51 can be seen in Figure 48.

No infiltration was considered as part of this scenario for the attenuation basins and are considered purely for attenuation of contributing flows.

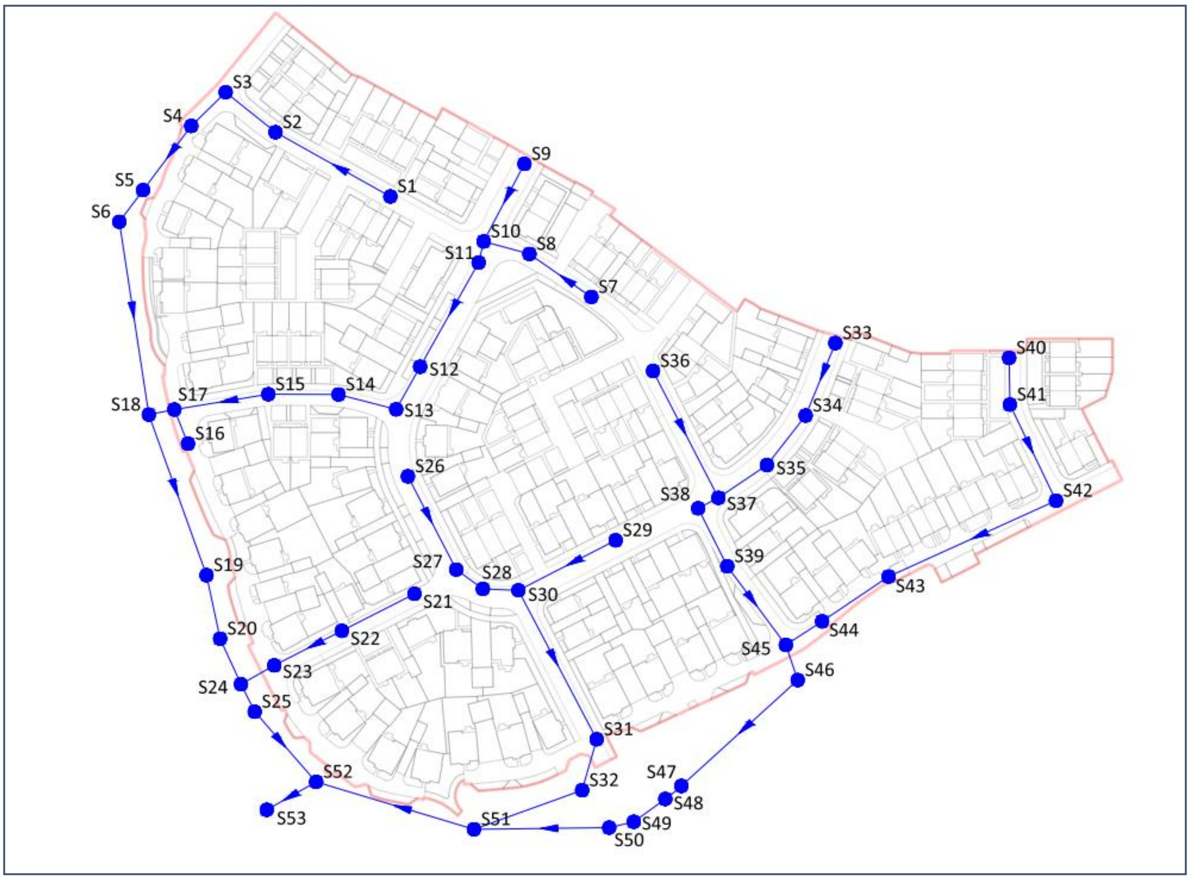


Figure 50 Overview of surface water network for the examined development site

9.2.5 Modelling assumptions

Several assumptions were made in order to allow for a direct comparison between different scenarios without any external factors or variables:

- No incoming flows would enter the system from the surrounding areas. It was assumed that the proposed surface water network is isolated, and no interaction with any other surface water or foul network was present. As the vast majority of new build development sites would be on the outskirts of existing urban areas, it was assumed that the development site would be located at the head of the surface water network.
- No infiltration into the surface water network has been included as part of this research. This is because this research is focused on new residential developments. Therefore it was reasonable to assume that all surface water pipes and connections would be sealed correctly, and there would be no degradation of the network.

- 100% of the factored contributing area was applied to each subcatchment. This represents the worst-case scenario for each subcatchment where all calculated areas will drain to the surface water network.
- Full uptake of each SuDS system was assumed for all areas that relate to the SuDS aspect being assessed.
- Ground conditions are acceptable for infiltration.
- All flooding was modelled as a ‘stored’ flood type. This means that volumes of flooding are stored in a flood cone above ground and re-enter the network when capacity is available. This, therefore, means that no volume is lost in the network once it floods.

9.2.6 Assessment criteria

The model simulations were analyzed by three assessment criteria, which are specified below, in order to determine the effectiveness of each scenario through the varying rainfall intensities. The assessment criteria used in this case study are:

- Individual flood volume: the individual flood volume for each node was assessed to determine whether localized flooding within the site can be reduced with the incorporation of SUDS. Scenarios were assessed for reduction of flood volume at each modeled node during the critical duration storm event. The impact of SuDS was also checked against non-critical duration storm events, and the most significant impact (positive and negative) was identified.
- Total flood volume (Catchment wide): this assesses the overall site wide benefit of SuDS, for instance, where a localized issue may predict no improvement or detriment; however, the remaining system overall showed significant improvement when assessing the total volume of flooding predicted.
- The total reduction in volume: that assesses the amount of infiltration that the SuDS options provide to reduce the volume in the network. In this case study, there was no modeled infiltration in the baseline scenario, so any infiltration predicted will be the direct result of the proposed options.

9.3 Examined area

The residential development is located in the South West of England and covers a total area of 4.124 ha, of which 2.798 ha is classified as impermeable and 1.326 ha permeable. There are 148 properties within the development site. The surface water network for this site contains 1,259.842 m of the sewer with 53 manholes. Figure 49 shows a surface breakdown of the development site.

Figure 51 Overview of runoff surface breakdown within the development site

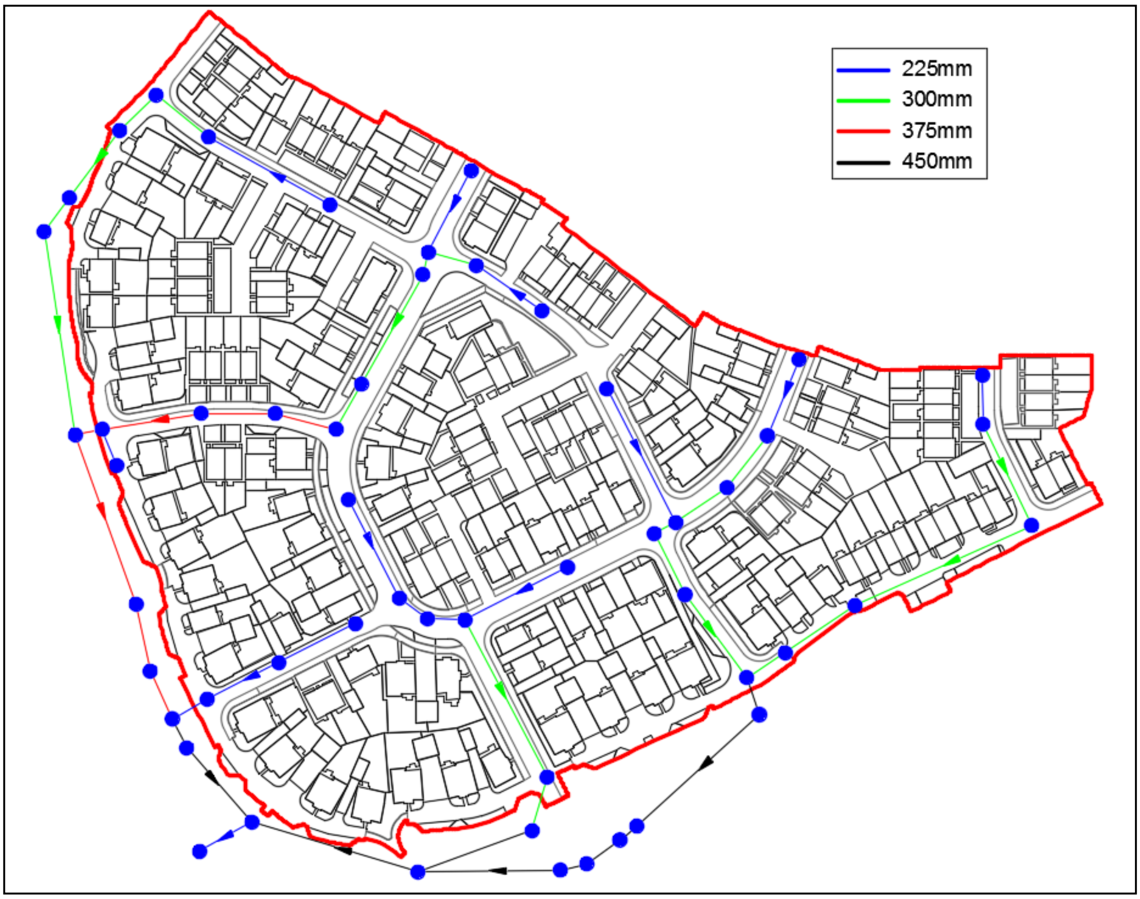


Figure 52 Pipe diameters within the network

Figure 50 shows the different pipe diameters with the network of the examined development. Furthermore, Table 20 provides the total length of each pipe diameter used in the network.

Table 19 Sewer diameters and lengths

Diameter (mm)	**Length (m)**
225	336.128
300	501.176
375	167.346
450	225.192

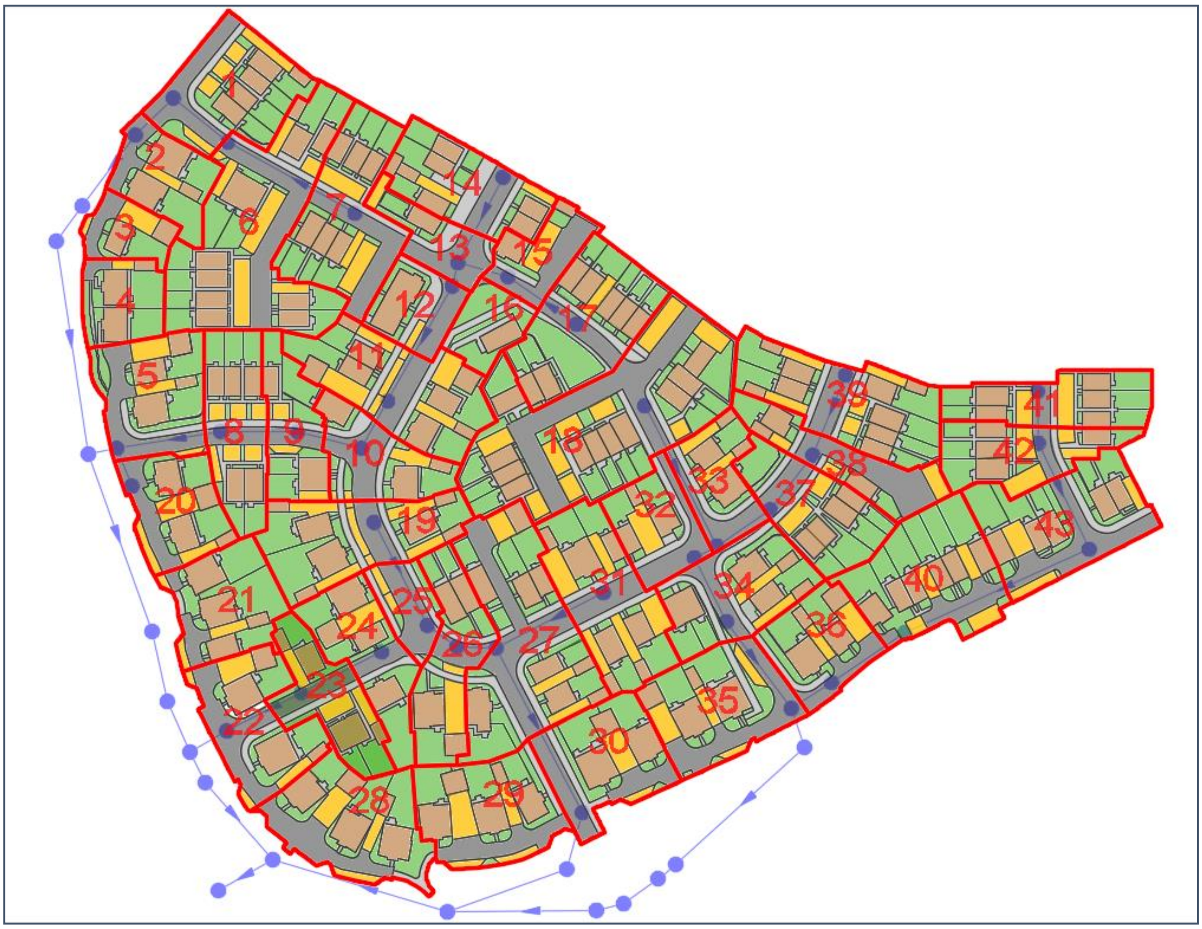


Figure 53 Generated subcatchments

9.4 Modelled rainfall event

Synthetic Flood Studies Report (FSR) rainfall with a return period of 1000 years was applied to the development site. Simulations were performed for storm durations of 30, 60, 120, 240, 360, 720, and 1440 minutes.

The FSR rainfall was developed using recorded rainfall from 1941 to 1970, and the rainfall model was calculated based on the rainfall depth during a 5-year 60-minute storm event for the geographic location provided.

Synthetic rainfall assumes a symmetrical profile, with rainfall intensities exponentially increasing over time to the rainfall peak exactly halfway during the rainfall event. From this point, rainfall intensity reduces at the same rate that it increased.

No climate change was considered as part of this research. In order to replicate the worst-case scenario for the surface water network, a summer profile has been selected for this study.

As the development site is located in the South West of England, MicroDrainage applied the M5-60 storm depth of 19 mm and a ratio R-value of 0.4.

The ratio R is the ratio of rainfall depths from storm events of 60 minutes divided by 2880 minutes (2-day duration). As per the rainfall depth, this is determined by the location of the model within the UK. These values were selected from MicroDrainage using the map browser to select a general area (south west England).

9.5 Results and discussion

The following results and discussion focus on the modeling outputs from MicroDrainage against the assessment criteria specified in Section 9.2.6.

9.5.1 Baseline scenario

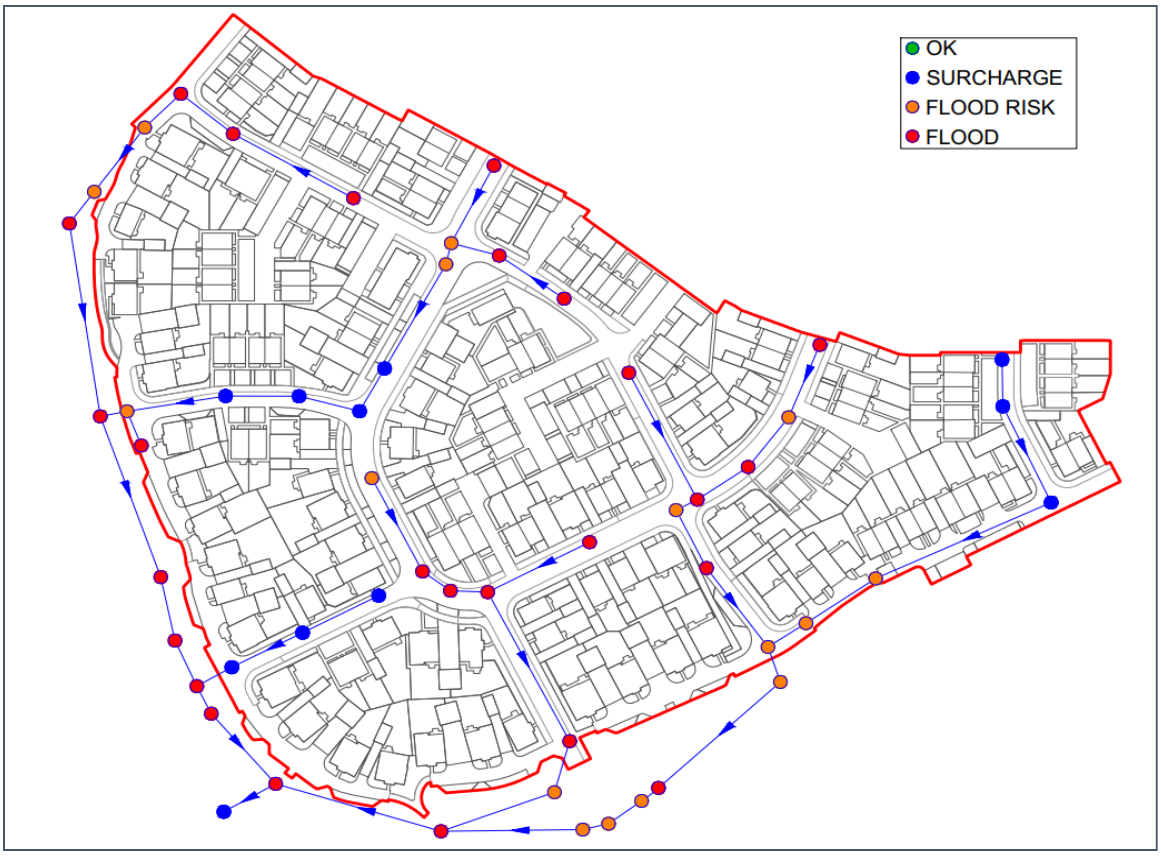


Figure 54 1000-year baseline flooding locations

The simulation results show significant flooding throughout the catchment. In total, there are 26 predicted flood locations and a further 16 flood risk locations. This number of flooding and near flooding locations (80% of all manholes within the catchment) shows that the entire system is inundated and there is insufficient capacity throughout the system to deal with a storm event of this magnitude.

Table 20 Max flood volume critical storm duration for baseline scenario

Manhole Name	Max Flood Volume (m^3)	Critical Storm Duration (min)
1	0.373	30
2	6.56	30
3	0.38	30
6	15.403	30
7	0.037	30
8	2.546	30
9	1.651	30
16	1.113	30
18	239.988	120
19	178.678	120
20	164.695	120
24	110.488	120
25	132.501	60
27	3.288	30
28	17.6	30
29	0.414	30
30	1.39	30
31	1.014	30
33	1.298	30
35	6.085	30
36	31.392	30
37	3.032	30
39	12.63	30
47	53.798	60
51	16.997	60
52	0.481	30

TOTAL	1003.83	-

9.5.2 Permeable paving

As shown in Figure 49, each subcatchment within the development site had a contributing parking area. This meant that the implementation of the permeable paving solution would provide additional storage volume throughout the network, in addition to catchment-wide infiltration of varying degrees depending on the total parking area within the individual subcatchments.

Simulations showed that critical durations were not altered by this solution, with short duration rainfall events still producing the worst case predicted flooding.

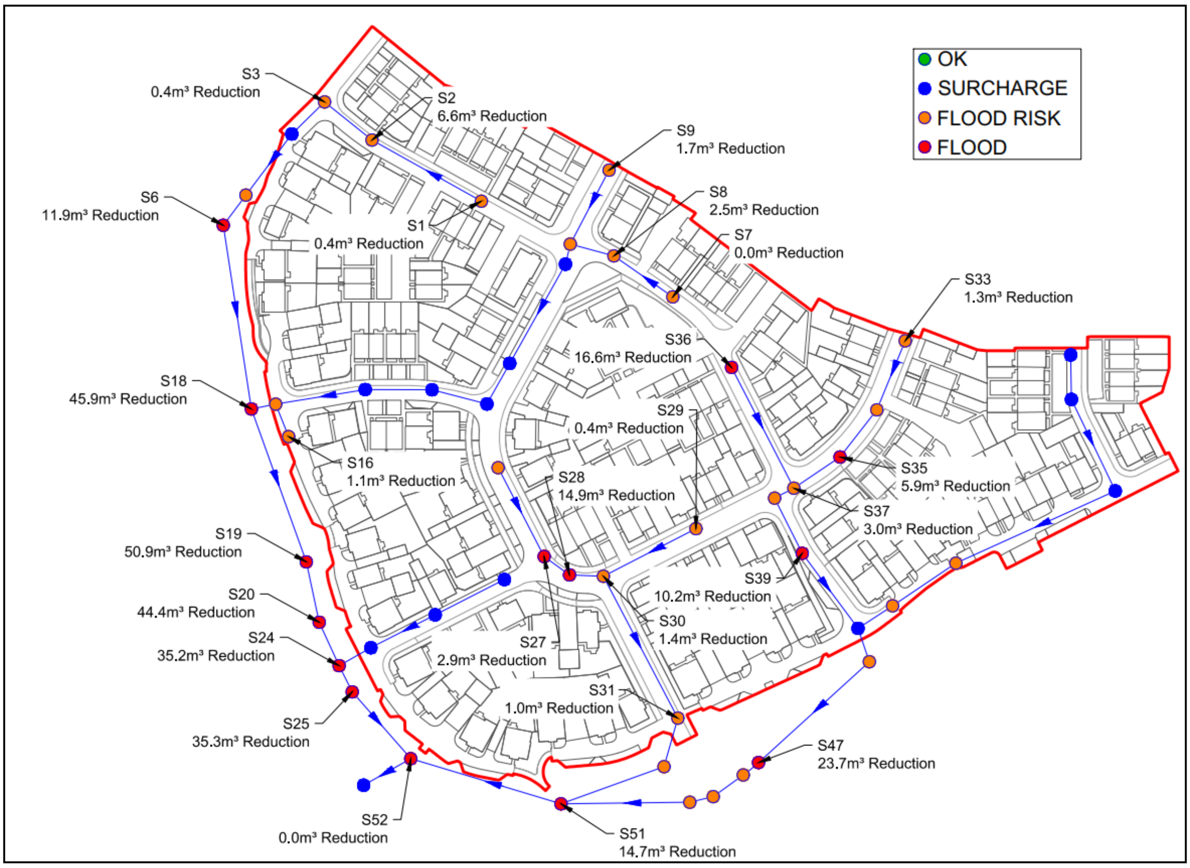


Figure 55 1000-year flooding locations - permeable paving

Table 21 Impact of permeable pavement on max flood volume

BASELINE			SCENARIO 1 (Permeable Paving)		
Manhole Name	Max Flood Volume (m³)	Critical Storm Duration (min)	Max Flood Volume (m³)	Impact (m³)	Impact (%)
1	0.373	30	0	-0.373	-100
2	6.56	30	0	-6.56	-100
3	0.38	30	0	-0.38	-100
6	15.403	30	3.47	-11.933	-77.5
7	0.037	30	0	-0.037	-100
8	2.546	30	0	-2.546	-100
9	1.651	30	0	-1.651	-100
16	1.113	30	0	-1.113	-100
18	239.988	120	194.11	-45.878	-19.1
19	178.678	120	127.731	-50.947	-28.5
20	164.695	120	120.34	-44.355	-26.9
24	110.488	120	75.315	-35.173	-31.8
25	132.501	60	97.179	-35.322	-26.7
27	3.288	30	0.373	-2.915	-88.7
28	17.6	30	2.607	-14.993	-85.2
29	0.414	30	0	-0.414	-100
30	1.39	30	0	-1.39	-100
31	1.014	30	0	-1.014	-100
33	1.298	30	0	-1.298	-100
35	6.085	30	0.123	-5.962	-98
36	31.392	30	14.73	-16.662	-53.1
37	3.032	30	0	-3.032	-100
39	12.63	30	2.473	-10.157	-80.4
47	53.798	60	30.122	-23.676	-44
51	16.997	60	2.322	-14.675	-86.3
52	0.481	30	0.48	-0.001	-0.2
TOTAL	1003.83	-	671.375	-332.46	-33.1

With widespread flooding predicted across the catchment, the permeable paving attenuation and infiltration capabilities potential provides a noticeable benefit to the site during critical durations. Figure 53 shows that predicted flood volumes were reduced or resolved to flood risk classification at six locations throughout the catchment. There were also four additional locations where water levels reduced from flood risk status to surcharge. The total reduction in peak flood volume is predicted to be 332.46 m^3, equating to a 33.1% reduction.

9.5.3 Rainwater harvesting

Rainwater harvesting scenario simulations provide attenuation for each subcatchment (with the exception of subcatchment 25, which has no contributing roof area). The areas calculated from the subcatchment generation process identified significantly higher areas on average compared against scenario 1, which consequently would lead to more attenuation available in the network. However, unlike the permeable paving scenario, the rainwater harvesting has been replicated with no infiltration into the ground, so while there is higher volume in the rainwater harvesting scenario, there will be more flow to attenuate/discharge.

Simulations showed that the implementation of rainwater harvesting did not impact the critical durations for peak flood volumes within the network.

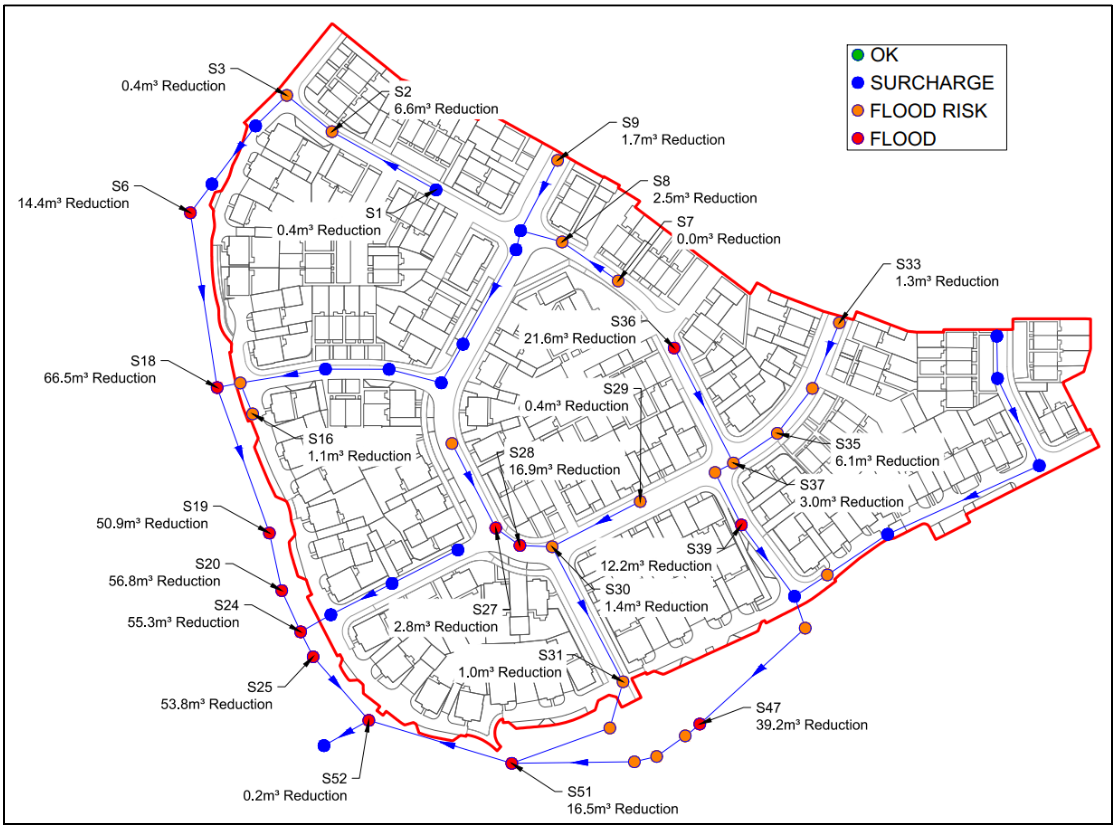


Figure 56 1000-year flooding locations - rainwater harvesting

Table 22 Impact of rainwater harvesting on max flood volume

BASELINE			SCENARIO 2 (Rainwater harvesting)		
Manhole Name	Max Flood Volume (m³)	Critical Storm Duration (min)	Max Flood Volume (m³)	Impact (m³)	Impact (%)
1	0.373	30	0	-0.373	-100
2	6.56	30	0	-6.56	-100
3	0.38	30	0	-0.38	-100
6	15.403	30	0.96	-14.443	-93.8
7	0.037	30	0	-0.037	-100
8	2.546	30	0	-2.546	-100
9	1.651	30	0	-1.651	-100
16	1.113	30	0	-1.113	-100
18	239.988	120	173.445	-66.543	-27.7
19	178.678	120	156.181	-22.497	-12.6
20	164.695	120	107.909	-56.786	-34.5

24	110.488	120	55.201	-55.287	-50
25	132.501	60	78.747	-53.754	-40.6
27	3.288	30	0.526	-2.762	-84
28	17.6	30	0.749	-16.851	-95.7
29	0.414	30	0	-0.414	-100
30	1.39	30	0	-1.39	-100
31	1.014	30	0	-1.014	-100
33	1.298	30	0	-1.298	-100
35	6.085	30	0	-6.085	-100
36	31.392	30	9.782	-21.61	-68.8
37	3.032	30	0	-3.032	-100
39	12.63	30	0.452	-12.178	-96.4
47	53.798	60	14.645	-39.153	-72.8
51	16.997	60	0.466	-16.531	-97.3
52	0.481	30	0.303	-0.178	-37
TOTAL	1003.83	-	599.366	-404.47	-40.3

It is predicted that the implementation of rainwater harvesting will provide sufficient benefit to the network to resolve 13 locations of predicted flooding across the network. The majority of these locations are located at the upstream end of the branches, indicating that the calculated attenuation volumes allow for sufficient storage during peak conditions to prevent flooding until capacity in the network is made available.

The total predicted flooding benefit is 404.47m³ of runoff across the 26 flood locations predicted during the baseline scenario, representing a 40.3% improvement to the network. Three other locations in the network were shown to improve from flood risk to a surcharge state.

9.5.4 Attenuation basins

The provision of attenuation basins in the downstream network where flooding is predicted provides significant benefit. However, the provision of attenuation downstream does not guarantee that flooding in the upstream branches of the network will be resolved. This scenario also assumes that the surrounding areas to the development site have no existing developments/uses that would limit or prevent the construction of large attenuation basins on the boundary borders.

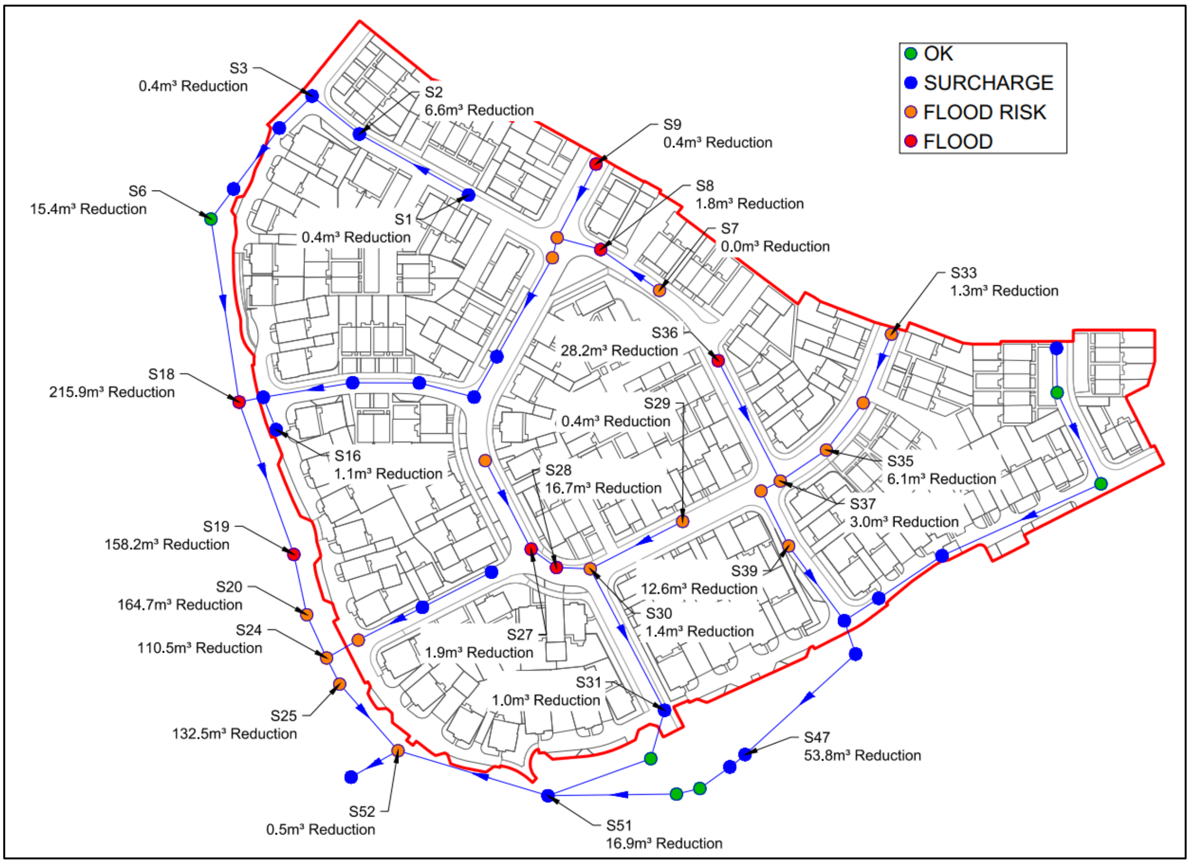


Figure 57 1000-year flooding locations - attenuated basins

Model simulations show that the majority of flooding in the catchment is resolved in this scenario with a total reduction in flooding of 951m^3, approximately 95%.

Table 23 Impact of attenuation basins on max flood volume

BASELINE			SCENARIO 2 (Rainwater harvesting)		
Manhole Name	Max Flood Volume (m^3)	Critical Storm Duration (min)	Max Flood Volume (m^3)	Impact (m^3)	Impact (%)
1	0.373	30	0	-0.373	-100
2	6.56	30	0	-6.56	-100
3	0.38	30	0	-0.38	-100
6	15.403	30	0	-15.403	-100
7	0.037	30	0	-0.037	-100
8	2.546	30	0.746	-1.8	-70.7
9	1.651	30	1.26	-0.391	-23.7
16	1.113	30	0	-1.113	-100
18	239.988	120	24.022	-215.966	-90
19	178.678	120	20.467	-158.211	-88.5
20	164.695	120	0	-164.695	-100
24	110.488	120	0	-110.488	-100
25	132.501	60	0	-132.501	-100
27	3.288	30	1.323	-1.965	-59.8
28	17.6	30	0.934	-16.666	-94.7
29	0.414	30	0	-0.414	-100
30	1.39	30	0	-1.39	-100
31	1.014	30	0	-1.014	-100
33	1.298	30	0	-1.298	-100
35	6.085	30	0	-6.085	-100
36	31.392	30	3.24	-28.152	-89.7
37	3.032	30	0	-3.032	-100
39	12.63	30	0	-12.63	-100
47	53.798	60	0	-53.798	-100
51	16.997	60	0	-16.997	-100
52	0.481	30	0	-0.481	-100
TOTAL	1003.83	-	51.992	-951.84	-94.8

10 : Chapter Conclusions

Extreme weather events can significantly affect the performance of the buildings. This study aimed to examine the resilience of three different types of buildings to extreme hot weather conditions and under extreme rainfall.

This thesis has presented six case studies, four regarding the resilience of buildings to extreme heat and two to extreme rainfall. Each case study was undertaken to examine improvement measures on the resilience of buildings to extreme weather events.

The examined case studies are:

1. Effect of window-to-wall ratio on thermal comfort and energy consumption
2. Effect of relative humidity on thermal comfort
3. Ventilation techniques to reduce the risk of overheating of a school building
4. Effect of automated natural ventilation and lighting strategy on the thermal comfort for a residential building
5. Effect of building development on the risk of the flooding
6. The effects of sustainable drainage systems on residential developments during extreme rainfall

The results of this research work present practical approaches of mitigating the effects of extreme hot weather and extreme rainfall events. This study has shown that buildings with fully glazed facades are likely to become intolerable for the occupants in the future and that buildings with lower window to wall ratios will have better thermal comfort conditions. Furthermore, it has demonstrated that relative humidity control can improve the thermal comfort conditions for the occupants of a building and therefore should be considered as measure to mitigate the effect of extreme hot weather. Additionally, this research has demonstrated that for a residential building automated control of the opening of the windows results in reduced operative temperatures and improved thermal comfort conditions. Based on the results of the simulations performed, this study recommends that for school buildings similar to the one examined in this research mixed mode ventilation should be preferred over mechanical ventilation strategy, as it results in less energy consumption. This research has also quantified the effect of three SuDS for a new build residential development.

The results of this Thesis serve as design guidelines for buildings to help increase their resilience to extreme hot weather and extreme rainfall events.

10.1 Case Study 1: Effect of window-to-wall ratio on thermal comfort and energy consumption

This case study examined eight variations of the window-to-wall ratio for an educational building and quantified its effect on the cooling and lighting loads and the thermal comfort conditions.

The results of the simulations have shown that a window-to-wall ratio of 30% results in the least amount of cooling loads and a window-to-wall ratio of 80% or 90% results in the least amount of lighting loads. Facades with a window-to-wall ratio of 40% to 50% have the lowest combined value of cooling and lighting loads.

Investigation of the thermal comfort conditions during the hottest day of the examined period has shown that lower window-to-wall ratios result in more comfortable conditions. Especially under the projected weather conditions of the 2050s, only when the building is modelled with a 20% or 30%, the window-to-wall ratio can thermal comfort conditions be achieved. The high PPD values of ratios from 40%-90% show that buildings with glazed facades are likely to become intolerable for the occupants in the future.

10.2 Case Study 2: Effect of relative humidity on thermal comfort

This study examined the effect of relative humidity on the thermal comfort of a fully glazed office building in West London under the current weather conditions and the projected weather conditions of the 2050s during the non-heating period from May to September.

Investigation of the effect of relative humidity on the thermal comfort has shown that when the relative humidity is set to 40%, thermal comfort is improved on 68% of the total occupied hours during the summer months.

10.3 Case study 3: Ventilation techniques to reduce the risk of overheating of a school building

This study examined the risk of overheating for a school building in 14 different locations in the UK using the CIBSE DSY weather data sets. It identified locations in the UK where naturally ventilated school buildings with similar construction are likely to achieve thermal comfort conditions even under extreme hot weather conditions. Furthermore, it examined the performance of the building in mixed mode and as mechanically ventilated, and it quantified the amount of cooling loads required in order to comply with the BB101 criteria. Finally, it performed simulations of the building under projected weather conditions of the 2050s and presented a comparison between the current and the future weather conditions.

This chapter has shown that in Glasgow and in Edinburgh classrooms of naturally ventilated school buildings are likely to comply with the overheating criteria set in BB101 under the current weather conditions. For the rest of the examined locations, the building requires mechanical cooling in order to achieve thermal comfort conditions, Simulations of the building in mixed mode and as mechanically ventilated have shown that mixed mode ventilation should be preferred over mechanical ventilation strategy, as it results in less energy consumption.

10.4 Case study 4: Effect of Automated Natural Ventilation and Lighting Strategy on the Thermal Comfort for a Residential Building

This study aimed to identify the effect of automated control systems on thermal comfort and lighting gains. More specifically, it examined a typical detached residential building in the UK using dynamic thermal simulation and the weather files from CIBSE and presented the results for a south facing and a north facing bedroom.

Automated control of the opening of the windows resulted in reduced operative temperatures and improved thermal comfort conditions. Operative temperatures of the examined rooms were compared with the 80% and 90% acceptability limits defined in ASHRAE 55-2010. Using automated control systems on the windows resulted in differences of up to 4°C during the daytime. Automated control of lighting based on target illuminance levels resulted in a 49% reduction of lighting gains for both rooms.

10.5 Case study 5: Effect of building development on the risk of the flooding

This chapter looked into the effect of building development on the risk of flooding under extreme rainfall conditions for an area with a 0.1% chance of flooding from surface water.

Two different scenarios were modelled, one represented the area in its current condition with very little building development, and the other with full building development.

Comparison of the results of the two scenarios shows that building development affects the risk of flooding from surface water, even in areas with a meagre chance of flooding. In the scenario with complete building development, the results have shown higher water depths and an increase in the areas of the examined field with a hazard above zero. Furthermore, water penetrated into all the modelled buildings, which had a fill height of 0.30 meters.

10.6 Case study 6: The Effects of Sustainable Drainage Systems on Residential Developments During Extreme Rainfall

This research set out to determine the quantitative benefits of three different types of SuDS (permeable paving, rainwater harvesting & attenuation basins) for a new build residential development.

The simulation results indicate that the implementation of SUDS shows a net benefit with regards to flooding volumes, which was expected as increasing storage volume or infiltrating flows from the network will reduce the demand on the network.

The rate of reduction between different SuDS solutions varies. For instance, the permeable paving solution (scenario 1) provides an approximate 33% benefit against the examined storm events. While this is found to be the smallest percentage benefit, it must also be considered that the available area for implementation of permeable paving is approximately half of the available area for scenario 2 (RWH). If the implementation of permeable paving were to be expanded to include different types of paving or footpaths, the predicted benefit would also increase.

Based on the determined areas within each subcatchment, it is clear that the implementation of rainwater harvesting would be the easiest solution to incorporate into new developments, as every development site is guaranteed to have a roof area, whereas the availability of paving suitable for permeable paving is unknown.

The implementation of scenario 3 (attenuation basins) showed the most significant benefit in terms of flood reduction and would also provide an amenity as well as biodiversity benefits for the development. In this scenario, flooding was limited to seven locations. However, it must be considered that the location of the attenuation basins and swales was outside the development site and cannot necessarily be transferred to a different development site, as the cost of purchasing this land for designated attenuation basins has not been assessed or incorporated into this research. It also cannot be guaranteed that the required land area would be available without further knowledge of the surrounding area.

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